ANNUAL REPORT 2001



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INTRODUCTION

Last year the Nuclear Physics Laboratory (NPL) officially became the Center for Experimental Nuclear Physics and Astrophysics (CENPA), with an expanded mandate. CENPA includes the activities of the former NPL and in addition fosters collaborative work among the members of the NPL and others in the University of Washington Physics Department and elsewhere. CENPA pursues a broad program of research in nuclear physics, astrophysics and related fields. Research activities are conducted locally and at remote sites. The current program includes "in-house" research on nuclear collisions and fundamental interactions using the local tandem Van de Graaff and superconducting linac accelerators, as well as local and remote non-accelerator research on fundamental interactions and user-mode research on relativistic heavy ions at large accelerator facilities in the U.S. and Europe.

A good ⁷Be(p,g)⁸B Phase I data taking run has been completed and the data are being analyzed. We used a 100 mCi target fabricated on a newly designed post backing with a breakaway washer, eliminating unwanted target tails. All important sources of systematic error were measured, including loss of ⁸B due to backscattering out of the target. We expect to meet our goal of 5% precision on the cross section and the astrophysical S-factor.

The SNO detector has been running in a production mode with pure heavy water in the acrylic vessel since November 1999. Analysis of the data taken since that time has been directed towards a measurement of the rate of charged-current interactions of ⁸B neutrinos, and will be completed soon. Both the SNO collaboration and the scientific community await this milestone with interest.

A new collaboration of CENPA members with the University of Mainz, Kernforschungszentrum Karlsruhe, and other institutions to carry out a large-scale experiment on tritium beta decay has formed. The objective is a direct kinematic measurement of the mass of the electron antineutrino with 0.5-eV sensitivity.

The notion of "large extra dimensions" has recently attracted a great deal of attention, particularly as a solution of the gravitational hierarchy problem. For example, the "true" Planck mass could be lowered to about 1 TeV if two of the extra 7 dimensions of string theory had sizes of around 1 mm. This would show up as a violation of the gravitational inverse-square law for separations less than a milimeter. We recently used a novel torsion balance instrument to test the inverse-square law down to 0.2 mm and found no evidence for anomalies, which implies an unification mass of > 3.5 TeV.

The big news in ultrarelativistic heavy ion physics this year is first data from the RHIC collider. Experimental results have been pouring in from all four experiments. The UW event-by-event program has pioneered a number of novel analysis techniques that are now being brought to bear on the first batch of STAR data. We have seen for the first time substantial dynamical fluctuations in event-wise mean transverse momentum, possibly signaling new QCD effects in Au-Au collisions, and charge- or isospin-dependent correlation structures possibly connected to novel structure on the hadronic freezeout surface formed during rapid traversal of the QCD phase boundary.

A study of collision-induced multifragmentation of C_{60} has been completed. Multifragmentation into three or more fragments each with three or more carbons in each fragment is found to be an important reaction channel for large deposition energies. An odd-even dependence of fragment yields implies sequential decay of chain or ring multifragmentation products.

As always, we encourage outside applications for the use of our facilities. As a convenient reference for potential users, the table on the following page lists the capabilities of our accelerators. For further information, please contact Prof. Derek W. Storm, Executive Director, Nuclear Physics Laboratory, Box 354290, University of Washington, Seattle, WA 98195; (206) 543-4080, or storm@npl.washington.edu. Further information is also available on our web page: http://www.npl.washington.edu.

We close this introduction with a reminder that the articles in this report describe work in progress and are not to be regarded as publications or to be quoted without permission of the authors. In each article the names of the investigators are listed alphabetically, with the primary author, to whom inquires should be addressed, underlined.

Derek Storm, Editor storm@npl.washington.edu (206) 543-4085

Barbara Fulton, Assistant Editor

TANDEM VAN DE GRAAFF ACCELERATOR

A High Voltage Engineering Corporation Model FN purchased in 1966 with NSF funds; operation funded primarily by the U.S. Department of Energy. See W.G. Weitkamp and F.H. Schmidt, "The University of Washington Three Stage Van de Graaff Accelerator," Nucl. Instrum. Meth. **122**, 65 (1974).

Ion	Max. Current	Max. Energy	Ion Source
	(particle m A)	(MeV)	
¹ H or ² H	50	18	DEIS or 860
³ He or ⁴ He	2	27	Double Charge-Exchange Source
³ He or ⁴ He	30	7.5	Tandem Terminal Source
⁶ Li or ⁷ Li	1	36	860
¹¹ B	5	54	860
¹² C or ¹³ C	10	63	860
* ¹⁴ N	1	63	DEIS or 860
¹⁶ O or ¹⁸ O	10	72	DEIS or 860
F	10	72	DEIS or 860
* Ca	0.5	99	860
Ni	0.2	99	860
I	0.01	108	860

Some Available Energy Analyzed Beams

* Negative ion is the hydride, dihydride, or trihydride.

Additional ion species available include the following: Mg, Al, Si, P, S, Cl, Fe, Cu, Ge, Se, Br and Ag. Less common isotopes are generated from enriched material.

ANNUAL REPORT

Center for Experimental Nuclear Physics and Astrophysics

University of Washington

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Introduction <u>Accelerator Beams available</u> (Much of this material is in PDF format. <u>Download Adobe Acrobat Reader</u>) <u>Detailed Table of Contents</u>

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1 Fundamental Interactions

1.1 Eöt-Wash data acquisition

E. G. Adelberger, B. R. Heckel, C. D. Hoyle, D. J. Kapner, S. Merkowitz,^{*} U. Schmidt[†] and <u>H. E. Swanson</u>

The current data acquisition code is written in Microsoft Visual C++. The User Interface which includes data plots and control panels is built with National Instruments Lab Windows CVI. A custom driver was written for the data acquisition hardware that reads sixteen 16-bit ADC's, switches among sixteen channels of a temperature-sensor multiplexer, and otherwise controls the experiment. This combination can run at an interrupt rate of up to 20 Hz where each interrupt is a burst of four at a 240 Hz rate. This burst of four is averaged to filter any 60 or 120 Hz component of the signal. These can be further averaged up to the period between two samples. Data is continually displayed whether or not it is being written to the disk. Two of the experiment data stations run variations of this code under the Windows 98 operating system.

<u>The Eöt-Wash II data station</u>: The data acquisition program for the Eöt-Wash II experiment was upgraded last year but remains a Turbo Pascal program running under the DOS operating system. A second computer houses the DSP based controller for the turntable speed. A Stanford Research Systems (SRS) function generator provides the clock which determines the turntable speed. It communicates with the acquisition program by serial link.

<u>The Eöt-Wash III data station</u>: The general features of this program have been previously reported.¹ Since then communication with the DSP turntable speed controller has been fully integrated into the acquisition program. The DSP generates the timing for both sampling the data and the turntable speed. It now includes code to drive stepping motors for the fiber attachment's angle and z position, and the screws which adjust the rough heights of the mounting legs. Precise control of the tilt of the apparatus is achieved by varying the temperature of these legs as described in Section 1.3.

The Short-Range data station: The Turbo Pascal program and 486 based computer used for the Rotwash experiment and first Short-Range measurement has been replaced by a pentium class computer running the software described above. It writes a compatible data file and has the same functionality as the old program such as automatic calibration of the attractor angle readout. Three phase locked (SRS) function generators control the sample period, and the periods of the attractor and calibration turntables. These can all be set to integer multiples of the pendulum period. GPIB communication with the function generators and lockin amplifiers is integrated into the code.

An independent Lab Windows program communicates with a Newport stepping motor controller to set the fiber attachment's angle, and x, y, and z positions. Another reads a capacitance meter measuring the pendulum - screen capacitance. In the future these functions will be added to the acquisition program.

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¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 13.

1.2 Millimeter-scale test of the gravitational inverse square law

E. G. Adelberger, J. H. Gundlach, B. R. Heckel, <u>C. D. Hoyle</u>, D. J. Kapner, A. Kopp,^{*} U. Schmidt,[†] D. Spain[‡] and H. E. Swanson

Since our last report,¹ we have made significant progress toward testing gravity at distances less than 1 mm with specially designed torsion balances. Our experiments are principally motivated by higher-dimensional string theories which predict deviations from the gravitational inverse-square law at short distances.² These deviations are typically parameterized as an addition of a Yukawa term to the Newtonian potential,

$$V(r) = -G(\frac{m_1 m_2}{r})(1 + \alpha e^{-r/\lambda}).$$
 (1)

We have achieved the best constraints to date on the parameters α and λ for short distances (see Fig. 1.2-1). These results have recently been published.³



Figure 1.2-1. Constraints on the strength, α , and range, λ , of a new interaction of the form given in Eq. (1). The heavy line labeled Eöt-wash is from this work. See C.D. Hoyle *et al.*³ for references regarding the theoretical predictions and other experimental limits.

Our apparatus consisted of a disk-shaped torsion pendulum containing 10 holes evenly spaced about the azimuth. The pendulum was suspended above a rotating attractor of similar geometry. A gravitational or Yukawa interaction between the holes produced a torque on the pendulum that varied periodically at 10 times per attractor revolution (higher harmonics were present as well). The attractor was composed of two stacked disks. The holes in the lower disk were rotated relative to

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¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 11.

²see, for example, N. Arkani-Hamed, *et al.*, Phys. Lett. B **429**, 263 (1998).

³ C. D. Hoyle *et al.*, Phys. Rev. Lett. **86**, 1418 (2001).

those in the upper disk in such a way as to suppress Newtonian torques, while leaving the signature of a short-range interaction unchanged. A thin, beryllium-copper electrostatic screen separated the pendulum and attractor.

Our published data³ constrained the Yukawa interaction modeled by the two extra dimension scenario to have a range less than 190 μ m, corresponding to a unification scale greater than 3.5 TeV. Testing gravity at even shorter length scales requires improvements in two main areas. First, the pendulum and attractor geometries must be optimized for the range of interest. Second, the separation between the pendulum and attractor must be made as small as possible. In the last year, we have concentrated much effort into these two areas.

To optimize the geometry, a detailed numerical integration code was developed. This code is described separately in this report (see Sec. 1.5). The optimization resulted in the design shown in Fig. 1.2-2. This new design has 26-fold symmetry. The Newtonian torques are suppressed to a very high degree and effects due to a short-range interaction are enhanced relative to the previous data.

Several innovations have been applied to achieve the smallest possible pendulum/attractor separation. A copper bellows in series with the torsion fiber reduced the vertical "bounce" amplitude to around 1 μ m, a factor of 10 improvement. An improved magnetic damper has also reduced the simple pendulum, "swing," mode. In addition, a thinner (10 μ m thick) electrostatic screen has been implemented. The active components of the pendulum and attractor are made of titanium and molybdenum respectively. These materials can be made very flat with careful machining and grinding techniques, reducing problems due to surface irregularities. Finally, we devised improved capacitive techniques for leveling and aligning the disks.

We are presently taking data with the new design and expect to have much improved results this year. Pendulum-attractor separations of less than 0.1 mm should be attained.



Figure 1.2-2. The pendulum and rotating attractor of our second-generation experiment. The shaded disks are the active components. The mirrors used for the optical readout system and aluminum support frame are also shown. The electrostatic screen has been omitted for clarity.

1.3 Feetback

E.G. Adelberger, B.R. Heckel, <u>U. Schmidt</u>^{*} and H.E. Swanson

Changing the tilt on our high precision torsion balances causes a twist of the fiber that the pendulum is attached to. This effect, labeled "tilt-feed through," is of the order of 1% in our experiments. The tilt of the laboratory floor typically changes by 1 μ rad per day, resulting in a daily false signal of the order of 10 nrad. The biggest correction to our previous measurement¹ of the compositiondependent test body accelerations was for laboratory tilt, and the uncertainty of the measured tilt feed-through was a major contribution to our systematic error budget. To eliminate the tilt effect, we developed an active leveling system.

Our apparatus rests on three feet. Two of them are active ones, which can change their height using temperature dependent expansion to compensate for the laboratory tilt. Fig. 1.3-1 shows a cross section through one foot. The expanding and shrinking components of one foot consists of two lead rings (1) which are soldered to a copper disk (2). Thermal energy can be pumped into or out of the copper disk by a peltier element, which is also thermally coupled to a brass block. The brass block is held at constant temperature by circulating water from a temperature-stabilized reservoir. Two G10 rings (5) thermally isolate the lead rings from the laboratory floor and a stainless steel disk on top, on which the apparatus rests. The peltier element and the brass block are clamped to the copper disk by one bolt (6). Specially formed G10 pieces provide thermal isolation between the bolt, the copper disk and the brass block.



Figure 1.3-1. Cross section of a foot of the Eöt-Wash III rotating torsion balance. For details see text.

We measure the tilt with two perpendicular Applied Geomechanics Inclinators (AGIs). The AGIs are mounted on the rotating top of the apparatus near to where the prehanger of the pendulum is attached. The analog signals of the AGIs are digitized by the data acquisition system.

The Eöt-Wash II rotating torsion balance rests on similar feet to the one shown in Fig. 1.3-1. Due to the heat capacity and the heat resistance of the copper disk and the lead rings, the response of the expansion of the lead rings to a change in the heat flux provide by the peltier element is

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¹S. Baeßler *et al.*, Phys. Rev. Let. **83**, 3585 (1999).

delayed by 14 seconds. Also the heat conductivity of the peltier element, which tends to bring back the temperature of the copper disk to the temperature of the heat bath, has to be taken into account. Therefore we need a model that predicts the response of a foot to a change in heat input to the peltier element. Fig. 1.3-2 shows the model used for calculating the response of the Eöt-Wash II feet. This model poses no problem for a real time calculation because it can be solved analytically. The delayed response of the feet together with the 8 sec integration time of the AGIs leads to a low-pass behavior of the leveling system. Therefore its response to fast changes of the tilt caused by imperfections of the turn tables ball bearing is limited. The tilt, caused by the imperfections of the turntable angle. Once these Fourier coefficient are calculated, they can be fed forward to compensate for the imperfections of the bearing. The simplified flow chart of the feed-back loop of Eöt-Wash II is shown in Fig. 1.3-2.



Figure 1.3-2. Thermal model and flow chart of the simplified feetback loop implemented at the Eöt-Wash II rotating torsion balance

With the feetback switched on, the typical 1 μ rad tilt per day is reduced to 20 nrad.²

For the Eöt-Wash III rotating torsion balance we optimized the foot design using finite element analysis. The response time of the optimized design is 6.7 seconds compared to 14 seconds for the old one. Also we used the results of the finite element analysis to make a more realistic numerical model of the heat flux inside a foot and therefore for the time dependence of the expansion. This numerical model can be solved in real time and is used in the feetback loop implemented at Eöt-Wash III. In order to measure the performance of the new feetback system we have to wait until all changes of the Eöt-Wash III apparatus are finished and we are able to run the feetback with temperature stabilized AGIs.

²Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 14.

1.4 Simple parallel computing with Mathematica

<u>U. Schmidt</u> *

Beginning with Version 3.0, Mathematica allows a user to connect a Mathematica front end to a Mathematica kernel running on a remote computer. On Windows based PCs, connecting to a remote kernel requires one to type commands on both PCs, making this feature not very useful. In addition, the file access takes place on the remote computer. Therefore, all needed input files have to be copied to the remote computer or the code has to be changed in order to access the input file through the network. Also, for large time consuming calculations it is desirable to have batch queues executing jobs automatically one after the other.

To solve these problems and to provide a basis for simple parallel computing I wrote the code for a server for Mathematica with the following features:

- Start a Mathematica kernel and provide automatic remote access to it.
- Start a modified Mathematica kernel, for which the file access is linked to a file server and provide automatic remote access to it.
- Act as a file server to enable remote file access for Mathematica kernels.
- Provide batch queues, which execute batchjobs automatically one after the other using local or remote kernels provided by a Mathematica server.

For data exchange between kernels on different computers the TCP/IP protocol is used. Beside the file server feature the code is written completely platform independent in Mathematica. This allows one to run the same code including file access on any platform without any modification. Also, the server provides FTP-like file exchange between computers.

The server requires user identification to retain security. To avoid password sniffing while using an unsecured public network, user identification is scrambled each time with a different key.

Tasks like calculating function values for different parameters can be easily split in a number of batch jobs. These batch jobs can be placed in queues and executed on different computers simultaneously. This code provides a very simple, but for many tasks, an effective way to do parallel computing. The feature was used extensively in computing the expected response of our short-range torsion balances.

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1.5 Data analysis and signal calculations for the short-range experiment

E. G. Adelberger, B. R. Heckel and \underline{U} . Schmidt^{*}

The procedures to calculate the signals of our short range torsion pendulum experiment,¹ to analyze the raw data and to calculate limits of the deviation of gravity from Newton's law were all written in Mathematica.

Calculation of the torque on the pendulum induced by the source: The pendulum torque arises from the interactions between the missing masses in the cylindrical holes in the pendulum and attentors. For the purpose of the torque calculation we can think of sets of cylinders with the dimensions and locations of the holes in our pendulum and source. The torque induced in the pendulum cylinder set by gravitational interaction with the source cylinder sets is equivalent to the torque induced by our source with holes in our pendulum with holes. The total torque is given by the sum over all pairs of source and pendulum cylinders. The locations of a pendulum cylinder and a source cylinder, together with the horizontal component of the gravitational force between the two cylinders, leads to the torque of this pair. The value of the horizontal force components is given by a 6-dimensional integral. In the case of Newton's 1/r-potential, 4 of the 6 dimensions can be integrated analytically. The remaining two dimensions have to be integrated numerically. In the case of a Yukawa interaction, only two dimensions can be calculated analytically. The Fourier coefficients of the total torque can be determined by calculating the total torque for different source angles. Each Fourier coefficient was calculated on a grid of different vertical separations and different horizontal offsets between source and pendulum. For the values of arguments between grid points, cubic spline interpolation was used. Also the gradients at the boundaries of the grid were calculated and used to improve the cubic spline interpolation. In addition to the values of these Fourier coefficients the maximal possible error of the values due to the numerical integration and the interpolation was calculated.

Extraction of the Fourier coefficients of the torque from the raw data: Each data run was divided in an adequate subset of data (the Fourier coefficients of interest have to be orthogonal). These subsets were fitted using the relevant Fourier coefficients and fiber drift terms. Bad subsets, where the data were affected by vibrations (small earth quakes) or fiber slips, were eliminated using the change in the value of the free torsion amplitude as a cut criterion. The measured value for each Fourier coefficient was calculated from the mean of the values of the subsets while the error was determined by the scatter of these values.

Calculation of the upper limits on Newton's law violating interaction: The 10ω , 20ω and 30ω measured Fourier coefficients were fitted simultaneously using a multidimensional fitting routine. The independent parameters were the horizontal offsets and the vertical separation between the source and the pendulum. Most fitting parameters like the offset of the z (vertical)-stage or the overall calibration were constrained by independent measurements. These constraints were included in the χ^2 calculation. The χ^2 minima as a function of the fit parameters were calculated on a grid of different coupling strengths α and Yukawa lengths λ . From the known probability of the underlying χ^2 -distribution, the single-sided 95% confidence level was determined by interpolation for each λ value.

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¹C. D. Hoyle *et al*, Phys. Rev. Let. **86**, 1418 (2001).

1.6 Gravity's gravity

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The theory of general relativity requires that gravitational binding energy undergoes the same acceleration as all other forms of mass and energy in the presence of a gravitational field. Lunar laser ranging measurements have confirmed that the earth and moon fall toward the sun with the same acceleration to 5 parts in 10^{13} , although their gravitational binding energies differ by 4 parts in 10^{10} . To use the earth-moon system as a test of the acceleration rate of gravitational binding energy, it is first necessary to confirm that the materials that comprise the earth and moon undergo the same gravitational acceleration.

Our Eöt-Wash II torsion balance has been operating with four test bodies: two that have a composition similar to that of the earth's core and two that have a composition similar to that of the moon (and earth's) crust. As the apparatus rotates in the lab, we look for a composition dependent acceleration of the test bodies toward the sun.

In last year's report,¹ we noted three important upgrades to the Eöt-Wash II rotating torsion balance. The first was the implementation of thermally controlled Pb leveling feet for the apparatus. Signals from tilt monitors on the rotating apparatus were used to generate a feedback signal to the Pb feet to hold the rotation axis vertical to within 10 nrad. A non-vertical rotation axis gives rise to a spurious fiber twist that leads to systematic errors. The leveling feet removed both the daily tilt of the laboratory floor and most of the wobble created by the turntable bearing. The second upgrade was the implementation of small bellows in series with the torsion fiber to isolate and damp vertical (bounce) modes of the pendulum. The third upgrade was the implementation of a real time data acquisition system. The new acquisition system had a feature that would remove energy from the torsional mode of the fiber if the torsion amplitude exceeded a threshold. Ion pump bursts and seismic events would give the pendulum a torsion amplitude too large to be useful for analysis, causing long sections of data to be discarded. With the automatic damping routine enabled, very little data needed to be rejected.

In 2000-2001, we accumulated data with the upgraded Eöt-Wash II apparatus. Analysis of this data is underway. The results should reduce our statistical errors by the square root of 2 without adding to the systematic uncertainties. The 6.8 magnitude earthquake of 2/2001 caused the Eöt-Wash II torsion fiber to break, providing a natural conclusion to this experiment.

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¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 14.

1.7 Measurement of Newton's constant G

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The gravitational constant, together with \hbar and c, is one of the fundamental and universal constants in Nature. Its value must be determined by experiment. Due to the weakness and non-shieldability of gravity, G is nowadays the least-well measured constant. In addition, several measurements conducted in the last decade deviated considerably from the accepted value, so that the 1998 recommended value for G was assigned an uncertainty of 1500 ppm.

We have developed a new torsion balance method to measure G. This method was designed to eliminate the largest sources of systematic error that effected previous measurements. A detailed description of our method can be found in several previous reports and in published papers.¹ We measure the angular acceleration of a torsion balance mounted on a continuously rotating torsion balance. The rotation rate of the turntable is changed so that the torsion fiber itself remains untwisted. Our method is therefore independent of most torsion fiber properties which may have led to a systematic bias in previous measurements. Our pendulum consists of a thin vertically hanging plate. The plate-pendulum makes this measurement practically independent of the details of its mass distribution. This simple arrangement reflects the biggest single reduction in systematic uncertainty compared to previous measurements. The attractor spheres are located on a separate coaxial turntable. This turntable is operated at a higher rotation rate. The angular velocity difference to the pendulum turntable is kept constant, so that the gravitational acceleration on the pendulum occurs with a constant and high frequency. Gravitational accelerations due to objects in the lab can be eliminated.



Figure 1.7-1. Angular acceleration Fourier spectrum. The signal of interest ($\approx 6.37 \text{ mHz}$) is over four orders of magnitude above the random background. The room fixed gravitational background ($\approx 1.7 \text{ mHz}$) is cleanly separated. The additional sharp peaks at $\approx 13 \text{ mHz}$ are the expected higher harmonic signals. The spectrum represents 10 hours of data.

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¹J.H. Gundlach and S.M. Merkowitz, Phys. Rev. Lett. 85, 2869 (2000).

We have completed two data sets consisting of six three-day runs each. After every run the spheres were moved to different positions on the turntable to subtract out interactions with the turntable itself. The spheres were reoriented to average over density fluctuations and non-sphericity of the spheres. The second measurement was done with a different set of four spheres. Our largest uncertainty was due to the attractor mass metrology. We used Invar micrometers that were fabricated in our machine shop. We calibrated the micrometers before and after each distance measurement with Invar standards that were in turn calibrated at NIST. The vertical spacing between the spheres was measured with small gauge blocks.

The signal frequency was set to ≈ 6.37 mHz. Systematic checks with exaggerated turntable speeds, magnetic fields and thermal gradients were conducted. The torsion balance turntable angle was numerically differentiated to yield angular acceleration. The data were subdivided and fitted. The scatter of the individual fit values determined the statistical error. The data analysis was tested with numerous simulations.

Our value for G is: $G = (6.674215 \pm 0.000092) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$.



Figure 1.7-2. Results of two data sets taken with different spheres. Each data point is the combination of a pair of attractor configurations that together eliminate accelerations due to the attractor turntable. Combining the three pairs taken with different sphere orientations averages over sphere-density and shape imperfections. The uncertainties are statistical.

Using the LAGEOS satellite results² we compute the mass of the Earth to be: $M_{\oplus} = (5.972245 \pm 0.00082) \times 10^{24}$ kg.

Our results are published in ref 1. A detailed publication intended for Physical Review D is in preparation.

¹⁰

²J.C. Ries et al., Geophys. Res. Lett. **19**, 529 (1992).

1.8 emiT: time reversal violation in neutron beta decay, preparations for a second run

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The emiT experiment is a search for time-reversal (T) invariance violation in the beta decay of free neutrons. Both CP (charge conjugation - parity) and explicit T violation have been observed in the neutral K meson system. However, some 36 years since the discovery of CP violation, neither CP nor T violation have been observed in any other system and possible origins are still not well understood. Although CP(T) violation in the Kaon system can be accommodated within the standard model of particle physics, both baryogenisis and attempts to develop unified theories indicate that additional sources are required.

The standard model predicts T-violating observables in beta decay to be extremely small (Second order in the weak coupling constant) and hence these are beyond the reach of modern experiments.¹ However, potentially measurable T-violating effects are predicted to occur in some non-standard models such as those with left-right symmetry, exotic fermions, or lepto-quarks.^{2,3} Thus a precision search for T-violation in neutron beta decay provides an excellent test of physics beyond the Standard Model.

The emiT experiment probes the T-odd P-even triple correlation between the neutron spin and the momenta of the neutrino and electron, $D \sigma_n \cdot P_e \times P_{\nu}$, in the neutron beta-decay distribution. The coefficient of this correlation, D, is measured by detecting decay electrons in coincidence with recoil protons from a polarized beam of cold (2.7 meV) neutrons. Four electron detectors (plastic scintillators) and four proton detectors (large-area PIN diode arrays) are arranged in an alternating octagonal array concentric with the neutron beam. The protons produced in the decay of free neutrons have a relatively low energy ($\leq 751 \text{ eV}$). While this allows for a delayed coincidence trigger between the proton and electron (eliminating much of the background) it increases the complexity of the detection scheme.

During the first run, high voltage related problems stemming from higher than expected energy loss in the PIN diodes (refer to the following section) led to damaged electronic components, high voltage related backgrounds and a non-symmetric detector. Systematic effects were less effectively canceled due to the lack of full detector symmetry and a more complex data analysis scheme was required. The result, $D = -0.1 \pm 1.3 \times 10^{-3}$, represents a small improvement over the current world average.⁴

To assure that the second run is not affected by these problems, a number of major detector upgrades are in progress at CENPA. The goals of these modifications are to increase the reliability of the proton detectors, reduce dead time and reduce systematic effects through improved characterization of the neutron beam. To accomplish the goal of increased detector reliability the majority of the proton electronics has been isolated through the use of analog fiber-optic links. This change

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¹M. Kobayashi and T. Maskawa, Prog. Theor. **49**, 652 (1973).

²P. Herczeg, *Progress in Nuclear Physics*, W.-Y.P Hwang, ed., Elsevier Sciences Publishing Co. Inc. (1991) p. 171.

³E.G. Wasserman, *Time Reversal Invariance in Polarized Neutron Decay*, Ph.D. thesis, Harvard University, (1994). ⁴L. J. Lising *et al*, Phys. Rev. C **62**, 055501 (2000).

also lowers the capacitance of the high voltage system, which will reduce damage due to discharges along the proton paddles. Both systems were completed during the last year. The high dead time seen during the first run was partly due to high voltage related backgrounds and partly due to the data acquisition system. In order to detect the low energy decay protons, they are accelerated and focused through a potential of approximately 30 kV. Various parts of the focusing assembly create sufficiently high fields that electron emission can take place. The electrons ionize absorbed gasses (most likely Hydrogen) in the ground plane. These ions are then accelerated back toward the detectors. We believe that this is the source of most of our high voltage related background. We are in the process of a complete design review of the focusing system, and the tests made to date indicate that it will be possible to completely eliminate this source of background. In addition, the thresholds of the ADC boards have been sharpened, allowing better background rejection and operation at lower, more stable voltages. Finally upgrades to the DAQ software will allow closer monitoring of the detector status, significantly increased data rates, and will improve the capability for real time data analysis. We have also made a decision to replace the PIN diodes with Surface Barrier detectors based on comparative studies of PIPS, PIN and Surface Barrier detectors. Surface barrier detectors have proven to be robust, and modifications to the detector that allow their use are nearing completion. We have developed plans to better characterize the neutron beam, and have developed procedures to obtain accurate polarization, flux and magnetic field maps that will be used to better understand systematic effects. In addition, an upgrade to the NIST reactor will result in a factor of approximately 1.8 higher neutron flux. It is expected that emiT will resume collecting data around the first of the year 2002, likely reaching the goal of D $< 5 \times 10^{-4}$ during the following summer.

1.9 Dead layers of proton detectors for the emiT experiment

M. Bhattacharya, H. P. Mumm, K. M. Sundqvist and J. F. Wilkerson

We have been conducting studies of dead layers on semiconductor detectors used for proton detection in the emiT experiment. Dead layers are layers of inactive material present on the surface of detectors. They are responsible for energy loss of incident particles before they are measured in the active portion of the detector. They inhibit low energy particle measurements by creating a natural energy threshold which particles must overcome in order to be detected.

The emiT experiment detects protons (in coincidence with the betas) from the decay of free neutrons. In order to detect the low energy protons (maximum kinetic energy of 760 eV) the emiT experiment uses a high voltage grid in front of the detectors to accelerate the protons. The applied voltage (-35 kV for emiT's first run) must compensate for the energy lost by the protons in the dead layer of the detectors. With the application of such high voltages care must be taken to prevent breakdowns as the resulting discharges could damage the detectors and associated electronics. It is therefore crucial to characterize these dead layers such that we may determine the lowest voltage required for the protons to be detected.

We measure dead layers in a tabletop vacuum box using 3.18 MeV alpha particles from a collimated ¹⁴⁸Gd source to make energy loss measurements as function of angle of incidence. At normal incidence, energy loss is a minimum as the particles take the shortest path through the dead layer. By making energy measurements at varied angles of incidence, one can determine the thickness of a dead layer by observing the energy difference in measured pulse heights. To accomplish this, our detector is mounted in front of the source on a micrometer arm which allows the angle of incidence to be varied without having to break vacuum.

PIN diode detectors were used in emiT's original experimental run. They have been measured with typical energy losses in their dead layers of 20 keV (corresponding to 25 μ g/cm² of Silicon). However, their dead layer was found to increase over the course of the run. We have decided to use surface barrier detectors for emiT's second run. These are factory specified with 40 μ g/cm² gold dead layer. Dead layers for new and unused surface barrier detectors were measured in our setup and we found the measured dead layers to be consistent with these specifications. It would be extremely valuable to know how dead layers change on detectors over time, perhaps as the result of radiation damage. This has been the primary motivation for these measurements, and it is hoped that in the near future we will be able to correlate how dead layers increase with detector usage.

1.10 ${}^{4}\mathrm{He}(\alpha,\gamma){}^{8}\mathrm{Be}$

R. Hazama, K. A. Snover and <u>D. W. Storm</u>

We are in the process of completing the analysis of our high-precision measurement¹ of the ${}^{4}\text{He}(\alpha, \gamma)^{8}\text{Be}$ reaction. The goal of this experiment is the determination of the isovector M1 decay width and the isovector E2 / isovector M1 mixing ratio for a precision test of CVC and second-class currents in the mass-8 system. Using three large NaI photon detectors placed at 40°, 90°, and 140° in the laboratory, in conjunction with a gas cell and the superconducting linac beam, we measured angular distributions for the ${}^{4}\text{He}(\alpha, \gamma)$ reaction as a function of excitation energy in ${}^{8}\text{Be}$. We have reported an earlier measurement² based on the same ideas.

The differential cross section is assumed to be given by an R-matrix calculation with an α - α formation channel for the 2⁺ doublet in ⁸Be near 17 MeV and isovector and isoscalar photon transitions from the resonant states to the 2⁺ state near 3 MeV as well as to the tails of the resonance doublet. Alpha widths for these states are obtained from other measurements, and the isovector and isoscalar E2 and M1 transition widths are obtained from fits to our data. Since the isovector M1 transition to the 3-MeV state is dominant and is also the width we are most interested in, we characterize the other transitions in terms of their mixing ratios relative to the isovector M1 amplitude. For the transitions to the tails of the 17-MeV doublet, we have determined the relative isovector M1 amplitude from a measurement of the spectrum.³ We assume other gamma widths to the tails of the 17-MeV doublet are negligible.² The remaining three amplitudes (isovector and isoscalar E2 and isoscalar M1) for transitions to the 3 MeV state are obtained relative to the isovector M1 amplitude from the shapes of the excitation curves over the 2⁺ resonance doublet. The magnitude of the isovector M1 width will be obtained from the overall normalization.

Last year we reported discrepancies in the absolute efficiency of the photon detectors determined from ${}^{10}B({}^{3}He,p\gamma){}^{12}C$ and ${}^{12}C(p,\gamma){}^{13}N$ measurements, both of which produce photons of approximately 15 MeV. Last year we also described how we obtained energy dependent detector response line shapes from about 8 to 15 MeV. We revised some of the parameters describing these lines to get better fits, and re-determined the efficiencies. We find that for all three detectors, the efficiencies determined by repeated measurements of the same reaction were consistent. However, the efficiencies (at 15 MeV) obtained for all three detectors from the ${}^{12}C(p,\gamma){}^{13}N$ reaction were $4.0\pm0.5\%$ lower than those obtained with the ${}^{10}B({}^{3}He,p\gamma){}^{12}C$ reaction. Since the ${}^{12}C(p,\gamma)$ reaction cross sections were originally obtained using the ${}^{10}B({}^{3}He,p\gamma)$ reaction to determine the detector efficiency,⁴ this discrepancy is puzzling.

We obtain relative yields from the measurements of ${}^{4}\text{He}(\alpha, \gamma){}^{8}\text{Be}$ by fitting the data with a convolution of the detector response and an R-matrix calculation of the spectrum shape. Adjustable parameters are the normalization and an energy offset. The efficiencies we have determined then enable us to compare the yields in the different detectors. The detectors at 40° and 140° are not quite at symmetric angles in the cm system, but are close enough (about 37° and 137° in the cm) that the relative yields are not sensitive to the mixing ratios in the angular distributions. Thus comparing these yields is a check on the relative efficiencies of the two detectors. In one of the

¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 2.

²L. DeBraeckeleer, et al., Phys. Rev. C 51, 2778 (1995).

³Nuclear Physics Laboratory Annual Report, University of Washington (1999) p. 6.

⁴R. E. Marrs, E. G. Adelberger, and K. A. Snover, Phys. Rev. C 16, 61 (1977).



Figure 1.10-1. One of two data sets with fits. The fits are described in the text. The energy axis is the actual beam energy at the entrance to the gas cell.

running periods the ${}^{4}\text{He}(\alpha, \gamma){}^{8}\text{Be}$ results, including the measured efficiencies compare very well, but in the other running period there is a discrepancy which we are attempting to resolve.

For the self-consistent run period, we fit the data from all three detectors, with the measured efficiencies applied. The free parameters were the three relative widths and a single overall normalization. The results are shown in Fig. 1.10-1.

1.11 Search for a permanent electric dipole moment in liquid ¹²⁹Xe

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We are presently working on the development of the liquid ¹²⁹Xe EDM experiment to search for new sources of CP violation beyond the Standard Model. In the last year we have constructed and tested the apparatus needed to produce polarized liquid ¹²⁹Xe and made measurements of the transverse spin relaxation time T_2 . We investigated the effects of magnetic interactions between ¹²⁹Xe atoms and found new non-linear effects in the response of the ¹²⁹Xe magnetization to a magnetic field gradient.¹ We have also constructed a magnetically shielded low-field system and observed the spin precession signal of ¹²⁹Xe atoms using a high- T_c SQUID.

The relaxation studies were performed in a magnetic field of 32 G. To suppress spin dephasing due to residual external magnetic field gradients, we used refocusing π pulses in a standard spin-echo sequence. However, spin-echo techniques do not prevent spin dephasing due to gradients created by polarized ¹²⁹Xe itself, since these gradients are also reversed by π pulses. For a uniform ¹²⁹Xe polarization in a spherical cell the magnetic field due to other ¹²⁹Xe atoms averages to zero. However, in the presence of a small gradient of the external magnetic field the magnetization of ¹²⁹Xe will develop a helix which in turn produces a gradient of the magnetic field. We found that this positive feedback mechanism causes the gradients of the magnetic field and the magnetization to grow exponentially in time and results in highly non-exponential decays of the transverse magnetization, as shown in Fig. 1.11-2. We developed a simple model for a spherical cell to calculate the rate of exponential growth of the gradients. We also found that imperfect π pulses suppress the exponential growth of the magnetization gradients. After the exponential growth of the gradients is suppressed, we measured the transverse spin relaxation time $T_2 = 1300$ sec, close to the longitudinal spin relaxation time $T_1 = 1800$ sec.

The SQUID measurements were performed in a magnetic field of 10 mG inside five-layer magnetic shields with a shielding factor of 10^6 . Unlike an NMR coil, whose signal is proportional to the derivative of the magnetic field flux, the SQUID detector allows us to detect ¹²⁹Xe spin precession in a very small magnetic field with high signal-to-noise ratio. We are now beginning to study the effects of magnetic field interactions between ¹²⁹Xe atoms in this new regime of very small magnetic fields. The results of these studies will allow us to finalize the design of the actual EDM experiment.

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¹M. V. Romalis and M. P. Ledbetter, submitted to Phys. Rev. Lett.



Figure 1.11-2. Envelope of the ¹²⁹Xe NMR signal obtained with a CPMG spin-echo sequence. Non-exponential decay of the magnetization due to magnetic field interactions is clearly seen. The onset of the non-exponential decay can be suppressed by using imperfect π pulses in the CPMG sequence, as indicated by the broken line, for which the length of the π pulses is reduced by 3%. This behavior is consistent with a simple pertubative model of the magnetic field interactions. Exponential fit to the later parts of the decay curve gives a value of $T_2 = 1300$ sec.

1.12 ft value of the $0^+ \rightarrow 0^+$ decay of ³²Ar: a measurement of isospin breaking in a superallowed decay

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The precisely measured ft-values of nine $0^+; T = 1 \rightarrow 0^+; T = 1 \beta$ -decays from ¹⁰C to ⁵⁴Co yield a result for $V_{\rm ud}$ that implies a deviation of more than 2σ from the unitarity of the CKM matrix¹. However, in order to extract $V_{\rm ud}$ from the measured ft value one needs accurate *theoretical* calculations for the *nucleus-dependent* isospin-breaking and radiative corrections. Given the impact of $V_{\rm ud}$ on the unitarity of the CKM matrix, it is important to check predicted corrections in systems where these corrections are particularly large. We have chosen to check the calculated isospin-breaking correction for the $T = 2 \rightarrow T = 2$ superallowed decay of ³²Ar, as the predicted correction in this system, $2.0\pm0.4\%$, is over 3 times greater than the largest isospin-breaking correction in $T = 1 \rightarrow$ T = 1 decays.

We recently performed an experiment at the National Superconducting Cyclotron Laboratory at Michigan State University with a goal of determining the superallowed branch of ³²Ar β -decay with a precision of 0.4%. We directly counted the ³²Ar parents and detected the delayed proton and gamma decays with high-efficiency detectors. Mass-separated ³²Ar ions from the A1200 spectrometer were implanted in a 500- μ m thick silicon surface barrier (SSB) detector which also served as our delayed-proton counter. The ³²Ar ions were produced in the fragmentation of a 3.6 GeV ³⁶Ar beam on a Be target. The implantation detector was sandwiched between two similar SSB detectors which served as our beta detectors. They also helped us determine the actual number of implanted ³²Ar ions and reject fast particles in the beam. A 500- μ m thick PIN Silicon counter located upstream from our telescope provided us with energy loss and time-of-flight information to identify the incoming fragments. In addition 5 high efficiency (three segmented *clover* units and two large single crystal) high purity germanium detectors surrounded our particle detection setup to look for $\beta\gamma$ and $\beta p\gamma$ decays of ³²Ar.

We are in the process of analyzing the data. A preliminary analysis from our initial run indicates that it should determine ft with a precision of better than 1%. In addition we detected a number of previously unobserved gamma decay branches and obtained an improved value for the ³²Cl mass.

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¹J. C. Hardy *et al.*, Nucl. Phys. A **509**, 429 (1990).

2 Neutrino Physics

2.1 SNO

2.1.1 Status of the SNO solar neutrino analysis

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The Sudbury Neutrino Observatory (SNO) is a second generation solar neutrino detector designed to measure the spectral distribution and flavor composition of the ⁸B neutrinos from the Sun. Using heavy water as its primary target SNO detects the charged-current interaction, neutralcurrent interaction, and elastic scattering of neutrinos. This gives SNO the unique capability to measure both the flux of electron neutrinos as well as the flux of other neutrino flavors. In the first phase of the experiment SNO runs with pure D_2O to make a measurement of the charged-current interaction of neutrinos with deuterium.

SNO has been online and taking production data since November 1999 while calibrating the detector and measuring the background rates at the same time. With an electronics threshold of about 0.25 photo-electron per channel and a multiplicity trigger of 18 N_{hit} the trigger rate is about 15 Hz and the hardware threshold corresponds to roughly 2 MeV. A number of calibrations are performed on a regular basis in SNO to measure the optical response of the detector, its energy resolution, and background rates. The optical calibration, performed using a laser source at different wavelengths and a diffuse laser ball suspended in the D₂O, shows that the timing resolution of the phototubes is near the expected design goal of about 2 ns.

Data cleaning cuts are applied before reconstruction to remove any unphysical events from the raw data set. In addition, a set of high-level parameters have been developed to describe the Cerenkov nature of events. They are based on the in-time light detected in the detector and the average angle between hit PMTs. The discrimination between single Cerenkov electrons and multiple vertex events, such as β - γ 's, is used to distinguish background events and select a candidate neutrino event set. The neutrino signal loss due to these high-level cuts is less than 2%.

A number of triggered and untriggered sources are used to determine SNO's energy response. These include ¹⁶N (6.13 MeV), a (p,T) source (19.8 MeV), a ⁸Li β spectrum and neutrons (6.25 MeV). In addition, the endpoint of the ⁸B spectrum itself provides a source-independent calibration of the neutrino data. As the systematics of the neutrino flux measurement is coupled to the uncertainty in the detection threshold, the goal of the SNO calibration program is to reduce the energy uncertainty to <1%. Preliminary results of SNO's energy calibration program are shown in Fig. 2.1.1-1. The ¹⁶N, ⁸Li, and (p,t) data are in good agreement with the Monte-Carlo prediction of roughly 8-9 hits/MeV, electron equivalent.

The ¹⁶N and ⁸Li sources are also used to determine the systematics associated with the event reconstruction and the angular resolution of neutrino events. The reconstruction systematics are position dependent and the resulting systematic error on the fiducial volume less than 3%.

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Figure 2.1.1-1. Comparison of SNO calibration data from ¹⁶N, ⁸Li, and (p,t) with Monte-Carlo predictions. The predicted energy scale is roughly roughly 8-9 hits/MeV, electron equivalent.

The backgrounds in the D_2O and H_2O are determined through radioassays and in-situ Cerenkov measures. The target levels for the internal Th and U backgrounds are each 7% of the Standard Solar Model equivalent in neutrons. These goals have been met and all radioactive backgrounds are at or below this target level.

The extraction of the neutrino signal is performed in two different ways for independent verification. One approach utilizes an essentially background free, small fiducial volume in the center of the detector while the second method extracts the different neutrino signals and background contributions for variable fiducial volumes and energy thresholds. Fig. 2.1.1-2 shows Monte-Carlo simulations of the radial distribution of neutrino signals and the primary backgrounds in the acrylic vessel (AV) and the light water. The units of the abscissa are normalized to equal volume elements and the radius of the acrylic vessel.



Figure 2.1.1-2. Monte-Carlo simulations of the radial distribution of neutrino signals and the primary backgrounds in the acrylic vessel (AV) and the light water. The two figures illustrate the threshold dependence of the background contributions.

All elements of the solar neutrino analysis have been developed on a subset of the neutrino data. Redundant analyses are in place to verify all components of the analysis. Once the analysis components have been finalized a blind data set will be used for statistical comparisons and to establish an unbiased result. First results from the SNO experiment are to be expected in the near future.

2.1.2 Verifying event building in SNO data

J.L. Orrell, <u>K.K. Schaffer</u> and J.F. Wilkerson

The SNO data acquisition system was designed to continuously read and record information from the detector's 9688 photomultiplier tubes (PMTs). Immediately after it is read from the hardware, information from individual PMTs is passed to the builder/recorder software, where it is assembled into "events" and recorded to disk and tape. An important verification of the hardware and the data acquisition process is to verify that PMT information is being properly associated with triggered events.

When the first set of the detector trigger conditions is satisfied, two sets of data are read from the hardware. The data containing information about the trigger type and time is read out from the Master Trigger Card. Data containing information from all individual PMT tubes that were hit is read out separately from the Front End Cards (FECs). A complete "event" is the combined information from the trigger (including the time of the event) and the information from the PMT tubes. Both types of data are tagged with a Global Trigger Identification number, or GTID. The builder uses this GTID to match together all of the data that constitutes a single complete event.

Two possible problems could interfere with proper building of events. First, hardware errors could attach faulty GTIDs to parts of the data; and second, event rates higher than the system's maximum throughput could force data to be recorded faster than it can be built into events. PMT information in these conditions will still be recorded, but it will not be associated with its "parent" triggered event. Therefore, such PMT data is called "orphan" data.

Surveys of the neutrino data have shown that the typical number of PMT hits that are "orphaned" (usually due to the hardware errors mentioned above) is on the order of only a few PMT hits per 10,000 recorded. Tools have been developed to monitor the rate of orphans, as an ongoing diagnostic. Additionally, software is being developed to ensure that data from rate conditions beyond the system throughput can be systematically rebuilt by reuniting the orphan PMT hits with the proper events.

2.1.3 Channel status verification for SNO data

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A project to verify the integrity of a crucial aspect of the SNO data was undertaken in 2000. The goal of the work was to check the reliability of the DQXX banks. These banks are created and written to titles files by the SHaRC program¹ at the start of each run. They contain channelby-channel status information for the entire detector. This information is used in Monte Carlo simulations of SNO data, and is critical to the reliability of the simulated data. It is important to the overall SNO analysis to demonstrate that the DQXX banks correctly reflect the detector configuration for every run.

The first step in this project was to compare the detector snapshots saved by SHaRC for each run with the DQXX titles files. Since the titles files are created from these same snapshots, this checks that there are no coding errors in translating information from the snapshot database to the titles files format. The results indicate that the titles files accurately reflect the SHaRC detector configuration for all runs.

The second step was to compare the titles files information with the SNO database, SNODB. Since the DQXX banks are eventually incorporated into SNODB, it was necessary to verify that the banks in SNODB are consistent with those in the titles files. Of the 3708 runs that were checked, it was found that 647 runs have some discrepancy. These were traced to two sources. One is that the start time of some runs is incorrect due to a problem with the clock used to determine this information. This problem will be addressed by recreating the correct time stamp using an alternate clock, and regenerating the affected titles files. The second source of errors was that some DQXX banks do not appear in the database, because the titles file was not copied to the appropriate directory in time to be included. This will be fixed by modifying the database update procedure to require that there be no gaps in the run number sequence. SNODB will be re-generated in the near future with these fixes, which should provide 100% agreement between the DQXX titles files and the database.

The final step was to compare the DQXX information with channel occupancy histograms. This was to check if channels which are "off" according to the DQXX banks indeed have zero occupancy according to the actual phototube data, and conversely, if channels which are "on" according to the banks have normal occupancies. Of the 294 neutrino runs which were checked, 44 runs showed some discrepancy between the DQXX information and the occupancy data. All discrepancies were cases where the channel is deemed "on" but has low or zero occupancy. These discrepancies are most likely channels which developed a hardware problem that hadn't yet been discovered and addressed by the detector operators. This should be resolved once a new set of analysis banks (ANXX) is implemented, which will flag such cases.

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¹SNO Hardware Acquisition Realtime Control program; see Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 19 and references therein.

2.1.4 Muons and muon induced spallation neutrons in SNO

Q.R. Ahmad,* <u>R. Hazama</u>, J.L. Orrell and J.F. Wilkerson,

The detection of the neutral-current (NC) reaction is one of the primary goals of the SNO experiment. In order to determine the NC reaction rate accurately, one needs to account for the various forms of background properly, especially the largest source of background which comes from neutrons produced by nuclear spallation of the ¹⁶O and ²H nuclei in water by muons. In addition to producing neutrons, nuclear spallation products emit electrons, positrons, and γ -rays with energies similar to the solar neutrino events. If muons can be accurately identified, one can eliminate muon-induced background events from the neutrino sample by placing a simple muon-tagged time cut based on a half-life of spallation products and a capture time of neutrons in a water. The depth of the SNO detector make such a time cut feasible. The measured muon rate at SNO is approximately 2.9 hour⁻¹, while that at the Super-Kamiokande (Super-K) is 7.9 ×10³ hour⁻¹, which is about 3000 times larger. However, in order to sacrifice as little live-time as possible, one needs to do a through and systematic study of all muon-induced spallation products.

Muons and muon-induced spallation products are identified by the following procedures. A list of candidate muons is obtained by running the SNOMAN process called *MuonID* on the selected SNO data files. This is a first pass filter which provides an initial best guess for the path length of an event, which is used to categorize the prospective muons into AV (Acrylic Vessel) and non-AV going events. Any event giving a track with a path length greater than 1179 cm (a muon that grazes the AV or is tangential to it will have a path length = 1179 cm) is categorized as an AV going muon. Since all muons that go through the detector (AV) can be responsible for producing spallation events within the fiducial volume of the detector, AV-though going muons are considered. The efficiency is evaluated by hand-scanning, and the *MuonID* is 99.1 % efficient at identifying true muon events and only contributes $\sim 0.4\%$ contamination to the final muon sample.

The muon correlated events were identified by first selecting a through going muon and then collecting events within a 20 second time window. The standard SNOMAN time fitter (FTT) was used to reconstruct the position and direction of these events. It was shown from Monte Carlo that free neutrons in the D₂O volume are typically captured by deuterium within 500 ms of their generation. Furthermore, only ~ 1% of the spallation products generated within 500 ms are $\beta - \gamma$ events. Therefore, only interactions following within 500 ms of a muon were considered.

The spallation neutrons after thermalization are captured on deuterium to produce a 6.25 MeV gamma. These neutrons can be utilized to perform an independent measurement of the SNO γ -ray energy calibration. Unlike deployable devices such as the SNO ¹⁶N γ -ray calibration source, muon-induced neutrons are being constantly produced at SNO and can be compared to the calibration source without any disruption to normal data taking. In this context, Super-K is using muons that stop in the detector and then decay to produce Michel electrons and corresponding neutrinos. However, the energy is much higher (~ 37 MeV) than that of solar neutrino events and cannot be used for an absolute energy scale, just for systematic checks. The number of μ -decay electron events at SNO is about 500 times lower than that at Super-K, so these events are not useful, but SNO can utilize the AV though-going muons for the systematic checks in addition to the 6.25 MeV gammas.

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2.1.5 SNO operations

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In its second calendar year of production data taking in the pure heavy water phase, the SNO detector continues to meet or exceed its target goals. The experiment has been in production mode since November 2, 1999, with a total integrated livetime of 90% including calibrations. A significant fraction of the non-live time has been due to circumstances beyond the collaboration's control, such as power outages in the INCO mine where the detector is housed. Over 98.5% of the 9688 PMT channels are fully operational, with a modest PMT death rate of 0.5% per year.

The average event rate showed a decline over the course of the year, going from approximately 15-20 Hz down to approximately 10-15 Hz, reflecting the decreasing radioactive background levels. In response to these lower rates, the hardware trigger threshold was lowered in December 2000 from 18 PMTs (roughly 2 MeV) to 15 PMTs above pedestal threshold. While the rates of instrumental backgrounds such as flashers, which are light-emitting breakdowns inside a PMT, remain constant, no new instrumental backgrounds have been observed. A complete set of data cleaning cuts has been developed and implemented to remove the instrumental backgrounds.

In last year's Annual Report, two calibration sources were described.¹ They were a laser source with a diffuser ball for the optical calibration, and a triggered ¹⁶N source for an energy calibration point at 6.1 MeV, near the analysis threshold. A number of new sources were commissioned and deployed in 2000. Two untriggered ²⁵²Cf sources were used to measure the neutron capture efficiency at low and high rates in order to predict the measured event rate due to the neutral current interaction of neutrinos with deuterium. Uranium and Thorium chain sources encapsulated in acrylic were deployed in both the heavy and light water regions of the detector to measure the shape of the U and Th backgrounds. A triggered ⁸Li source which produces electrons up to roughly 16 MeV was employed to investigate the sacrifice of the data cleaning cuts, and to verify the SNO energy scale and event reconstruction algorithms.

The analysis threshold for neutrino data is determined by the backgrounds in SNO. Water assays indicate that background levels in the H_2O and D_2O are near or below the design goals, with continuing improvement in water cleanliness as the D_2O is recirculated.

Overall, SNO has operated very smoothly in its first phase of data-taking, and the collaboration looks forward to implementing the neutral current measurement phases of the experimental program. The University of Washington group continues to be actively involved in the daily operations of the detector, providing manpower for regular monitoring shifts as well as for maintenance activities and general detector support.

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¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 18.

2.1.6 The SNO data acquisition system

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The SNO data acquisition system has been described extensively in previous reports.¹ Only a summary of operations and significant updates is given here.

In its second calendar year of production data taking, the SNO data acquisition (DAQ) system continued to perform in a stable and reliable manner. Relative to previous years where various parts of the DAQ system required one or more major upgrades, there were very few changes to the system in 2000. The only significant new feature added to the SHaRC² program was a series of system checks which compares key aspects of the detector configuration with a standard configuration at the start of each neutrino run and reports any anomalies. A modification to the event builder code, along with corresponding updates to the embedded processor code and the SHaRC program, has been shown to reduce the residency time of SNO events in the builder queue due to an improved building algorithm. This update has been tested extensively, and will be put into production use in late April, 2001.

In addition to the above enhancements, there were a number of minor (mostly cosmetic) changes to SHaRC. Several memory leaks were found and fixed, which has improved the system's reliability. The overall stability of the DAQ system has been remarkably good, with an average of 1 or less SHaRC crashes per month.

The DAQ group has continued to provide continuous off-site support, and regular periods of on-site support during significant upgrades.

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¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 19 and references therein. ²SNO Hardware Acquisition and Realtime Control.

2.1.7 Time stamp validation in the SNO experiment

J.L. Orrell and J.F. Wilkerson

The Sudbury Neutrino Observatory (SNO) is a "real time" detector. The SNO detector is capable of achieving 20 nanosecond resolution of event trigger times. The photo-multiplier tubes used can achieve approximately 100 picosecond resolution within an event. This nanosecond by nanosecond data collection allows for the reconstruction of physics events.

The data acquisition and record keeping must deal with time records spanning 17 orders of magnitude. Of primary importance for proper neutrino analysis, the accurate determination of a physics event's time of occurrence is needed. Additionally, the SNO scientists must be able to communicate accurate event times to the physics community at large. This is particularly germane to the SuperNova Early Warning System (SNEWS) project.¹

The SNO detector uses three separate time keeping devices in conjunction to produce event time stamps. There are two clocks located at the detector site which are used for moment to moment data collection. These clocks are referred to as the 10 MHz and 50 MHz clocks because of the rate at which they "tick". The experiment also utilizes the Global Positioning System (GPS) as an absolute time reference. The 10 MHz clock is periodically synchronized with GPS time and, thus, is the time standard used to determine absolute event times. The 50 MHz clock serves as the relative time basis for event-to-event timing. That is, detector global triggers are latched on the 20 nanosecond ticks of the 50 MHz clock.

The 50 MHz clock can also act as a secondary time standard. A secondary time standard is needed in situations where the 10 MHz clock has failed, the GPS communication is down or unavailable, or there are other uncertainties in the validity of the time stamps supplied by the 10 MHz clock. However, since the 50 MHz clock is not synchronized to GPS time we need to ensure we know the actual rate at which the supposed 50 MHz clock is ticking.

It is possible to use a long period of detector data taking to determine the actual rate of the 50 MHz clock. We select events during periods known to have valid GPS synchronizations. For a given period we compare the elapsed times of the 50 MHz clock to that of the 10 MHz (i.e. GPS verified) clock. For each period a linear fit through the origin is used to determine *difference* between 50 MHz and the actual rate of the 50 MHz clock. It is then trivial to convert to the actual rate. From 27 periods (of durations between 2 and 45 days) we have determined the 50 MHz clock's actual rate:

$$R_{50} = 49999462.68 \pm 0.87(\text{Hz}). \tag{1}$$

A weighted mean and error are used in this calculation because the measurement intervals are not uniform. This information will help ensure that accurate timing information is being used in neutrino data analysis.

¹SNEWS: http://hep.bu.edu/~snnet/

2.1.8 Variation of neutrino flux with (local) solar position

S.R. Elliott and <u>M.W.E. Smith</u>

The solar neutrino flux is expected to vary with solar position, as measured with respect to a local set of co-ordinates: θ_{\odot} (zenith angle), ϕ_{\odot} (azimuth), and r_{\odot} (Earth-Sun distance). These variables are being studied with the Sudbury Neutrino Observatory (SNO).

The coordinate r_{\odot} varies seasonally, with the Earth making its closest approach to the Sun (perhelion) in early January and furthest (apehelion) in early July. With this comes a modulation in the solar neutrino flux that goes as $1/r^2$. This can be seen in the simulated SNO charge current (CC) event rate shown in Fig. 2.1.8-1. In addition to this $1/r^2$ behavior, there may be a variation of the neutrino species due to neutrino oscillation. The CC reaction is sensitive only to electron neutrinos, so that this additional modulation may show up in this reaction. Finally, assuming a no-oscillation hypothesis, the month-to-month behavior of the SNO event rate will provide a systematic check of detector stability.

The zenith angle is a measure of an object's location with respect to the horizon; $\theta_{\odot} = 0$ for objects directly overhead and $\theta_{\odot} = \pi$ for objects directly underfoot. For $\theta_{\odot} < 0$, the solar neutrinos are coming from below the horizon, and hence are passing through substantial Earth material. Under certain oscillation scenarios, this can lead to an enhancement of the electron neutrino flux, known as the *Earth-matter* or *day-night* effect. The path length through the Earth goes as:

$$L = -2R_{\oplus}\cos\theta_{\odot} \qquad \theta_{\odot} < 0$$

where R_{\oplus} is the Earth radius. For many regions of Mikheyev-Smirnov-Wolfenstein (MSW) parameter space, the amount of regeneration is proportional to L. For other regions, the amount of regeneration also depends on the composition of the material. Thus, a higher regeneration is possible when the sun is behind the Earth and the neutrinos pass through the Earth's outer core, where the electron density is higher than the mantle. Fig. 2.1.8-2 shows the Earth density profile being used to model the Earth-matter effect. Under the no-oscillation hypothesis, the neutrino flux will be unaffected.



Figure 2.1.8-1. Simulated CC reaction in SNO. The high statistics of this simulation shows the expected seasonal modulation caused by the eccentricity of the Earth's orbit. The rate is shown relative to that at 1 AU.


Figure 2.1.8-2. Density profile as a function of radius from Earth center. Due to SNO's latitude, only the region to the right of the dashed line is accessible.

2.1.9 Neutrino events with solar flares revisited

R. Hazama and R. G. H. Robertson

Now we are in the maximum solar activity during solar cycle 23, and intense solar flares occurred in July and November 2000, just 11 years after big events in October 1989. In particular, the proton flux (≥ 10 MeV) as measured by the GOES satellite reached a maximum of ~ 24000 p.f.u. (= protons cm⁻² s⁻¹ sr⁻¹) on July 15, 2000 1230UT. This flux is about one order higher than that in March 1989 (and April 1984), which is the search period of the Kamiokande report,¹ and almost equivalent to flux on August 4, 1972 0617UT. That is when the largest energetic proton event occurred during solar cycle 20, with the maximum proton flux (≥ 10 MeV) of 25000 p.f.u., and this is just the time of the first reported excess neutrino capture rate in the Homestake (³⁷Cl) detector. No significant neutrino signal was found by Kamiokande for the period of July 1983 -July 1988 and in March 1989, giving a limit on the time-integrated solar-flare ν_e flux.

The sensitivity of SNO is presented in Fig. 2.1.9-1. SNO has a good sensitivity for low energy neutrinos. One possible loophole the Kamiokande result cannot rule out is that the ³⁷Ar excess in the chlorine detector is caused by very-low-energy neutrinos, e.g., those from positron emitters produced by flare particles in the Earth's atmosphere. Furthermore SNO is the most northerly underground neutrino detector in the world and the geomagnetic field guides cosmic rays into the earth's atmosphere. Thus, the flux of low energy neutrinos will be larger at SNO than at more southerly sites (Super-Kamiokande). Now we are reanalyzing the production rate of low energy neutrinos via cosmogenic radioisotopes produced by the interplanetary protons. Especially β^- emitters are important in SNO, because we can identify a $\bar{\nu}_e$ by utilizing detection of two neutrons in coincidence with a positron.



Figure 2.1.9-1. The sensitivity of the SNO detector to the solar-flare ν_e flux plotted as a function of ν_e energy, corresponding to one neutrino event in the detector. The dashed line is for the Kamiokande detector.

¹Kamiokande Collaboration, K.S. Hirata *et al.*, Phys. Rev. Lett. **61**, 2653 (1988); ibid. **62**, 694 (1989); Astrophys. J. **359**, 574 (1990).

2.2 SNO/NCD

2.2.1 Neutral current detectors in SNO

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In the third phase of the SNO experiment, an array of ³He proportional counters will be installed within the D_2O volume. These Neutral Current Detectors (NCDs) will allow direct, real-time detection of the neutrons produced in neutrino neutral current reactions with D_2O , facilitating a better measurement of the total active neutrino flux from the sun as well as a more precise measurement of the shape of the charged-current spectrum. When neutrons enter the NCDs, they capture on the ³He via:

 $n + {}^{3}He \longrightarrow p + {}^{3}H + 764 \text{ keV}.$

The charged particles produced in this reaction ionize the gas within the NCD, resulting in a pulse signal that travels down a central anode wire to be read and processed by the NCD electronics.

In order to minimize radioactive backgrounds, extremely high purity materials were required in the production of the NCDs. The detector bodies are made from chemical-vapor-deposited (CVD) nickel, with specially designed CVD endcaps and quartz high-voltage feedthroughs. The high purity materials were chosen to specifically minimize contamination by uranium and thorium. Cosmogenic ⁵⁶Co in the nickel detector walls could also cause backgrounds, so the NCDs will be stored underground before deployment, allowing the ⁵⁶Co to decay according to its 79 day halflife. This "cool down" period will also be used for measuring Uranium and Thorium backgrounds and characterizing the NCD array. As an additional measurement of backgrounds from the NCD materials, a device built from the same materials (the CHIME calibration source) was successfully deployed in SNO during August, 2000.

There are currently 262 NCDs stored underground on site. Ten completed NCDs await shipment to site, and 21 more remain at UW, requiring repair or gas fill. The data acquisition and analysis tools for the NCD array continue to be developed and tested. The NCD electronics and deployment equipment are being completed, and the NCDs are expected to be installed in Spring or Summer of 2002.

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2.2.2 NCD data taking and analysis

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Over the last year, the analysis of NCD data has been ramping up in preparation for a larger influx of data. With the complete electronics system nearly ready for installation, and with 87% of the array in its "cooldown" phase at SNO, the amount of data that we will be taking is going to drastically increase. The main push in our analysis ramp up has been the development and verification of software tools to be used in analyzing the data. These tools include low and intermediate level filters, rate counters, an ion tail removal routine, and a high level pulse shape fitter. In addition, the tools already in place have been packaged into a software program called Analyst assembled from sequential modules. Furthermore, the chain of required analysis routines has been outlined in order to direct further developments.

In addition to software development, there have also been two data analysis studies in progress this year. The first of these was the "Water Wall" study. In this experiment, data was taken from a few NCD strings that were set up in a water enclosure underground at SNO to measure and compare the thermal and fast components of the neutron flux. These data may also be used for the development of neutron identification and data analysis routines.

A second project involved the assembly of two short counters with high levels of ²¹⁰Po contamination. One counter has the contamination in the end cap region, while the other has the contamination in the mid-body of the counter. The goal of this project is to characterize the risetime vs energy distributions of alphas originating from the end cap region where the electric field is weak. These events might mimic neutron events that would otherwise be distinct from the distributions of bulk and surface alphas. This data has recently been taken and analysis of the data will be carried out once the required tools are in place.

Analysis effort has also gone into determining counter rates from recent, as well as past, cooldown data. The average gas event rate for counters that were in the water wall was about 11 events/hour, while that for counters outside the water wall was about 29 events/hour. The individual counter rates, along with other relevant information, have been stored in a database created for pre-deployment data. The backgrounds will provide part of the information needed to assess readiness for deployment.

2.2.3 NCD electronics

C. A. Duba, A. W. Myers, R. G. H. Robertson, T. D. Van Wechel and J. F. Wilkerson

The Sudbury Neutrino Observatory (SNO) provides a unique window into both the neutral and charge current neutrino flux through the use of heavy water. SNO needs to differentiate between neutrons and other events in order to distinguish potential neutral-current neutrino flux. The Neutral Current Detector (NCD) array is set to be placed within SNO in one year, and has the potential to provide extremely accurate neutron recognition. The low expected rate of neutral current events generated by solar neutrinos necessitates event-by-event recognition while the high neutron rate from galactic supernovae requires a fast data acquisition system.



Figure 2.2.3-1. The NCD Electronics control diagram.

The NCD electronics were designed with both of these goals in mind. Dual data paths provide the low-rate scenario with digitized data while allowing for high-rate data taking. Each string of NCD counters has a pair of independent thresholds, one level for low rate pulse digitization and one for high rate signal integration. The NCD electronics also provide 8 individually controllable high voltage power supplies for selective distribution amongst the NCDs 96 strings. All signals that come from charge deposited on the NCD center anode are run through a preamplifier, which separates out the current pulse from the high DC voltage. The pulse is carried into one of eight multiplexing (MUX) boxes, where it is split into the fast and slow data paths. The fast data path carries the signal through a MUX box and a shaper into an ADC, which takes the integrated signal and converts it to a digital charge value. If the event has sufficient peak current to trigger the digitizing threshold in the MUX box, a delayed signal will be latched through a log amp and into both digitizers.

The ADC information passes through a VME bus to a SBS 618 VME controller. The SBS 618 connects to the controlling computer with a fiber-optic line. In parallel, an event that triggers digitization results in the MUX controller placing the hit information onto a line of the 32bit differential I/O module while triggering the appropriate digitizer. The computer grabs the hit information through VME, and requests the digitized event from the digitizer through GPIB.

When the system is complete and installed into SNO, the trigger pulse will be copied to the Global Trigger I.D. (GTID) counter. The GTID counter will request a SNO GTID from the SNO Master Trigger Card Digital (MTCD). The computer will grab the GTID information and tie this value to any events coming in at this time. In the final system, an independent Embedded CPU (ECPU) will be placed in the VME crate to control the electronics, so that ephemeral computer functions will not interfere with electronics performance. The ECPU control will also increase the total data acquisition speed of the system by sharing some of the event organization and packing duties with the control computer.

The high voltage distribution system is controlled by a set of hardware very similar in design to the threshold control hardware in the MUX control. There are 8 high voltage Spellman 3kV power supplies that connect to a high voltage distribution panel. The power supplies can be selectively connected to differing numbers of strings, and each individual power supply has sufficient current and stability to power the entire NCD array. The digital to analog converter board (DACs) is used in the high voltage system to set the NCD anode voltages to within a few volts. The high voltage control board operates the HV DACs board and regulates the power to the Spellman supplies. The HV safety system prevents the hardware from damaging the NCDs through a number of failsafe mechanisms.

2.2.4 Overview and status of the NCD DAQ software

G.A. Cox, M.A. Howe, F. McGirt* and J.F. Wilkerson

The Neutral Current Detector data acquisition (NCDDAQ) software is taking shape as more and more of the finalized electronics become available. NCDDAQ will provide an easy-to-use graphical interface to the NCD system at the Sudbury Neutrino Observatory (SNO). It is written in C++ and is compiled with the MetroWerks compiler for running on Macintosh computers. NCDDAQ uses much of the code base of the successful SHaRC DAQ control software¹ that has been in routine operation at SNO for several years.

The main dialog of the NCDDAQ interface provides the operator with a complete overview of the system's current status. All of the various parts of the detector are shown in a layout that matches the electronic schematic of the system. By clicking on the various elements of the picture, dialogs for controlling that part of the system are displayed. Most of the major elements that are needed for the final system are well developed, including system initialization, a database for storing electronics constants, run control, high-voltage control, and an alarm system. The following figure shows NCDDAQ in use.



Figure 2.2.4-1. A screen dump of the NCD DAQ in use.

One of the most important things that NCDDAQ provides is a means for conveniently initializing the system. For this purpose, there is a Hardware Wizard that allows an operator to program in a highly selectable set of hardware parameters. The Hardware Wizard is closely coupled to a database that holds all electronic constants.

A well-developed run control system is in place for testing the current system. As well as

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¹Nuclear Physics Laboratory Annual Report, University of Washington (1997) pp. 20-23; (1998) pp. 18-20; (1999) pp. 16-18.

providing a one-button start run capability, it also provides controls for setting the length of a run and whether a run is to be repeated. In this developmental phase of the hardware/software the run control also provides controls for taking data with sub-parts of the system, i.e. just data from the digital scopes. In addition, all actions are logged to a status file on a run-by-run basis.

A high-voltage control and safety system is built into NCDDAQ. HV supplies can be ramped using custom ramping profiles. Each supply can be controlled separately or as part of a group. The HV supplies are constantly monitored to protect the NCD tubes at all times. The monitoring includes checks to verify that the set voltage matches the read-back voltage, the relays are set to the proper state, and whether the electronic racks are on and communicating. In the event of any problems or inconsistencies, alarms are posted to alert the user, and if necessary, the software enters a safe mode that may ramp the HV to zero in certain extreme conditions. Also the operator can panic ramp the high voltage back to zero at any time for a particular supply, or for the entire detector. The state of the HV system is displayed on all hardware-display dialogs.

An alarm system is in place for alerting the operators to unusual events. Each alarm can provide detailed help on what the problem is and how to solve it. So far, most of the defined alarms are for the HV system. Other alarms are being added as needed.

The final data path is now under development. In this phase, the actual data taking will be moved off of the Mac and into an embedded eCPU running in the VME crate. The eCPU will read the hardware as needed, do some initial event building, and put the data into a dual-port memory where it can be grabbed by the Mac and dispatched to the analysis and event-by-event monitoring tools.

2.2.5 First Deployment of a Neutral Current Detector in the Sudbury Neutrino Observatory: The CHIME Engineering Run

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The use of ultra-low background ³He proportional counters as neutron detectors in the SNO detector will provide a means of measuring the neutral-current interaction rate of solar neutrinos. Since the binding energy of the deuteron is only 2.2 MeV gamma rays from natural decay chains in the proportional counters photodisintegrate the deuteron and thus simulate the neutral current signal. This poses stringent limits on the radiopurity requirements for the counters. An *in-situ* background test was performed in the heavy water volume of the SNO detector using seven Neutral Current Detectors. The goal of this measurement was to look for any unexpected backgrounds from the production counters used in the Neutral Current Detector array.

The Neutral Current Detector (NCD) array consists of 775 m of ³He proportional counters arranged in 96 strings with 300 counters. The counter bodies are made of about 450 kg of ultra-pure CVD nickel which contains natural Uranium and Thorium in equilibrium. The photodisintegration gammas are produced in the decays of the ²³²Th (²⁰⁸Tl \rightarrow ²⁰⁸Pb, E_{γ}=2.615 MeV) and ²³⁸U (²¹⁴Bi \rightarrow ²¹⁴Po, E_{γ}=2.445 MeV) chains and in the decay of the relatively long-lived ⁵⁶Co (⁵⁶Co \rightarrow ⁵⁶Fe, E_{γ} >2.224 MeV).

A Construction Hardware In Situ Monitoring Experiment (CHIME) has been designed to measure the NCD originated background in the presence of the D_2O contribution prior to the deployment of the entire NCD array. It is an *in-situ* measurement of the construction materials used in the NCD array. Seven individual counters arranged in a close-packed configuration with a total mass of about 5000 g and an overall length of 112 cm form a background test source that can be deployed in the SNO detector. The construction materials and procedures for the CHIME counters are essentially identical to those in the real NCD array.

To assure its cleanliness before deployment the CHIME unit was checked for leachable Radon and surface dust deposition. Extensive tape lift studies of the CHIME and the Neutral Current Detector array in underground storage were made to estimate the amount of surface contaminants that will be introduced into the heavy water during the installation of the NCD array.

The CHIME has been stored underground since December 20, 1998 in order to allow the cosmogenically produced 56 Co to decay. In September 2000 the CHIME was deployed into the inner volume of the SNO detector. The CHIME is negative buoyant and was deployed along the central axis of SNO using a specially designed deployment mechanism with an ultra-clean Vectran line. During a 71.8 hrs long commissioning run no sign of unexpected backgrounds was detected. In principle, this verifies the successful execution of the cleanliness procedures during NCD construction. A detailed analysis of the CHIME engineering run is in progress. A longer CHIME run is required to determine the activity of 232 Th in the Neutral Current Detectors and thus determine an upper limit on the photodisintegration background generated by the radioactivity in the NCD array.

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2.2.6 The NCD laser welding equipment

J.F. Amsbaugh, T.A. Burritt, P.J. Doe, B. Morissette^{*} and T.D. Van Wechel

We have completed construction and testing of the laser welding equipment needed for neutral current detector (NCD) deployment¹ in the Sudbury Neutrino Observatory (SNO) detector. The NCD welding will occur in two stages with the welding fixture (WF) and its controller used for both. During the first stage, pre-deployment, individual detectors are welded into the largest segments that can fit into the room above the SNO detector. For this operation, the WF is mounted horizontally on a bench supported rail, with several roller–wheel carriages supporting the NCDs for insertion into the WF. During the second stage, deployment, these segments are welded together as they are inserted into the SNO detector. Here the WF is mounted vertically on a linear rotary shaft so it can be raised, lowered and swung out of the way during the welding and insertion procedures.

The WF uses inflating cuffs to grip two NCD tubes or one tube and an end component. One tube which can move opens a gap for center conductor connection. The WF either twists the NCD tubes or orbits the laser output head when welding in the vertical configuration. The output head mount rotates to relieve fiber cable stress of the orbiting mode and slides with a tube follower to maintain laser focus on an out-of-round NCD tube. A motor and linkage assembly provides the relative rotation and locks tube rotation end to end. A He leak checking station is at one



Figure 2.2.6-1. The weld fixture in use during March 2001 safety measurements. Point of view is from lower side opposite the laser-head. The WF is configured for pre deployment welding and mounted on similar rail for tests.

end. The WF opens up for cleaning weld dust and changing the laser output lens protective cover.

^{*}Sudbury Neutrino Observatory, Lively, Ontario, Canada P3Y 1M3.

¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 27.

Microswitches on the WF indicate door closure, motor engagement, and slide holdout release for the interlock system.

The welding control provides safety and process interlocks, manifolds for cuff and cover gases, motor controls, a leak test volume pressure gauge, status indicators and the laser remote control panel. The interlock signal voltages to and from the laser are isolated by a master interlock relay from the weld control interlock voltage system. The primary laser safety is a shutter at the input to the fibre optic output cable and all laser, weld control, and process interlocks must be met before it will open.

The operator can be seen adjusting laser parameters on the weld control in Fig. 2.2.6-1. The WF access door is open and two short NCD sample tubes are inserted. A roller–wheel carriage is in the foreground near the leak check station.

The right angle weld view camera installed in place of the alignment eyepiece on the laser fibre output housing is seen on the left in Fig. 2.2.6-2. This housing is the middle black cube with the stainless steel fibre termination coming up from below.

The welding laser² delivers 1 kW peak optical power in 8.5 ms long pulses at 3 Hz pulse repetition rate. The WF design prevents this laser emission from escaping and measurements indicate that the accessible exposure level is below the Class I laser device limit. Air samples of the welding dust were taken and are below the permissible exposure limit.



Figure 2.2.6-2. The welding fixture during laser emission measurements. Point of view is looking down along the NCD axis.

²Model LuxStar-50, Lumionics Ltd., Warwickshire CV21 1QN, England.

2.2.7 NCD deployment equipment progress

J.F. Amsbaugh, M. Anaya,^{*} T.A. Burritt, P.J. Doe, G.C. Harper, G. Miller,^{*} J. Wilhelmy^{*} and J. Wouters^{*}

Development continues on the equipment needed to deploy the neutral current detectors (NCDs) into the heavy water acrylic vessel (AV) of the Sudbury Neutrino Detector (SNO). Also many suggestions and problems indentified by the design and procedure review¹ have been implemented. This progress includes a revised glove box glove mount, a laser welding fixture, a counter balanced fixture mount, a predeployment welding bench, a redesigned hauldown mechanism, and a gantry crane. During the NCD deployment, the calibration glove box is replaced with the deployment plate. The plate has several 8–inch ports for gloves, view ports, covers and cameras. The new glove mount allows easier exchange of gloves and cover ports on the deployment plate. One of these interchangable covers will be modified to mount the neck view video camera to be used to thread the NCD cables into the correct pre-amplifier bulkhead feed-through. All components have been recieved but the housing design is not yet finalized. The bench supporting the laser welding fixture and NCDs horizontally for predeployment welding was completed and tested in Nov. 2000. Several improvements and changes were added. The laser welding fixture is described in Section 2.2.6 of this report.

The NCD anchor is engaged in a float that the hauldown mechanism manually pulls down with a 1/16-inch vectran line. The remotely operated vessel (ROV) can then take the NCD string from the float to its correct attachment point. The mechanism then pulls the float back up to the deployment plate for the next NCD. The minumum vectran length is 3 times the AV depth, about 175 feet in total, and before installation it must be stored on the takeup spools. The new hauldown mechanism has greater vectran line capacity and improved user controls. The friction brake which locked the elevation and impeded motion has been replaced with two ratchet assemblies. This prevents accidental NCD movement if the operator releases one of the cranks during haul up or haul down. With both engaged the float is locked in position. A full NCD string can be as much as 50 lbf bouyant so a gear train reduces the required force an operator needs to apply to haul it down. The new mechanism is finished and was shipped to the test pool at Los Alamos National Laboratory.

The gantry crane is a commerical² all aluminum construction A-frame unit with 2000-lb capacity. The cross beam has been hard anodized and the fixed turning pulley for the 5/16-inch vectran rope is all stainless steel as is its mounting hardware. The vectran rope is wound on an all aluminum manual winch³ with automatic brake and enclosed gear train. Finally, the casters were replaced with clean room compatible ones.

Preventing contamination of the heavy water and damage to the acrylic vessel are important considerations. To address this, radon and leaching tests on the ROV and other equipment that will enter the AV or heavy water are planned. Clean laboratory space to do such tests were damaged by the recent fire in the Los Alamos area delaying the tests. The leach tank calibration tests have begun and the equipment tests should be completed soon.

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¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 26.

²Model 1ALU1208B, Spanco, Morgantown, PA 19543.

³Model CMA-1760, Jeamar Winches, Inc., Buffalo, NY 14206.

2.3 Lead as a neutrino detector

2.3.1 Lead perchlorate as a neutrino detection medium

M. K. Bacrania, P. J. Doe, S. R. Elliott and L. C. Stonehill

Due to its apparent transparency, large interaction cross section and relatively low cost, lead perchlorate $Pb(ClO_4)_2$ is an attractive candidate for a Cerenkov type neutrino detector. Neutrino interactions with lead may occur by either charged current (CC) or neutral current (NC) reactions:

$$\nu_{e} + {}^{208} \operatorname{Pb} \longrightarrow {}^{208} \operatorname{Bi}^{*} + e^{-} \qquad (CC)$$

$$\downarrow^{}_{208-X} \operatorname{Bi} + \operatorname{N}\gamma + Xn$$

$$\nu_{x} + {}^{208} \operatorname{Pb} \longrightarrow {}^{208} \operatorname{Pb}^{*} + \nu'_{x} \qquad (NC)$$

$$\downarrow^{}_{208-X} \operatorname{Pb} + \operatorname{N}\gamma + Xn$$

At 30 MeV the CC cross section with lead is about 600 times that of carbon and the NC cross section is about 100 times that of carbon. The signature of a CC interaction consists of a prompt electron followed by gamma rays and neutrons. The signature for NC interactions consists only of gamma rays and neutrons with no prompt electron. The number of neutrons (0, 1, or 2) depends upon the energy of the interacting neutrino. Because lead perchlorate solutions contain an appreciable amount of hydrogen, the neutrons quickly thermalize in the solution and are captured by the ³⁵Cl which then emits an 8.6 MeV gamma ray. The gamma ray is detected by subsequent Compton scattered electrons. This is the same reaction that will be utilized by the SNO Cerenkov detector to identify neutrons with high efficiency.

To determine if a lead perchlorate Cerenkov detector can be built we have investigated the optical properties of the solution. Studies using a spectrophotometer revealed that there were no obvious absorbtion lines between wavelengths of 250 to 600nm. We constructed a special apparatus to measure the attenuation of 460 nm light in various strength solutions. Initial measurements yielded attenuation lengths of less than half a meter, which is insufficient to build a large lead perchlorate Cerenkov neutrino detector. Diluting the solution further reduced the attenuation length, suggesting that light loss may be due to the formation of Pb salts which scatter the light. To remove scattering particles we filtered the lead perchlorate solution using a series of filter pore sizes from 5.0 microns down to 0.2 microns. This resulted in the attenuation curve shown in Fig. 2. 3.1-1. This improvement is sufficient for a reasonably sized Cerenkov detector and suggests that additional filtering might further increase the attenuation length.

Currently we are characterizing the Cerenkov light production of various strengths of lead perchlorate solutions. Once the production and attenuation of light has been understood and quantified we will be in a position to make meaningful assessment of the physics opportunities presented by this exciting new detector.



Figure 2.3.1-1. Attenuation of 460nm light in a 70% lead perchlorate solution. The attenuation length is approximately 4.3m.

2.3.2 Supernova neutrino detection using lead perchlorate

M. K. Bacrania, P. J. Doe, <u>S. R. Elliott</u>, R. G. H. Robertson, L. C. Stonehill and D. I. Will

With a relatively high cross section and relatively low cost, lead is an attractive neutrino detection medium. An important feature is that both charged and neutral current reactions are available to distinguish electron neutrinos from other neutrino flavors. Furthermore, the number of neutrons emitted in a Pb- ν reaction is very sensitive to the neutrino energy.

Many of the virtues of Pb as a supernova neutrino detector have been identified in reports by Hargrove *et al.*¹ and Cline *et al.*² In particular, the importance of the neutron production was noted by Fuller *et al.*³ Incorporating Pb in a Čerenkov medium with neutron sensitivity greatly enhances its value for supernova neutrino physics. The average energies of neutrinos emitted by a supernova are expected to follow a heirarchy: $E_{\nu_e} < E_{\bar{\nu}_e} < E_{\nu_{\mu,\tau}}$. The observation of high energy ν_e would be an indication of $\nu_{\mu,\tau}$ oscillations. Pb(ClO₄)₂ has the potential of measuring the charged and neutral current reactions independently due to its sensitivity to neutrons, electrons and photons. Furthermore, although Pb has a low cross section for interaction with $\bar{\nu}_e$, Pb(ClO₄)₂ is a water based solution and the $\bar{\nu}_e$ can be detected through their interaction with H. However, $\bar{\nu}_e$ can produce only one neutron via its reaction with H, whereas ν_e can produce one or two neutrons depending on its energy. It is thus possible to measure the average energy of the ν_e and $\bar{\nu}_e$ neutrinos in one detector. A comparison of these energies can then be interpreted in terms of neutrino oscillations.⁴

The following two figures show the strength of observing the energy of the recoil electrons in coincidence with the neutrons. The identification of the electrons permits one to separate the charged current and neutral current events. The number of neutrons permits one to separate the events into ν_e and $\bar{\nu}_e$ events. As shown in Fig. 2.3.2-1, determining the average energy of the electrons in coincidence with 1 (2) neutron indicates the $\bar{\nu}_e$ (ν_e)temperature. Since the 2-neutron production cross section for ν_e is so sensitive to ν energy, the relative number of 1- and 2-neutron events is a good indicator of the relative energies of the ν_e and $\bar{\nu}_e$. This is demonstrated in Fig. 2.3.2-2. In a similar way the neutral current production of 1- and 2-neutron events can indicate the flux of ν_{μ} and ν_{τ} .

¹C.K. Hargrove *et al.*, Astropart. Phys. **5**, 183 (1996).

 ²D.B. Cline *et al.*, Phys. Rev. D **50**, 720 (1994); P.F. Smith, Astropart. Phys. **8**, 27 (1997).
 ³G. Fuller, W. Haxton, and G.C. McLaughlin, Phys. Rev. D **59**, 085005 (1999).
 ⁴S.R. Elliott, Phys. Rev. C**62**, 065802 (2000).



Figure 2.3.2-1. The solid (dashed) line is a contour plot of the average energy of the electrons in coincidence with 1 (2) neutron(s) as a function of neutrino temperature.



Figure 2.3.2-2. This is a contour plot of the ratio of the number of 2 neutron events in coincidence with an electron to 1 neutron events in coincidence with an electron. The contours are plotted as a function of the ν_e and $\bar{\nu}_e$ temperatures.

2.4 SAGE

2.4.1 SAGE summary

B. T. Cleveland,* S. R. Elliott and J. F. Wilkerson

The Russian-American Gallium Experiment (SAGE) is a radiochemical solar neutrino flux measurement based on the inverse beta decay reaction, 71 Ga(ν ,e⁻) 71 Ge. The threshold for this reaction is 233 keV which permits sensitivity to the p-p neutrinos which comprise the dominant contribution of the solar neutrino flux. The target for the reaction is in the form of 55 tonnes of liquid gallium metal stored deep underground at the Baksan Neutrino Observatory in the Caucuses Mountains in Russia. About once a month, the neutrino induced Ge is extracted from the Ga. 71 Ge is unstable with respect to electron capture ($t_{1/2} = 11.43$ days), and, therefore, the amount of extracted Ge can be determined from its activity as measured in small proportional counters. The experiment has measured the solar neutrino flux extractions between 1990 and 2000 with the result: $77\pm6\pm3$ SNU (statistical and systematic uncertainties respectively) SNU. This is well below the standard solar model expectation of 128 SNU¹ and very close to the minimum flux required by the well-known solar luminosity of 80 SNU. The experiment continues to operate with the goal of reducing the uncertainties so a meaningful comparison can be made to this lower limit constraint.

The University of Washington plays a role in the analysis and interpretation of the data. The focus is now on acquiring enough solar neutrino data to lower the statistical uncertainties so they will be comparable to the systematic uncertainties.

^{*}SNO Institute, INCO Creighton #9 Mine, P.O. Box 159, Lively Ontario, P3Y 1M3, Canada. ¹J.N. Bahcall, M.H. Pinsonneault, and S. Basu, astro-ph/0010346v2

2.4.2 Verification of the technology for production of an intense ³⁷Ar neutrino source from a Ca target irradiated in a nuclear reactor

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All four solar neutrino experiments (Chlorine, Superkamiokande, SAGE, and GALLEX) show that the measured solar neutrino flux at the orbit of the Earth is considerably less than predicted by the Standard Solar Model. Because the reduction of the solar neutrino spectrum is most pronounced at intermediate energies ($\sim 1 \text{ MeV}$), new detectors that can measure the neutrino radiation from the Sun in this energy regime are especially needed. Several such detectors are in various stages of development and deployment, such as BOREXINO at Gran Sasso, KAMLAND in Japan, and the iodine detector at Homestake, South Dakota. To be certain of their response to low-energy neutrinos, these detectors must be calibrated by exposure to an intense artificially-produced source of neutrinos of about 1 MeV. Because of the extremely small cross section for neutrino capture, source intensities of about 1 MCi are necessary.

Two possible sources for this purpose are ⁵¹Cr and ³⁷Ar. Sources of ⁵¹Cr of ~1 MCi activity have been used to measure the low-energy ν cross section of Ga. An even more useful source is ³⁷Ar, which decays by electron capture and emits a monoenergetic ν . ³⁷Ar has several advantages compared to ⁵¹Cr. The ν is higher energy (814 keV vs. 747 keV). It has a longer half-life (35 d vs. 28 d). Because the Ar is easy to separate, there are almost no accompanying gamma rays from contamination thus reducing the need for bulky shielding and simplifying source transportation. Finally an Ar source can be very precisely calibrated by counting a small aliquot. Both KAMLAND and the iodine project have expressed an interest to calibrate their detectors with an intense ³⁷Ar source. These experiments are sensitive to Compton scattered electrons and thus require a calibration source, like ³⁷Ar, that has a reduced high-energy photon emission.

The use of ³⁷Ar to calibrate solar neutrino detectors was originally proposed by Haxton in 1988.¹ ³⁷Ar will be produced by fast neutrons using the reaction ${}^{40}\text{Ca}(n,\alpha){}^{37}\text{Ar}$. Previous work² showed that calcium oxide, CaO (2.4 g Ca/cm³) was the most suitable calcium-containing target. A 1-MCi ³⁷Ar source could be produced by placing about 200 kg of Ca in a fast flux reactor. Argon is easily removed from this target by dissolving the CaO in water or acid and flowing a carrier gas (such as He) through the solution. Argon is easily separated from helium with a trap at low temperature and reactive gases, such as hydrogen, can be removed from argon by flowing the gas through a getter at high temperature. After purification, the ³⁷Ar will be encapsulated in a minimal volume as the prototype of a source. The activity of this prototype will be determined by various methods, such as by measuring the rate of decay of a small aliquot of Ar in a proportional counter and by measuring the inner bremsstrahlung activity.

The work to produce a 100 Ci prototype source is supported by CRDF award number RP2-2276.

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¹W. Haxton, Phys. Rev. Lett. **60**, 768 (1988).

 $^{^{2}}$ V. N. Gavrin *et al.*, Preprint INR 777/92 (1992); and J. N. Abdurashitov *et al.*, to be published in Instruments and Experimental Techniques.

2.5 MOON (Mo Observatory Of Neutrinos) for low energy neutrino physics

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Measurements of two correlated β rays from ¹⁰⁰Mo are shown to make it possible to perform both spectroscopic studies of neutrinoless double β -decay ($0\nu\beta\beta$) with a sensitivity of the order of $\langle m_{\nu} \rangle \sim 0.03$ eV and real-time exclusive studies of the low energy solar and supernova ν 's by inverse β decays.¹ The fine localization in time and in space is crucial for reducing background rates in realistic detectors. Several options are under investigation for detector readout: a) sheets of Mo between plastic scintillator sheets with wavelength-shifter (WLS) fiber readout, b) scintillator-fiber detection and readout, c) liquid scintillators, and, d) cryogenic calorimetric readout. A test of prototype detector for a is in progress at RCNP, Osaka. It is composed of 8 layers of plastic and WLS-fiber ensembles; each 4-layer group is covered by a different type of reflector for comparison. One layer has the dimension of 20 × 20 × 0.25 cm. Light outputs are collected by a 16-anode PMT through 64 WLS fibers placed with 2.5 cm interval for the x direction at the front side of the plane and the same for y at the back side, each with 1 mm square size.

An attractive approach offering higher energy resolution to reduce the intrinsic two neutrino double β -decay ($2\nu\beta\beta$) coming into the $0\nu\beta\beta$ window is low temperature bolometry, being investigated at UW. Previously, the use of oxide compounds, which substantially increase Debye temperature and consequently decrease the heat capacity, such as lead molybdate (PbMoO₄) was tested for a molybdenum bolometer/scintillator below 100 K.² However, it contains ²¹⁰Pb radioactivity and the scintillation light of lead molybdate is only 16 % of that of NaI(Tl). Recently the specific heat of molybdenum was measured down to 0.2 K and the superconducting transition occurred at about 1 K.³ E. Fiorini and T. O. Niinikoski also estimated the energy resolution at 5 mK for a mass of 1 kg molybdenum; that is 47 eV(FWHM)/ 3.034 MeV~ 0.0015% molybdenum is in principle a good candidate for the high energy resolution bolometer.⁴ However, in practice the transfer of heat from broken Cooper pairs to the lattice is very slow. MOON requires good radiochemical purity and the chemistry of Mo lends itself to the same type of purification through the carbonyl as has been used for Ni for the Sudbury Neutrino Observatory. The estimation of cosmogenic backgrounds induced by muons and fast neutrons is in progress for the required depth underground.

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¹H. Ejiri, J. Engel, R. Hazama, P. Krastev, N. Kudomi, and R. G. H. Robertson, Phys. Rev. Lett. **85**, 2917 (2000).

²M. Minowa *et. al.*, Nucl. Instrum. Methods A **320**, 500 (1992); E. Fiorini, Nucl. Phys. B (Proc. Suppl.) **91**, 262 (2001).

³W. Duffy, Jr. *et al.*, J. Appl. Phys. **72**, 5628 (1992).

⁴E. Fiorini and T. O. Niinikoski, Nucl. Instrum. Methods **224**, 83 (1984).

3 Nuclear Astrophysics

3.1 Reanalysis of $\alpha + \alpha$ scattering and β -delayed α decay from ⁸Li and ⁸B

E.G. Adelberger and M. Bhattacharya

The broad, low-lying $J^{\pi} = 2^+$ structure in ⁸Be is of considerable interest for at least 2 reasons:

- 1. The ⁸B neutrino spectrum, which dominates the counting rates of the Kamiokande, Super-Kamiokande and SNO solar neutrino detectors, depends on the shape of this ⁸Be final-state continuum. To understand if neutrino mixing distorts the solar neutrino spectrum one clearly needs to have good confidence in the undistorted spectrum shape.
- 2. A controversy exists over the shape of the 2^+ continuum in ⁸Be. Barker¹ argued that to get a consistent R-matrix fit to both the $L = 2 \alpha + \alpha$ phase shifts and the β -delayed α spectra from ⁸Li and ⁸B decay data, one needs to introduce *two* low-lying 2^+ states where only a single level is expected. The presence of such a low-lying intruder state violates well-tested ideas of nuclear structure. This raises the possibility of unknown systematic errors in the experimental results, perhaps some calibration errors in the delayed alpha spectra.

Warburton² responded to Barker's point by arguing that the low-lying intruder state was an artifact of Barker's choice of a large (about 7 fm) matching radius; he showed that one could fit both the $\alpha + \alpha$ data and the beta-delayed α spectra without a low-lying intruder state if one used a more conventional matching radius of 4.5 fm. However, a problem remained; the width and position of the lowest ⁸Be 2⁺ level extracted from the beta decay data disagreed with those extracted from elastic scattering.

We reanalysed the same delayed-alpha spectra and $L = 2 \alpha + \alpha$ phase shifts considered by Barker and Warburton. We adopted Barker's R-matrix formalism for analyzing β -delayed alpha spectra as cited in Eqs. 9 and 15 of Warburton. Following Warburton, the final-state continuum was decomposed into 3 physical levels, the broad 3-MeV state and the narrow doublet at 16.626 and 16.922 MeV, and a "background level" placed at $E_x = 37$ MeV. The energy and width of lowest level and the width of the background level were treated as adjustable parameters, as were the Gamow-Teller matrix elements of the ground state, the T = 0 component of doublet, and the background state. However, we included the effect of lepton recoil broadening on the delayed alpha spectra that was ignored by these authors. Lepton recoil broadening plays an exceptionally large role in ⁸Li and ⁸B decay because of the large energy releases in the β decays, the small mass of the daughter nucleus and the unusually strong $e - \nu - \alpha$ triple correlation A = -1. We also found that Wilkinson's approximation³ for the mass-8 lepton recoil effect was incorrect because it ignored the triple correlation factor. We found that lepton broadening has a significant effect on the level parameters extracted from the delayed alpha spectra, and our analysis yields good agreement between the scattering and delayed alpha spectra. This resolves the discrepancy described above and gives confidence in using the delayed alpha spectra to infer the shape of the ⁸B neutrino spectrum.

¹F. C. Barker, Aust. J. Phys. **22**, 293 (1969).

²E. K. Warburton, Phys. Rev. C **33**, 303 (1986).

³D. E. Alburger, P. F. Donovan and D. H. Wilkinson, Phys. Rev. **132**, 334 (1963).

3.2 β -delayed alpha spectra from ⁸Li and ⁸B decays and the shape of the neutrino spectrum in ⁸B decay

E.G. Adelberger, M. Bhattacharya and H.E. Swanson

As was described in the previous report, the shape of the final-state continuum in ⁸Be populated by ⁸B β -decay is interesting not only because of its non-trivial nuclear structure but also because of its importance in determining the shape of ⁸B neutrino spectrum.¹ The shape of the final-state continuum can be inferred from either the shape of the beta spectrum or the beta-delayed alpha spectrum from ⁸B decay. Bahcall *et al.*¹ showed that the existing singles delayed-alpha spectra are inconsistent with each other and used a single beta spectrum shape measurement to obtain the standard ⁸B neutrino spectrum. Recently, a coincidence measurement of the delayed-alpha spectrum was performed by Ortiz *et al.*² where the authors placed their detection system in a magnetic field to avoid detecting the betas. However, due to the presence of the magnetic field their alpha detection efficiency had a strong dependence on the incident alpha energy which had to be accounted for using a detailed Monte-Carlo calculation.

Because of the difficulties involved in making an accurate beta spectrum shape measurement and to avoid introducing distortions in the spectra inherent to a coincidence measurement, we have chosen to make a precise singles measurement of the beta-delayed alpha spectra from ⁸Li and ⁸B decays.

We use the existing Mass-8 rotating target and movable catcher foil system to implant ⁸Li and ⁸B in 10 μ g/cm² C foils. The foils are viewed on opposite sides by a pair of 75- μ m thick silicon surface barrier (SSB) detectors (E-counters). The detectors are collimated to subtend small solid angles ($\Delta\Omega/4\pi=2.2\times10^{-3}$) so that the energy summing of the alphas with the preceding betas is minimized. In addition two 75- μ m SSB detectors located on either side of one of the E-counters at 45° allow us to obtain beta spectra in our E-counters in coincidence with alphas in these detectors that are then used for low energy beta background subtraction. The detectors are operated at 0°C and our amplifiers are mounted in a temperature-controlled rack for improved energy resolution. The gain drifts of our system is monitored using a precision pulser, high-resolution, spectroscopicgrade alpha sources are periodically introduced in front of the detectors, without breaking vacuum, for energy calibration of our detectors. In addition a PIN diode and alpha source assembly is also placed in the vacuum chamber for periodic monitoring of our catcher foil thickness.

Initial tests of our apparatus indicate that the setup works as expected and that we can calibrate our energy scale to 1 keV over an 8 MeV range.

¹J. N. Bahcall *et al.*, Phys. Rev. C **54**, 411 (1996).

²C. E. Ortiz *et al.*, Phys. Rev. Lett. **85**, 2909 (2000).

3.3 ${}^{7}\text{Be}(\mathbf{p},\gamma){}^{8}\text{B}$

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The existence of precise measurements of the flux of high-energy solar neutrinos (e.g. SNO and Super-K) makes it imperative that the cross section of radiative proton capture on ⁷Be be known to high accuracy. Our measurement of the ⁷Be(p, γ)⁸B reaction detects the alpha particles that result following the β decay of ⁸B. Measurements of the cross section as well as all important systematic errors have been carried out and are currently undergoing analysis.

We use a pair of electromagnetic coils to raster the incident proton beam at incommensurate frequencies to produce a uniform flux over the size of the target.¹ This avoids the large uncertainty due to uncertain and/or irregular areal density of the target which enters in a more conventional small-diameter beam experiment.

In the past, target fabrication difficulties were encountered in constraining the ⁷Be deposition to lie within a small area. This problem was solved with a redesign of the target backing. The new target backing consists of a central post surrounded by a washer that are machined together to form a solid piece. A 96-mCi deposition was made on this flat surface as previously,² and then the washer was removed, leaving ⁷Be activity only in the central region (see Fig. 3.3-1). With this new backing design, beam flux needs to be homogenous only over a small central area.



Figure 3.3-1. Circles are activity before removal of washer. Squares indicate activity after removal. The distribution of squares outside of the central area exhibits a slope which is due to the resolution function.

The flux uniformity requirement was verified by measuring the ⁷Li(d,p)⁸Li reaction yield (di-

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¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 39.

²A. Y. Zyuzin *et. al.*, Nucl. Instrum. Methods A **438**, 109 (1999).

vided by the integrated beam flux) versus raster amplitude. Since the ⁷Li in the target is mostly due to the decay of ⁷Be, the ⁷Li distribution mirrors that of the ⁷Be, allowing the diagnostic use of this high cross section reaction (though it was not used elsewhere in the measurement). This measurement as well as numerical calculations based upon measured ⁷Be activity scans and beam flux profiles show that remarkable uniformity is achieved under the conditions used to measure the ⁷Be(p, γ)⁸B cross section.

Using the rastered-beam technique, one does not need to know the areal density of the target, but only the total number of target scatterers. This was obtained from absolute target activity measurements *in situ* with a collimated Ge detector. The efficiency of the Ge was calibrated using $\pm 0.8\%$ (1 σ) sources of ⁵⁴Mn, ¹²⁵Sb, ¹³³Ba, ¹³⁴Cs, and ¹³⁷Cs from Isotope Products Corp, as well as a second ¹³⁷Cs source of similar precision from the French laboratory CERCA/CEA.

The numerous activity measurements carried out were also a useful check for sputtering of target material by the beam during the experiment. Examination of the activity measurements shows a non-negligible ($\sim 3\%$) sputtering over the duration of the experiment (see Fig. 3.3-2).



Figure 3.3-2. ⁷Be activity (corrected for decay) versus time to show sputtering. Errors shown are statistical – the total error per point is $\pm 1.5\%$.

The energy resolution of the UW Tandem Van de Graff was measured using narrow resonances in ¹⁹F(p, $\alpha\gamma$)¹⁶O at E_p = 340, 484, and 872 keV by detecting the resonance γ -rays with our large NaI spectrometer. The 90 degree analyzing magnet of the accelerator was cycled before any downward energy change so that all measurements were taken on the same hysteresis curve of the magnet. The total reproducibility in $\Delta E/E$ was determined to be $\pm 0.17\%$.

An additional importance is the energy thickness of the target. The energy width of an 96 mCi target was measured using a ${}^{7}\text{Be}(\alpha,\gamma){}^{11}\text{C}$ resonance at $E_{\alpha} = 1.376$ MeV also using the large NaI spectrometer. The mean energy loss of the α beam in the target was ≈ 26 keV (see Fig. 3.3-3). A pure ${}^{7}\text{Be}$ target of this activity would have a mean energy loss of about 13% this value, consistent with our previous fabrication of high-purity metallic ${}^{7}\text{Be}$ test targets.



Figure 3.3-3. Measurement of narrow resonance in ${}^{7}\text{Be}(p,\alpha\gamma){}^{11}\text{C}$ to determine energy thickness of target.

Considerable effort was also invested in creating a setup to measure the backscattering of ⁸B out of the target during proton bombardment. Such backscattering results in a systematic reduction of the measured ⁷Be(p, γ)⁸B yields, and therefore, if uncorrected for, in the deduced ⁷Be(p, γ)⁸B cross section.

To make the measurement, the beam passes through an aperture in a large copper catcher plate mounted on the end of the flipping arm and strikes a fixed ⁷Be target. Backscattered ⁸B ions are captured on the catcher plate, which is then rotated in front of the Si detector for counting of the alpha particles that result from the decay of ⁸B. Increased efficiency was obtained by placing catcher plates on both ends of the flipping arm. Backscattering measurements made during the experiment indicated that the backscattering probability for our latest ⁷Be target is low, < 2%.

Modifications to the accelerator allowed beams of up to 20μ A at E_p as low as 220 keV. High beam current, combined with a high activity target allowed the gathering of excellent statistics. This, combined with the careful measurement of the systematics involved in the measurement should allow us to reach our goal of \pm 5% total uncertainty on the cross section and the astrophysical S-factor.

3.4 ⁷Be $(p,\gamma)^8$ B Phase II

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We plan to carry out a Phase II ${}^{7}\text{Be}(p,\gamma)^{8}\text{B}$ cross section measurement extending to proton energies about a factor of 2 lower than those reached in our present Phase I project. Our goal here is to reach a level of precision of 5% in the cross section determination, comparable to the Phase I goal. The motivation is to reduce the uncertainty in the determination of the astrophysical Sfactor. Measurements at lower proton bombarding energies reduce this uncertainty for several reasons in addition to the obvious reason that the energy difference between the Gamow window and the energies at which the cross section is measured is reduced. Although this reaction at low bombarding energies is predominantly extranuclear direct capture, there is a non-negligible nuclear contribution. This nuclear contribution, which is uncertain theoretically, decreases with decreasing proton energy. There is also a model dependence – different cluster models and potential models – which can be reduced by restricting the range of acceptable models to those which reproduce the measured energy dependence of the cross section. Although no surprises such as unknown resonances are expected in the extrapolation, this S-factor is of such importance for solar neutrino physics that the extrapolation uncertainty should be minimized with experimental data as close to the Gamow window as possible.

Measurements at lower proton energies present several challenges. In order to reach proton energies as low as 120 keV or so with reasonable beam intensities of 10-20 microamps, modifications of the accelerator and TIS (Terminal Ion Source) are required, including the installation of a straight-field accelerator tube section as described in more detail in Sec. 7.3 of this Report.

Target improvements represent another challenge. Higher activity (>100 mCi) targets with smaller energy thickness are desirable. For the 100 mCi ⁷Be target used in our Phase I measurements earlier this year, the mean energy loss of α -particles at the $E_{\alpha} = 1376$ keV resonance in the ⁷Be(a, γ)¹¹C was about 26 keV. The low sputtering rates observed in proton and alpha bombardments of this target suggest that the energy thickness is not due to ⁷Be diffusing into the Mo backing, but instead is due to nonuniform target thickness and/or to a ⁷Be/contaminant ratio (with primarily low-Z contaminants) that varies with depth. Nonuniformities in the target thickness may be reduced by using polished Mo backings. Presently both possibilities are being investigated at TRIUMF.

A beam-off background of about 1.5 counts/hr is observed in our Si α -particle detectors, with a peak at about 5.3 MeV and a continuum extending out to about 6.3 MeV. The peak is due apparently to Polonium decay from Radon contamination of target chamber interior surfaces, while the tail may be due to U/Th contamination of surfaces which are viewed by the Si detector. The U/Th contamination seems to be present mainly in aluminum surfaces, which means that detector shielding with other materials can be used to reduce this background. In addition, since one of the main sources of error in the Phase I measurement is our solid angle normalization technique using a near/far detector ratio and the ⁷Li(d,p)⁸Li reaction, we are looking for an improved method of solid-angle/efficiency determination for our close Si counting detector for Phase II.

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3.5 WALTA: The Washington Large-area Time-coincidence Array

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Ultra-high energy cosmic rays are currently the topic of hot debate in the particle astrophysics community. Where are these particles coming from and what could accelerate a particle to such high energies are just two of the questions physicists would like to answer. WALTA (Washington Large-area Time-coincidence Array) is a project to investigate cosmic rays through a large distributed network. We plan on installing detectors on the roofs of high schools and middle schools in Seattle and the surrounding areas. A major component of WALTA is to directly involve students and teachers in the research.

We have continued to run simulations of the Seattle-area array using the CORSIKA code.¹ In addition to analyzing the response of the full array, we have performed simulations on the detector layout of individual school sites. Each school will monitor and analyze data from their own site. Ideally, we would like to use the school sites to look at the cosmic ray spectrum around the knee, a distinct feature in the energy spectrum at approximately 10^{15} eV. Confirmation of the knee will help verify that our system is running properly. With this in mind, we are working to determine the optimum spacing and number of detectors to use at each site. Simulations indicate that using 4 detectors with a spacing of between 10 and 15 meters is the most appropriate. To get a good measurement at knee energies, we will want to set up a few sites with a larger number of detectors. We will continue simulations to determine what the layout of these larger sites should be.

Approximately 160 scintillators (61 cm x 61 cm x 1.3 cm), 160 photomultiplier tubes, and 60 low to high voltage converters were retrieved from Dugway, Utah. This equipment was used in the Chicago Air Shower Array (CASA),² an experiment to study cosmic rays that was in operation from 1990 - 1998. These scintillators, PMTs and power converters will constitute the initial detectors used in the WALTA array. Research has been conducted on the efficiency of the CASA detectors and on ways to improve this efficiency. After determining the detector refurbishment procedure, we will organize/develop 1-day workshops to give high school students laboratory experience working with the WALTA equipment and helping with the refurbishment.

We adapted a charge-to-time (QTC) converter from the Super-Kamiokande experiment to use for the WALTA array until a custom data acquisition board can be developed. Data acquisition software was developed to accompany the QTC electronics board. This setup has been used as a test station to study the CASA hardware.

In Fall 2000, the WALTA group hosted the Cosmic Ray Physics with School-Based Detector Networks Workshop. During the workshop, the North American Large-scale Time-coincidence Arrays (NALTA) Consortium was formed. As a continuation of this collaboration, we are working with the University of Nebraska to run an outreach program at the Snowmass 2001 conference.

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¹D. Heck *et al.*, 1998, Karlsruhe Report FZKA 6019; http://www-ik3.fzk.de/ heck/corsika/Welcome.html ²M. A.K. Glasmacher *et al.* Astroparticle Physics **10**, 291 (1999).

4 Relativistic Heavy Ions

4.1 HBT physics at STAR

4.1.1 Summary

J.G. Cramer and the STAR HBT Physics Working Group*

The HBT Physics Working Group (a group of approximately 20 physicists led by co-convenors J. G. Cramer and M. A. Lisa) has made very significant progress in the past year in analyzing the data from the initial operation of the STAR detector at RHIC. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory produced the first gold + gold collisions in June, 2000. Since that time, about a million central collision events and a million minimum-bias events have been recorded by the STAR detector for Au + Au collisions at a CM energy of $\sqrt{s_{NN}} = 130$ GeV.



Figure 4.1.1-1. The multiplicity dependence of the Pratt-Bertsch HBT parameters is shown for $(0.125 < p_T < 0.225 \text{ GeV/c})$ on the left, while for central collisions the m_T -dependences are shown on the right. Error bars indicate statistical uncertainties; systematic uncertainties are shown by the shaded regions in each panel.

The STAR HBT Physics Working Group was well prepared for the initial operation of RHIC. By August, 2000, we had completed the initial HBT analysis of the momentum-space correlations of pions in the STAR data at 130 GeV/A. We have written a Physical Review Letter reporting these initial HBT results for pions at 130 GeV per nucleon. The paper is in the final stages of approval by the STAR Collaboration. Fig. 4.1.1-1 and Fig. 4.1.1-2, taken from this paper show the

^{*}See the HBT PWG web site at http://connery.star.bnl.gov/STAR/html/hbt_l

dependence of the HBT observables on multiplicity, transverse momentum, and collision energy.



Figure 4.1.1-2. The energy dependence of π^- HBT radii extracted at midrapidity from central Au+Au or Pb+Pb collisions at $p_T \approx 0.17$ GeV/c. Lower energy points are from AGS and SPS measurements. Error bars on NA44, NA49, and STAR results include systematic uncertainties; error bars on other results are statistical.

We have found some interesting surprises in the pion HBT analysis, among which are: (1) The spatial size of the fireball produced in RHIC collisions is about the same size as that observed at the CERN SPS, an order of magnitude lower in energy. (2) The duration of pion emission from the fireball is remarkably short, in contradiction to theoretical expectations of a long emission duration. (3) The pion phase space density at freezeout is remarkably close to that observed at the CERN SPS, suggesting an invariant behavior that may be useful for making predictions. (4) The freezeout temperature of the fireball seems to be slightly lower than that observed at the CERN SPS. (5) The collective radial velocity of the expanding source at freezeout is very high, and has a value that approximates $c/\sqrt{3}$, the velocity of sound in a relativistic fluid. This implies that the source is literally exploding and may be forming a shock wave, a behavior not anticipated by pre-RHIC theoretical models.

In summary, the STAR HBT Physics Working group has mounted an active program for performing Bose-Einstein and other correlation analyses on the data produced by the STAR, and this analysis has produced many interesting and surprising results. It has been a busy and productive year, and we look forward to more to come.

4.1.2 Pion phase space density from STAR HBT analysis

J.G. Cramer and the STAR HBT Physics Working Group*

The 6-dimensional position-momentum space occupied by pions produced in RHIC collisions can be divided into "phase-space cells" having a six dimensional volume \hbar^3 . The phase space density, i.e., the average number of pions per phase space cell, is of great interest because it determines the importance of multiparticle HBT correlation effects and because it can be directly compared with thermal models to provide estimates of dynamic collision characteristics such as freezeout temperature and average flow velocity.

The phase space density $\langle f \rangle$ can be calculated from the observed pion momentum spectrum $d^2N/dy \, dm_T$ and the HBT observables λ , R_O , R_S , and R_L . At midrapidity the phase space density as a function of transverse mass m_T , with E_{π} , the total pion energy, is given by the relation: $\langle f \rangle = \frac{(\hbar c)^3}{2E_{\pi}m_T} \frac{d^2N}{dy \, dm_T} \frac{(\lambda \pi)^{\frac{1}{2}}}{R_O R_S R_L}$.

Fig. 4.1.2-1 shows this phase space density for STAR data at midrapidity. The lower lines represent static Bose-Einstein phase space densities at temperatures of 99.5, 94.3, and 89.7 MeV. Uppermost line shows an extrapolation made by fitting the m_T dependence of the pion spectrum and the HBT observables. The other upper curves are calculations for temperatures of 94.3, and 89.7 MeV, made using a linearized Tomasik model that includes the effects of radial flow in a Bose-Einstein phase space density. The analysis gives an intrinsic pion freezeout temperature of 94.3 ± 1.0 MeV. Combining this temperature with the observed effective temperature of the pion spectrum (185 ± 5 MeV) gives an average radial flow velocity of $\beta_T = 0.587 \pm 0.02$. This is a remarkably high flow velocity that approximates $\beta_S = 1/\sqrt{3} = 0.577$, the velocity of sound in a relativistic fluid.



Figure 4.1.2-1. Phase space density calculated from spectra and HBT observables for CERN Experiment NA49 (squares) and the STAR experiment at RHIC (stars). See text for a description of the curves.

We observe a pion phase space density for RHIC collisions that is remarkably similar to that for collisions at the SPS, suggesting a universal freezeout behavior. The value of the transverse flow velocity from STAR data suggests that it may be hard against the sonic limit.

^{*}See HBT PWG web site at http://connery.star.bnl.gov/STAR/html/hbt_l

4.1.3 A fast algorithm for finite-size and -resolution Coulomb correlations

J.G. Cramer and the STAR HBT Physics Working Group*

In analyzing the Bose-Einstein correlations of charged pions to extract source geometry observables, a correction must be made for the Columb interaction between the charged particles. However, this correction procedure is complicated by the dependence of the Coulomb correlation itself on source geometry. Therefore, the analysis is often done iteratively until a self-consistent source geometry is extracted. The procedure is further complicated because the low-relative momentum part of the Coulomb correlation is strongly modified by the finite momentum resolution of the particle detector. For these reasons, a fast and reliable way of calculating finite-size Coulomb correlations including momentum resolution effects is of great interest.

We have developed an analytic procedure for calculating finite-size and -resolution Coulomb correlations. The procedure includes the smearing effects of detector momentum resolution. The algorithm is based on an approximation developed by Sinyukov¹ and previously coded in FORTRAN by Lednicky. The present algorithm is simplified for speed and has been modified from the Sinyukov form to include the effects of momentum resolution on the low-Q part of the correlation function. It can be coded in about 6 lines of C++ code.

Fig. 4.1.3-1 shows a comparison of the functions $C_f(\pi^+\pi^+)$ (upper) and $1/C_f(\pi^+\pi^-)$ (lower) for $R_{cou} = 6$ fm and $Q_{res}=0$ (no resolution correction), as calculated with 5-dimensional Monte Carlo integration of Coulomb wave functions over the source using the Pratt code (points) and calculated with the new algorithm (lines).



Figure 4.1.3-1. Comparison of like-sign (upper) and opposite sign (lower) Coulomb correlations (see text) for $R_{cou} = 6$ fm, computed with 5-D Monte Carlo integration (points) and with the new algorithm (lines). The horizontal scale is Q_{inv} in GeV/c.

Fig. 4.1.3-2 shows the simulation of resolution effects. The Coulomb correlation $C_f(\pi^+\pi^-)$ calculated with 5-dimensional Monte Carlo integration (points) assuming a source size of $R_{cou}=6$ fm and momentum resolution values of $Q_{res}=0$, .002, .003, .004, .005, and .006 GeV/c (upper to lower) is compared with the new algorithm (lines).

^{*}See the HBT PWG web site at http://connery.star.bnl.gov/STAR/html/hbt_l ¹Phys. Lett. B **432**, 248 (1998).



Figure 4.1.3-2. Resolution effect simulation for finite size $C_f(\pi^+\pi^-)$ Coulomb correlation functions. Here $R_{cou} = 6$ fm and $Q_{res}=0$, .002, .003, .004, .005, and .006 GeV/c (highest to lowest). The horizontal scale is Q_{inv} in GeV/c.

The correspondence between the Pratt code and the approximation appears to be very good over the range of radii and momentum values that is appropriate for the STAR detector. The approximation can reproduce in a very short time a calculation which takes many hours on a fast computer using the Pratt code.

4.1.4 Elliptic flow effect on pion interferometry analysis in ultra-relativistic heavy-ion collisions

J.G. Cramer and Q.J. Liu

In ultra-relativistic heavy-ion collisions there are three types of correlations among final-state pions: correlations with the reaction plane induced by elliptic flow, correlations with a jet axis produced by the parton cascade structure of jet production, and Bose-Einstein correlations arising from boson quantum statistics. The common feature of these correlations is that they all cause pions to cluster in momentum space. In pion interferometry analysis, the effects of the other two correlations types need to be estimated if they can not be avoided.

Correlations caused by jet production exist dominantly among particles with high transverse momentum. Since pion interferometry analysis at STAR is restricted to momenta below 1 GeV/c by track merging effects, jet correlation effects on HBT analysis should not be significant.

Elliptic flow in ultrarelativistic heavy-ion collisions is characterized by v_2 , the second harmonic coefficient of an azimuthal Fourier decomposition of the momentum distribution. Given v_2 , the decomposed azimuthal distribution¹ at central rapidity region of central collisions of ultra-relativistic heavy-ions is approximately expressed as follows:

$$\frac{dn}{d\phi} = C \left(1 + 2 v_2 \cos(2\phi) \right) \tag{1}$$

Here ϕ is the azimuthal angle of a particle relative to the event reaction plane and C a normalization factor. It has been reported² that elliptic flow for charged particles increases from 3.5% at SPS to 6% at RHIC. This systematic increase of elliptic flow implies that it is of interest to estimate the elliptic flow effect on pion interferometry analysis at RHIC.

Our approach is to simulate correlations induced by elliptic flow according to Eq. 1, then incorporate this simulation into a Monte-Carlo generator program that simulates the pions produced in ultrarelativistic heavy-ion collisions and builds Coulomb corrections and Bose-Einstein correlations up to 6th order into the simulated data according to the formalism described in Cramer and Kadija.³ With the DST files produced by the program as input to HBT analysis codes, one can study elliptic flow effect on pion interferometry analysis.

We have implemented a module for simulating correlations induced by elliptic flow. Additionally, we have finished two modules for sampling pion transverse mass in our simulation of pions produced in heavy-ion collisions at RHIC according to either a Boltzmann distribution or a Bose-Einstein distribution. We have prepared a module for simulating radial flow, because pions produced at freeze-out have been measured to have an expansion velocity that characterizes the radial flow.

We are currently testing the integration of the newly implemented modules into the Monte-Carlo program. After the integration is tested, we plan to generate the DST files and use these DST files to study the effects of elliptic and radial flow on HBT analysis.

¹S. A. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996).

²STAR Collaboration, K. H. Ackermann, et al., Phys. Rev. Lett. 86, 402 (2001).

³J. G. Cramer and K. Kadija, Phys. Rev. C **53**, 908 (1996).

4.2 Event by event physics at STAR

4.2.1 Summary: EbyE physics at RHIC

Q. J. Liu, D. J. Prindle, J. G. Reid and <u>T. A. Trainor</u>

A major development in EbyE physics at the SPS has been the observation of charge-dependent fluctuations and correlations in transverse momentum, with no substantial evidence for chargeindependent or dynamical fluctuations. In contrast, one of the most prominent features of the new EbyE landscape at RHIC is the observation of substantial charge-independent or dynamical fluctuations and correlations. The EbyE program in STAR has, by the time of the Quark Matter conference only months after first experimental data from RHIC collisions, produced a wealth of new results. The program has benefited from direct transfer of UW analysis infrastructure from NA49, facilitating quick implementation of the STAR EbyE analysis and insuring reliable A-B comparisons between the CERN SPS and RHIC.

The most prominent evidence of dynamical correlations comes from charge-independent variance excess in $\langle p_t \rangle$ fluctuations. One measure of this excess indicates a fractional effect at the 10% level, to be contrasted with an observed upper limit in the same measure of 1% at the SPS. The RHIC result is also comparable to event-wise fractional 'temperature' fluctuations of about 0.5%.

Excess/deficient $\langle p_t \rangle$ fluctuations are predicted to have counterparts in two-particle p_t correlations, and these are observed. The corresponding charge-independent saddle feature in the two-particle density ratio on $p_t \otimes p_t$ agrees with prior simulations of event-wise T fluctuations and can be related to the structure of single-particle p_t distributions in high-energy p-p collisions (Lévy or power-law distribution) which signal particle production by hard QCD processes (hard parton scattering) and incomplete equilibration.

The observations reported here however are restricted by design to the soft component of the p_t distribution – below 1 GeV/c – which eliminates direct contributions from hard processes such as hadronization of jets and minijets, reserved as a separate area of study. Possible sources of charge-independent p_t correlations at RHIC include indirect soft p_t production from minijet quenching (parton energy loss) in color-deconfined nuclear matter and recently-proposed particle production from critical decay of a gluon Polyakov-loop condensate.⁴ Thus, the details of this particular EbyE result are of considerable immediate interest relative to some central issues of the RHIC program: color deconfinement, parton dynamics in a deconfined medium and semiclassical critical phenomena on the glue field.

Charge-dependent structures in transverse phase space are still evident at RHIC, but with somewhat reduced amplitude compared to the SPS, which may however be a trivial effect of combinatoric dilution in events with higher multiplicity. New analysis is now available for axial phase space, specifically $\eta \otimes \eta$ and $\phi \otimes \phi$ correlations where charge-dependent effects dominate the correlation landscape, and charge-independent structure plays a minor role. Similar structure was first observed 25 years ago in the axial phase space of *p*-*p* collisions. However, the details of Au-Au correlations at $\sqrt{s_{NN}} = 130 \text{ GeV}$ differ markedly from *p*-*p* results at $\sqrt{s_{NN}} = 20 \text{ GeV}$. The recent results for charge-dependent $\eta \otimes \eta$ correlations suggest a similar mechanism to that for transverse charge-dependent correlations, the difference in detail coming mainly from the relative magnitudes

⁴A. Dumitru and R. Pisarski, Phys. Lett. B **504**, 282 (2001), hep-ph/0010083, hep-ph/0102020

 $(\beta\gamma)$ of flow in axial and transverse directions.

 $\phi \otimes \phi$ correlations are dominated by a large elliptic flow signal at RHIC, a sign of hydrodynamic behavior achieved at early times in the collision. The challenge then is to study other azimuthal correlations which may underly the flow signal. Elliptic flow is predominantly a charge-independent dynamical effect. An important early analysis task then is to investigate the azimuthal structure of observed charge-dependent correlations in axial and transverse momentum space.

4.2.2 STAR $< p_t >$ fluctuation analysis

J.G. Reid and T.A. Trainor

There has been a great deal of theoretical interest in the measurement of fluctuations in the transverse momentum distribution in relativistic heavy-ion collisions. Measuring these fluctuations is a simple matter of comparing the rms width of the inclusive p_t distribution to the multiplicity-scaled width of the event-wise mean p_t distribution: $\Delta \sigma_{p_t} = \sqrt{N} \sigma_{< p_t > -} \sigma_{p_t}$.

According to the central limit theorem, if these two widths are the same $(\Delta \sigma_{p_t} = 0)$ then fluctuations observed in the data are consistent with independent sampling of a static parent distribution. In other words, if we see no fluctuations in excess of the statistical reference then equivalently the data are consistent with independent particle emission from a thermalized source.

Of course, one must take care to only include the momenta of particles which originate from the collision itself (primary particles). The inclusion of secondaries from resonance decays, split tracks, mis-reconstructed tracks, *etc.* will lead to fluctuations beyond statistical expectation. Thus, we apply a strict set of track quality cuts to the data before performing the analysis.

After these cuts are applied the mean event multiplicity in a sample of 45k central (15%) events is 222, and we find excess fluctuations measured by $\Delta \sigma_{p_t} = 35 \text{ MeV/c} \pm 3 \text{ MeV/c}$ (statistical). This is quite striking since the NA49 experiment found no significant excess fluctuations at the level of 1 MeV/c. This suggests that there is a source of significant dynamical fluctuations in RHIC collisions which are not present at SPS energies.

Furthermore, one can perform this analysis separately for different charge species and combine the results to isolate charge-dependent and charge-independent components:

$$\Delta \sigma^{2}{}_{\Sigma} = \frac{1}{N} (N_{+} \Delta \sigma^{2}_{p_{t_{+}}} + N_{-} \Delta \sigma^{2}_{p_{t_{-}}} + 2\sqrt{N_{+} N_{-}} \Delta \sigma^{2}_{p_{t_{+}} p_{t_{-}}})$$
(1)

$$\Delta \sigma^2_{\Delta} = \frac{1}{N} (N_+ \Delta \sigma^2_{p_{t+}} + N_- \Delta \sigma^2_{p_{t-}} - 2\sqrt{N_+ N_-} \Delta \sigma^2_{p_{t+} p_{t-}}).$$
(2)

Where $\Delta \sigma^2_{\Sigma}$ measures the charge-independent piece and $\Delta \sigma^2_{\Delta}$ measures the charge-dependent piece. We have calculated these charge-specific fluctuation measures as a function of centrality:

Both fluctuation measures are slowly varying with centrality, and we find that the dominant non-statistical fluctuations are produced by a charge-independent mechanism. We observe a smaller but still significant charge-dependent component, of the same sign as but slightly smaller than that seen in the NA49 experiment at the CERN SPS.



Figure 4.2.2-1. Centrality dependence of charge-dependent and charge-independent fluctuation excesses in the $\langle p_t \rangle$ distribution.

4.2.3 STAR $m_t \otimes m_t$ correlation analysis

J.G. Reid and T.A. Trainor

Two-point correlations on transverse mass m_t are directly related to overall $\langle p_t \rangle$ fluctuations in the data. A more differential way to analyze $\langle p_t \rangle$ fluctuations therefore is to study two-particle correlations on transverse mass. Following the same technique used in NA49 we form a two-point density of sibling pairs, and a conjugate two-point density formed from mixed pairs from nearestneighbor events in a space defined on event properties such as vertex position and event multiplicity, which we use as a reference. By dividing these two $m_t \otimes m_t$ distributions we get a two-point density ratio space where deviations from unity may indicate interesting physics correlations.





In Fig. 4.2.3-1 we show first results for $m_t \otimes m_t$ correlations from the STAR detector at RHIC. The four plots represent like-sign charge combinations ++ and --, unlike-sign combination +and density ratio for pairs undifferentiated with respect to charge cc. There is a clear large-scale saddle feature common to all the plots which represents a deficiency of pairs with large momentum difference and an excess at large mean pair momentum in the sibling-pair distribution when compared to the mixed-pair reference. This feature was anticipated by Monte Carlo simulations of relative temperature fluctuations at the 0.5 percent level.

We can make a connection between this analysis and the $\langle p_t \rangle$ fluctuation analysis by decomposing the two-point density ratios into a charge-dependent part and a charge-independent part. To do this we combine the two-point ratio histograms as ([++] + [--]) * ([+-] + [-+])/4for the charge-dependent part and ([++] + [--])/([+-] + [-+]) for the charge independent part. The notation [++] represents the two-point ratio for positively charged pairs only, [+-] for pairs where the first particle is positively charged and the second negatively charged, and so forth. When this histogram arithmetic is completed we find results which are qualitatively consistent with our results for $\langle p_t \rangle$ fluctuations. In the charge-independent part we find the dominant large-scale saddle shape common to all the $m_t \otimes m_t$ analysis results. In the charge-dependent part we find a distribution which has a small but significant quadratic dependence on momentum difference, similar to that observed in NA49.

Thus, the large charge-independent effect seen in the $\langle p_t \rangle$ fluctuation analysis has a counterpart in the saddle shape which is observed in the two-particle correlation analysis. This saddle shape is related to power-law or Lévy distributions used to describe momentum distributions for partially equilibrated systems. We also find a charge-dependent result similar to that observed at the SPS.

4.2.4 STAR η and ϕ correlations

I. Ishihara,^{*} J. Seger[†] and <u>T. A. Trainor</u>

Previous work on two-particle correlations in NA49 and STAR has focussed on transverse phase space, and specifically correlations on transverse mass m_t . Here we describe first results from an analysis of longitudinal phase space: two-particle correlations on pseudorapidity η and azimuth angle ϕ . This is a precision analysis, with observable effects typically appearing at the *permil* level due to combinatoric dilution in these high-multiplicity events. Nevertheless, regular correlation structures with substantial statistical significance are observed.

The 2D distributions shown in Fig. 4.2.4-1 are ratios of two-particle density distributions for sibling pairs (from same event) and mixed pairs (from different events). Events are ordered in a space of global event properties, and mixed pairs are then formed from 'nearest-neighbor' events in this space. This minimizes systematic errors due to event property variation – an important issue for an event sample obtained with a collider in which the vertex position varies considerably relative to the detector. Correlation structures can be separated into charge-dependent and charge-independent components, depending on different linear combinations of the relative signs (pion-pair total isospin) of the pair charges. Charge-independent components typically correspond to dynamical effects within the collision process: incomplete equilibration, hierarchical momentum transfer, collective degrees of freedom. Charge-dependent components may reflect short-range isospin correlations in configuration space formed during chemical freezeout and manifest in momentum space via radial and axial flow correlations. The charge-dependent structures in the two left-most panels have some general similarity to structure observed in p-p collisions at lower energies $(\sqrt{s_{NN}} \approx 20 \ GeV/c)$ in the mid seventies and included phenomenologically in the Lund string model. However, there are important differences in detail which will be the subject of future quantitative analysis. The third panel shows new structure on pair mean pseudorapidity which has vet to be interpreted.

The right-most panel shows the expected strong cosine correlation on angle difference $\Delta \phi$ due to elliptic flow. The amplitude of the observed two-particle correlation corresponds to the previously

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Figure 4.2.4-1. Two-particle correlations on η and ϕ . Left panel shows charge-dependent correlations on $\eta \otimes \eta$ featuring a prominent valley for small values of $\Delta \eta$ near the main diagonal. The next two panels show 1D projections on difference and sum diagonals showing again the prominent valley on difference and a quadratic structure on the sum. The rightmost panel shows charge-independent correlations on $\phi \otimes \phi$. The most prominant structure is the $\cos(2\Delta\phi)$ periodicity corresponding to elliptic flow. There is also a contribution at small $\Delta\phi$ from quantum (Bose-Einstein) correlations.

measured flow amplitude for the centrality range of this data sample. Study of two-particle azimuth correlations with precision techniques should enable study of effects other than elliptic flow which can provide important new information on the angular structure of the collision.

4.2.5 Multi-particle azimuthal correlations and jet production in central collisions of Au on Au at $\sqrt{s_{NN}} = 200$ GeV in a Monte-Carlo model

Q. J. Liu and T. A. Trainor

It was suggested recently that jet production in ultra-relativistic heavy-ion collisions be investigated through two-particle azimuthal correlations analysis. In this report, based on the argument that jet production is a preferential emission of multi-particles and thus jet-induced correlations are a kind of multi-particle correlation, we propose to study jet production in heavy-ion collisions at RHIC via analysis of multi-particle correlations.

The methodology used in this report is similar to the one described in a previous publication.¹ It includes splitting an event into n-particle sub-events and calculation of an n-particle azimuthal correlation function. The function is defined as follows:

$$F(U_n) = \frac{D(U_n)}{B(U_n)}, \text{ where } U_n = \frac{1}{n} |\sum_{i=1}^n \frac{p_i^t}{|\vec{p_i^t}|}|$$

Here $p_i^{\vec{t}}$ stands for the transverse momentum vector of the *i*th particle in an *n*-particle sub-event, from which one U_n is obtained from the azimuthal angles of the *n* particles in it. For each event with a multiplicity M, the number of *n*-particle sub-events one can have is $\Omega = \frac{M!}{n!(M-n)!}$. $D(U_n)$ is the U_n distribution of *n*-particle sub-events from real events and $B(U_n)$ is the U_n distribution of *n*-particle sub-events, in which *n*-particle azimuthal correlations do not exist. The real events refer to the ones from an experiment or an event generator. As for how to

¹Q. J. Liu, Phys. Rev. D **54**, 3659 (1996).

build background events and other details of the methodology, the interested reader is referred to Ref. 1.

 U_n is capable of reflecting the extent to which the emission of n particles is aligned. In a subevent of n particles, if the emission of n particles is completely aligned, $U_n = 1$; if no alignment exists at all for them as a whole, $U_n = 0$. If there are no correlations due to flow or jet production, for example, assuming particles are produced isotropically in a event of heavy-ion collisions, then $F(U_n)$ should be 1. In case of elliptic flow or jet production, an enhancement of $F(U_n)$ when U_n is close to 1 should be observed.



Figure 4.2.5-1. $F(U_n)$ for collisions of Au on Au at $\sqrt{s_{NN}} = 200$ GeV in the region of $|\eta| < 1$ in Hijing 1.36, with Fig. a and b showing n and transverse momentum dependence, respectively.

Shown in Fig. 4.2.5-1 are $F(U_n)$ calculated from 30000 Hijing 1.36² events with zero impact parameter. The errors are statistical. One can see from Fig. 4.2.5-1 that an enhancement of $F(U_n)$ in the vicinity of $U_n = 1$ appears. This enhancement reveals that a preferential emission pattern of final-state particles exists in the collisions. Among jet production and flow, which give rise to an enhancement of $F(U_n)$ near $U_n = 1$, flow (both elliptic and directed) are not expected to exist in events of Au on Au collisions generated with Hijing 1.36 with zero impact parameter. Fig. 4.2.5-1b shows that the higher the transverse momenta of the particles, the more preferentially emitted are the particles, as signified by the enhancement of $F(U_n)$. Hence, one can conclude that the enhancement shown in Fig. 4.2.5-1a and Fig. 4.2.5-1b is solely from jet production, and high-order $F(U_n)$ can signal jet production more evidently.

Multi-particle azimuthal correlations in collisions of Au on Au at $\sqrt{s_{NN}} = 200$ GeV in Hijing1.36 have been studied with multi-particle azimuthal correlation functions introduced in this report.

²M. Gyulassy and X. N. Wang, Comp. Phys. Comm. 83, 307 (1994).

High-order multi-particle azimuthal correlation functions calculated with moderate transverse momentum cuts are shown to be alternative observables for studying jet production in ultra-relativistic heavy-ion collisions.

4.2.6 Power-law structure of minimum-bias multiplicity distributions

Q. J. Liu and <u>T. A. Trainor</u>

It was observed recently¹ that the minimum-bias multiplicity distribution (distribution of event frequency on event multiplicity with minimal trigger bias) for heavy ion collisions approximates power-law behavior, *i.e.*, approximates a straight line on a log-log plot. The standard log-linear plot format is shown in the top panel of Fig. 4.2.6-1 for STAR Au-Au collision data restricted to negative hadron (h_{-}) multiplicity. The exponent of the power law is very close to -3/4, and we speculate that this might be exact for some generic nuclear geometry. The bottom panel of Fig. 4.2.6-1 shows the same data replotted in the form $(N/N_0)^{3/4} d\sigma/dN$. For exact power-law behavior with exponent -3/4 the new plotting format should result in a constant distribution. This is indeed a good approximation except near the high end or *terminus* of the distribution, where the shape is dominated by fluctuations in particle production relative to participant number.



Figure 4.2.6-1. STAR minimum-bias multiplicity distribution for negative hadrons plotted as $d\sigma/dN$ in standard semilog format (top) and as $d\sigma/dN^{1/4}$ in linear format (bottom).

The factor $4(N/N_0)^{3/4}$ is the Jacobian from d/dN to $d/dN^{1/4}$. This suggests that in an ideal case the distribution $d\sigma/dN^{1/4}$ is uniform up to the terminus, with shape determined by fluctuations. This is a major development in the analysis of such distributions. First, it provides a precision reference to study the centrality dependence of particle production in terms of deviation from a power-law hypothesis. Second, the terminus half-max point provides an unbiased estimator for the

¹D. Hardtke, LBNL, private communication

width of the parent minbias distribution. Third, the shape of the terminus provides new access to particle production fluctuations independent of participant number fluctuations for central events. Until now, participant fluctuations have been an unknown component of measure fluctuations, introducing a substantial error to any fluctuation measurements based on a centrality trigger. Sec. 4.6 illustrates this power-law reference applied to a study of particle-production mechanisms.

4.2.7 Multiplicity fluctuations in STAR

D.J. Prindle and T.A. Trainor

In heavy-ion collisions one source of excess multiplicity fluctuations is impact-parameter variations. Finite-number fluctuations are treated as a known reference. Remaining sources of excess fluctuation correspond to correlations of interest in the collision final state.

Some bipolar quantities (charge, baryon number and strangeness) are conserved. If the acceptance is partial, measured quantities can fluctuate about mean values, but to a degree *reduced* compared to a finite-number reference (canonical suppression). Fluctuations in global event variables may be scale dependent. Some charged particles come from the decay of neutral particles (*e.g.*, ρ mesons) such that every positive charge is associated with a negative charge somewhere in the acceptance. If the angular acceptance is larger than a typical pair opening angle the measured net-charge fluctuations may be suppressed below the finite-number reference level.

Our measure of charge difference fluctuations is $\sigma_{\Delta}^2/N_{ch} = \overline{(\delta N_+ - \delta N_-)^2}/(N_+ + N_-)$ where δN is a deviation from the mean and N_+ and N_- are the numbers of positive and negative charged particles measured in an event. This ratio is unity in the case of finite-number or Poisson fluctuations. STAR has reasonable tracking efficiency for pseudorapidity values out to $|\eta| \approx 1.5$, or $\Delta \eta = 3$, which is therefore the largest acceptance that we can probe reliably. For this study we restrict to the interval $|\eta| \leq 1$ to minimize possible systematic effects at acceptance boundaries.

A scaling analysis measures fluctuations in successively smaller acceptance windows (bins). We have examined rapidity bins with size (scale) $\delta \eta = 0.25, 0.50, 1.0$ and 2.0. In the smallest bin we anticipate minimal correlation from hadronic resonances, and so expect $\sigma_{\Delta}^2/N_{ch} \approx 1.0$. As we in-



Figure 4.2.7-1. σ_{Δ}^2/N_{ch} as function of centrality and acceptance. The multiplicity increases with centrality, so the most peripheral events are on the left and most central on the right. The circles are for $\delta \eta = 0.25$, squares for $\delta \eta = 0.5$, triangles for $\delta \eta = 1.0$, and stars for $\delta \eta = 2.0$.

crease the bin size we expect correlations and charge conservation (canonical suppression) to reduce this ratio. As an added complication, the sources of correlation or physics (e.g., hadronic resonance abundances) may change with centrality, so we carry out the analysis in multiple centrality bins as well. Measured ratios are shown in Fig. 4.2.7-1 as a function of acceptance and centrality bin size.

Clearly σ_{Δ}^2/N_{ch} deviates further from unity as the acceptance increases. We study how much this change results from canonical suppression and how much is caused by hadronic resonance or other nontrivial correlations. We are also analyzing Monte-Carlo events with known resonance contributions and mixed events formed from a positive charge multiplicity from one event and a negative multiplicity from a different event with the same total multiplicity.

4.3 Event by event physics at the SPS

4.3.1 Summary: EbyE physics at the SPS

J.G. Reid and <u>T.A. Trainor</u>

A coherent picture is emerging from event-by-event analysis results for Pb-Pb collisions at the SPS. This coherence is due to two new developments: 1) a unified treatment of fluctuations in global variables $\langle p_t \rangle$ and N for two charge states based on a full covariance matrix and 2) detailed comparisons between net two-particle correlations and central-limit covariance comparisons. The second arises from our demonstration of the algebraic connection between variance differences and integrals of net two-particle correlations.

We observe for excess/deficient $\langle p_t \rangle$ fluctuations (relative to a central-limit reference) a negligible charge-independent component and a substantial charge-dependent component (of order several *percent*). The former would be related to dynamical correlation sources affecting all particles independent of charge state, as for instance elliptic or radial flow for azimuthal fluctuations (not considered here). The latter must be related to charge-dependent correlation sources, which were unanticipated when this program was begun and which may be connected to the isospin structure of hadronic configuration space at chemical freezeout. This charge-dependence model is supported by results for two-particle correlations discussed below.

We observe for excess/deficient N fluctuations a pattern of substantial deviation (of order unity) from a Poisson reference expectation. Part of this excess is due to expected participant (geometry) fluctuations within a finite trigger acceptance. Part is due to expected hadronic resonance correlations. However, the precise manifestation of these correlations and the role of canonical suppression of difference fluctuations is still not well defined. In the absence of a more substantial model for geometry fluctuations and hadronic correlations, and reliable corrections for canonical suppression, this analysis is still at an early stage, and not yet able to provide quantitative tests for nonhadronic physics.

We observe for two-particle p_t correlations a substantial charge-dependent structure at the *permil* level which is roughly quadratic on momentum difference and no significant charge-independent component within the present statistical limits. These results are consistent with the $\langle p_t \rangle$ fluctuation results and provide more detailed information on possible causes.

We can make two inferences from the p_t correlations and fluctuations analysis: 1) hoped-for dynamical fluctuations/correlations which might have signaled a QCD phase transition are not apparent at the present statistical level of 0.6 *permil* in a two-particle density ratio or 1 *percent* in a relative fluctuation measure analogous to $\delta T/T$, and 2) unexpected charge-dependent fluctuations and correlations are observed at the level of several *permil* in a two-particle density ratio and several *percent* in a relative fluctuation measure. Inference 1) also rules out unequilibrated residuals of hard QCD processes in the soft component of the p_t distribution at the SPS. The details of inference 2) point to radial flow as an agent in the phenomenon. The quadratic structure is seen over momentum differences of order 1 GeV/c. This is a very large momentum difference unlikely to be produced by two-body interactions. But collective radial or axial flow is certainly capable, for one- and two-particle distributions, of producing such a large-scale structure. However, to produce a charge dependent effect requires that flow be experienced differently by different charge-pair types, which suggests an isospin-dependent structure in configuration space. Possible mechanisms for this type of structure have been proposed previously.¹

4.3.2 NA49 $< p_t >$ fluctuations

J.G. Reid and <u>T.A. Trainor</u>

Event-wise mean p_t ($\langle p_t \rangle$) fluctuations have been advocated as a means to search for critical phenomena in heavy-ion collisions associated with the QCD phase boundary. An initial hope had been that strong dependence of fluctuation amplitudes on centrality, energy and nucleus size might provide signals of a phase transition to a quark-gluon plasma. More recently we have concluded that critical fluctuations, while not ruled out, certainly do not dominate the situation at the SPS. We have focussed therefore on increasing the precision of the measurements, better defining fluctuation measures and extending measurements to a study of charge dependence of fluctuations.



Figure 4.3.2-1. In the left panel is shown a contour plot of $\langle p_t \rangle_+ \otimes \langle p_t \rangle_-$ for 100k central (5%) events. The right panel shows corresponding difference factors (see text) for three charge combinations and cc (all particles without regard to charge).

The basic variance reference is provided by the central limit theorem (CLT) which predicts the variance for a distribution of N-sample means given the variance of the parent (inclusive) distribution. We then have the CLT hypothesis $N\sigma_{< p_t>}^2 - \sigma_{p_t}^2 = 0$. Deviations from this hypothesis indicate the presence of net two-particle correlations and/or event-wise variation of the collision dynamics. To maintain continuity with previous analyses using the measure Φ_{p_t} we report the difference factor from the CLT variance difference: $\Delta \sigma_{p_t} \equiv \sqrt{N}\sigma_{< p_t>} - \sigma_{p_t}$ as an *rms* fluctuation measure ($\Delta \sigma_{p_t} \approx \Phi_{p_t}$). We can extend this definition to define difference factors for various charge combinations (*cc* represents all particles without regard to charge), which must then be related by the expression $N\sigma_p\Delta\sigma_{cc} = N_+\sigma_{p_+}\Delta\sigma_{++} + 2\sqrt{N_+N_-\sigma_{p_+}\sigma_{p_-}}\Delta\sigma_{+-} + N_-\sigma_{p_-}\Delta\sigma_{--}$, where $\sqrt{N}\sigma_{< p_t>}$ for +- is defined by $\sqrt{N_+N_-\sigma_{< p_+>< p_->}/2}/\sqrt{\sigma_{p_+}\sigma_{p_-}}$ in a consistent system, and we assume the inclusive $\sigma_{p_+p_-}^2 \approx 0$.

Analysis results for 100k central (5%) events are shown in the right panel of Fig. 1. The value for cc (point) is consistent with zero, confirming an earlier NA49 analysis. New results are shown for three charge combinations (triangles). Unlike-sign pairs show excess fluctuations, whereas like-sign pairs show a suppression of fluctuations relative to the CLT expectation. The like-sign results have been corrected for the presence of quantum correlations and track-pair efficiency. The magnitude

¹T. A. Trainor, hep-ph/0004258, hep-ph/0005176, Nuclear Physics Laboratory Annual Report, University of Washington (2000), pp. 52,54.

of nonzero deviations – 5 MeV/c – should be compared to the rms of the inclusive distribution $\sigma_{p_t} \approx 350 \text{ MeV}/c$. The rapidity acceptance is $y_{\pi,lab} \in [4, 5.5]$, with full azimuthal coverage. The p_t acceptance is $p_t \in [0.005, 1.5]$ GeV/c. Statistical error on the difference factors is typically about 1 MeV/c. The significant nonzero difference factors represent a very substantial charge-dependent component of $\langle p_t \rangle$ fluctuations (box). This new result implies a possible isospin-dependent correlation of pions in configuration space at chemical freezeout.

4.3.3 NA49 $p_t \otimes p_t$ correlations

J.G. Reid and <u>T.A. Trainor</u>

The direct connection between global-variables fluctuations and two-particle correlations which we have described in detail¹ makes it possible to study differentially any observed deviations from a CLT reference. In particular, sources of exceptional $\langle p_t \rangle$ fluctuations have counterparts in two-particle p_t correlations. We have described some of these results in a previous Annual Report.² We review them more concisely here for comparison purposes.

We observe in NA49 data large-scale structure in two-particle distributions represented by the third panel of Fig. 4.3.3-4.3.3. The observed large-scale structure is in the form of a quadratic dependence on p_t difference q which depends on the relative sign of hadrons. For like-sign pairs (shown in the figure) the structure is convex upward, for unlike-sign pairs convex downward, with similar amplitude. We can explain this structure by reconsidering the effect of radial flow on



Figure 4.3.3-1. Left panels show effects of varying degrees of radial flow on projections of twoparticle p_t distribution on mean pair p_t (k) and p_t difference (q). Right panels show a lego plot of the two-particle density ratio (sibling/mixed pairs) on p_t for 100k central (5 %) Pb-Pb events and a 2D fit of the large-scale structure.

momentum distributions. The usual treatment is based on a Wigner density $S(x_1, x_2, p_1, p_2)$ defined on phase space. In the usual treatment this is factorized into an emission density $g(x_1, x_2, p_1, p_2)$ on configuration space and a Cooper-Frye representation of the flow-dependent momentum density. If we consider the possibility that particle emission is not independent (the usual assumption) we factorize g into a dependence g_+ on mean position x and g_- on pair separation y. We further represent the transverse flow field as having the simplest possible gradient structure: Hubble flow with Hubble constant H. We then obtain for the two-particle density (omitting the interference

¹T.A. Trainor, preprint hep-ph/0001148.

²Nuclear Physics Laboratory Annual Report, University of Washington (2000), p. 52.

term containing short-range quantum correlations)

$$P_2(\mathbf{k}, \mathbf{q}) = m_{t1} m_{t2} e^{-\frac{m_{t1}+m_{t2}}{T}} \cdot \int d^4 x g_+(x, k) \exp\left(\frac{2H}{T} \mathbf{k} \cdot \mathbf{x}\right) \cdot \int d^4 y g_-(y, q) \exp\left(\frac{H}{2T} \mathbf{q} \cdot \mathbf{y}\right)$$

The center factor contains the flow-dependent cosh distortion on k represented in the first panel of Fig. 4.3.3-4.3.3, and the right factor contains the distortion on q. This distortion is present for all pairs. However, the amplitude depends on the pair autocorrelation $g_{-}(y,q)$. If one pair type is more likely to occur close together it will experience less flow, and hence a smaller cosh distortion. A pair type that is anticorrelated will experience more flow and a larger cosh amplitude. This behavior is precisely what we observe in NA49 data, as shown in the third and forth panels.

4.3.4 NA49 multiplicity fluctuations

J.G. Reid and <u>T.A. Trainor</u>

Event multiplicity fluctuations present another aspect of global variables fluctuations (in addition to $\langle p_t \rangle$ fluctuations) which yields information on the correlation structure of the collision final state. In an analysis similar in structure to $\langle p_t \rangle$ analysis we study the charge dependence of multiplicity fluctuations in order to disentangle different contributions to nonstatistical fluctuations. We use as a reference the central limit theorem in the form of Poisson statistics: for an uncorrelated system $\sigma_N^2/N = 1$. We search for nonzero values of $\Delta(\sigma_N^2/N) \equiv \sigma_N^2/N - 1$.



Figure 4.3.4-1. In the left panel is shown a contour plot of $N_+ \otimes N_-$ for 100k central (5%) events. The right panel shows corresponding variance differences for three charge combinations and sum or *cc* (dot) and difference (box) fluctuations. Difference fluctuations are uncorrected for canonical suppression. Statistical errors are smaller than the symbols.

Analysis results are shown in the right panel of Fig. 4.3.4-1. Deviations of the σ_N^2/N ratio from a Poisson expectation of unity are substantial – in the range 0.5 - 1.0. The entry for +– is for the covariance ratio $\sigma_{N+N_-}^2/\sqrt{N_+N_-}$. The sum variance (cc, dot) then satisfies $\sigma_{\Sigma N}^2 =$ $\sigma_{N_+}^2 + \sigma_{N_-}^2 + 2\sigma_{N_+N_-}^2$, whereas the difference variance (box) satisfies $\sigma_{\Delta N}^2 = \sigma_{N_+}^2 + \sigma_{N_-}^2 - 2\sigma_{N_+N_-}^2$.

Possible contributions to increased or decreased multiplicity fluctuations include participant fluctuations due to variation of collision geometry within the trigger acceptance (increases sum fluctuations only), thermal hadron resonance correlations (increases sum fluctuations and decreases difference fluctuations symmetrically), charge-independent dynamical fluctuations (increases sum and difference fluctuations), charge-dependent of isospin correlations (reduces difference fluctuations only) and proposed fluctuation suppression due to rapid traversal of the QCD phase boundary.

A variety of predictions have been made for these various contributions. The fluctuation observables are not sufficient in number to be determining. However, for no combination of hadronic fluctuation predictions is there appreciable room for recent predictions of dramatic suppression of difference fluctuations due to QGP formation. Suppression predictions would be of order 0.25 - 0.5 if shown in the right panel. The upper limit on this magnitude consistent with hadronic predictions and experimental results is about 0.05.

Further analysis involves a study of the scale and centrality variation of these variance differences, which can help to further untangle the various contributions to charge multiplicity fluctuations.

4.4 Scale dependence of global-variables fluctuations

Q. J. Liu, J. G. Reid and <u>T. A. Trainor</u>

Global-variables fluctuation analysis is motivated by analogy with bulk-matter statistical mechanics: event ensembles are treated as grand canonical ensembles exhibiting small deviations from gaussian random fluctuations. Differential study of fluctuation amplitudes in a covariance matrix should reveal the *effective* number of degrees of freedom, equivalently the internal correlations in the system, as a function of state variables. Differential analysis requires a well-defined reference, provided in this case by the central limit theorem. If there are deviations from the CLT there is the problem to intercompare different experiments and interpret nontrivial results. Thus, it is essential to understand the implications of a CLT (co)variance comparison in terms of scaling behavior.



Figure 4.4-1. Scale dependence of fluctuation measures: scale-invariant CLT reference (top), scale-local correlation sources represented by nonzero autocorrelation difference ΔA_2 (middle) and corresponding CLT variance comparisons revealed as definite integrals of autocorrelation differences (bottom). The result of a variance comparison depends on the end points of the scale integral.

We can write a CLT variance comparison for measure m as a definite integral of a corresponding autocorrelation difference (between object and reference distributions) on a space variable x.

$$\left(\bar{n}\sigma_{<\!m\!>}^2 - \sigma_m^2\right)/\hat{m}^2 = \int_l^{\Delta x} \Delta A_2(\delta x) d\delta x$$

where the lower scale limit l is determined by particle density on x and the upper limit Δx is determined by the experimental acceptance on x. For example, we could have $m \to P_t$ (total binwise p_t at scale δx) and $x \to \eta$, pseudorapidity. While the variance comparison has the advantage of familiarity and correspondence to thermodynamic measures for bulk-matter systems, the real objective must be the scale-local autocorrelation densities which reveal in a more differential way the correlation structure of events. Given that these measures are oversubscribed by different physical phenomena a differential approach is essential for interpretation and intercomparison.

4.5 K_{Long}^0 detection in STAR

J.G. Cramer, <u>D.J. Prindle</u> and R.L. Ray*

STAR is a large, multi-purpose detector designed to study Ultra-Relativistic Heavy Ion collisions at RHIC. Particle identification is done using a wide variety of techniques. Protons, charged Kaons and pions can be identified by their energy loss spectra in the TPC gas. Other particles, such as K_{Short}^0 (K_S^0) and Λ decay before reaching the TPC. These can be reconstructed by finding tracks that form a vertex distinct from the primary vertex. In this case the quality of the particle reconstruction can be checked by examining the invariant mass. Multi-purpose detectors like STAR are not normally used to reconstruct K_{Long}^0 (K_L^0) decays because of the long lifetime and because almost all the decay modes include a neutral, unobservable, particle.

The lifetime of the K_L^0 is $c\tau = 15.51$ m. For most high energy physics experiments a low momentum particle has an energy of a few GeV and for detectors of a few meters size virtually all the K_L^0 pass completely through the detector before decaying. For central Au-Au collisions measured in STAR the Kaons appear nearly thermal with a slope of around 300 MeV. Since STAR measures at mid-rapidity most of the Kaons will have total momentum of a few hundred MeV/c. A K_L^0 with p = 500MeV/c has a 10% chance of decaying before traveling 1.65 meters, so a fairly large fraction of the K_L^0 should decay within the active volume of the STAR TPC.

The branching ratios of interest for STAR are;

$$\begin{array}{rcl} {\rm K}^{0}_{\rm L} \to & \pi^{\pm} e^{\mp} \nu_{e} & 38.78\% \\ \to & \pi^{\pm} \mu^{\mp} \nu_{\mu} & 27.18\% \\ \to & \pi^{+} \pi^{-} \pi^{0} & 12.55\% \\ \to & \pi^{+} \pi^{-} & 0.21\%. \end{array}$$

The CP violating decay $K_L^0 \to \pi^+\pi^-$ should have a small background and there should be a similar number of $K_L^0 \to K_S^0$ conversions in the material of STAR so given enough events we should be able to measure a K_L^0 spectra by observing K_S^0 -like decays far from the interaction point. To observe the major K_L^0 decay modes we need to account for the neutral particle. This can be done if we not only measure the two charged particles but identify them, thus inferring the mass of the neutral. Assuming a K_L^0 from the primary vertex we can use energy and momentum conservation to calculate the three momentum components of the K_L^0 .

Preliminary Monte-Carlo investigations show that if we require the decay to be within the active volume of the TPC we can expect to reconstruct about one K_L^0 per central Au-Au event with a modest background. Whether or not the background is small enough to be able to extract physics results is still under investigation. With Monte-Carlo events we will know the size of the background. With real data we can get an indication of the background by making a lifetime plot and also perhaps by looking at the ratio of branching ratios.

If it is possible to observe K_L^0 decays in STAR one asks what will be learned from doing so? To first order K_L^0 and K_S^0 should measure the same properties. We would be able to measure the K_L^0 at a lower momentum than the K_S^0 and that might be useful. More interesting is the fact that the hadronic eigenstates produced in the interaction are K^0 and \bar{K}^0 but once outside the collision

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system these propagate as K_L^0 and K_S^0 . There are a few possible consequences of this, one of which is an HBT-like correlation between the K_L^0 and K_S^0 . This correlation strength measures the difference in the K^0 and \bar{K}^0 sources. We expect the K^+/K^- and K^0/\bar{K}^0 ratios to be the same and the former has been measured to be 1.12. Also, the \bar{K}^0 hadronic cross section is much larger than the K^0 hadronic cross section so one might expect the K^0 to freeze out earlier with a larger slope parameter. We are currently investigating how sensitive $K_L^0 - K_S^0$ and $K_S^0 - K_S^0$ correlations are to reasonable variations in K^0 and \bar{K}^0 sources.

4.6 Particle-production mechanisms at RHIC

T.A. Trainor

There is considerable interest in the mechanism of particle production in heavy ion collisions at the SPS and RHIC. That is, given a certain number of incident nucleons which actually undergo significant momentum transfer (participants), what is the number of final-state hadrons produced, and how does this ratio vary with centrality and collision energy. At the SPS particle production is well described by the so-called wounded-nucleon model, in which produced particles scale simply as the number of participants. At another extreme, produced particles could scale as the number of nucleon-nucleon binary collisions, which is the expected behavior at much higher energies.

In Fig. 4.6-1 are shown Glauber-model (Woods-Saxon form factor) predictions for participant scaling (WN - solid curve) and binary-collision scaling (BC - dashed curve). These curves mark limiting cases within which we expect collision data to fall. The data are plotted as $d\sigma/dN^{1/4}$ relative to a power-law reference, as described in Sec. 4.2.6. This makes possible precision comparison between data and production models.



Figure 4.6-1 Minimum-bias distributions relative to a power-law reference for STAR data and the Hijing Monte Carlo compared to Glauber-model simulations for a wounded-nucleon scenario (WN), a binary-collisions scenario (BC) and two hybrids.

The Hijing Monte Carlo calculation is based on strong minijet production and is expected to scale closer to a binary-collision scenario. This expectation is confirmed in Fig. 4.6-1. STAR data, corrected for multiplicity-dependent tracking efficiency and for trigger inefficiencies at small event multiplicity, exhibit a dependence closer to, but significantly different from, participant scaling. (The σ_{NN} cross section used in the Glauber WN calculation is the 42 mb total inelastic cross section observed for p-p-bar at a CM energy equivalent to RHIC)

The Hijing and STAR data curves can be represented by admixtures of participant and binarycollision scaling, as described by the 'hybrid' curves in the figure. However, this linear superposition model is not quite right. What is actually dominating these dependencies is a probing of *nucleon* structure by the nuclear surface shape. At the SPS, nucleon internal structure does not play a strong role, and the wounded-nucleon model is therefore successful – sensitivity to the nucleus surface shape is limited. At higher energies, where the collision increasingly involves partonic degrees of freedom, the effective two-particle cross section becomes quite small and the binary collision model dominates. This situation depends strongly on what particles are integrated in the final state. Restriction to high- p_t particles should favor a binary-collision scenario even more.

4.7 Particle identification at STAR/RHIC

H. Bichsel

The study of the energy loss spectra of fast particles in Ar gas has been continued.¹ The simulation of particle tracks with calculations based on a realistic model of collisions of the particles with Ar atoms² described in previous years has been applied to the STAR geometry. The studies are described in two reports which have been distributed to a limited audience. They are:

Particle identification in TPC, Univ. of Washington, May 2000 and

Simulations for STAR TPC, Univ. of Washington, August 2000.

The comparison of calculated and measured energy loss spectra for a single segment gave close agreement except that a larger than expected noise-contribution was needed. Subsequently it was found that this was due to a spurious spread in the amplification chain of the detector analyzer.

It was also found that the identification spectra are not Gaussian, which may cause misidentification of particles if gaussian approximations are used.

¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 65. ²H. Bichsel, Rev. Mod. Phys. **60**, 662 (1988).

4.8 Defining a generic event-by-event data summary format

J.G. Reid

Given the increasing number of relativistic heavy ion experiments with similar experimental programs it makes sense to develop an experiment-independent data format. This infrastructure would allow for multiple use of complex analysis codes, as well as simple and reliable A-B comparisons between experimental results. Since most experiments in the field are now using ROOT in some form for data handling and analysis it is the logical choice for a common data format framework.

We have been working within NA49 and STAR, as well as consulting with ALICE, to develop a ROOT-based miniDST format. This EbyE DST is a simple ROOT which contains the most commonly used event-by-event quantities. The data structure is as small as feasible while still containing the necessary kinematic particle data for event-by-event data analysis.

We are encouraging other experiments to adopt this format, at least in part to increase the amount of code sharing and communication between experiments. Since we are all working on the same problems it is logical to do what we can as a community to conserve our resources and avoid repeated efforts on common problems. And most importantly, we have to be able to make reliable comparisons between different energy regimes and collision systems.

5 Atomic and Molecular Clusters

5.1 High energy fragmentation of C_{60}

R. Vandenbosch

The coincidence experiment initiated last year¹ has been completed. The emphasis in this study is on multifragmentation where three or more fragments heavier than the carbon dimer are produced. This process is believed to be the dominant contributor to fragments in the size range of ten to thirty carbon atoms. The experimental apparatus enables us to scan the light fragment size distribution in coincidence with two heavier fragments with similar size.

The 45 kev C_{60} + Ar ($E_{c.m.}=2370$ ev) reaction has been studied using a C_{60} beam incident on an Ar gas target. As an example of the triple coincidence results, the relative yield of different light fragment masses in coincidence with n=18 and n=19 is shown in Fig. 5.1-1. The three-fragment coincidence yield varies only weakly with light fragment mass over this size range. An enhancement of the yield of light fragments with an odd number of carbons is observed. This enhancement is also observed in double coincidence results for the light fragment size distribution in coincidence with either even or odd number heavy fragments. The observed effect probably results from energetic considerations on the sequential decay of heavier primary fragments. Both for chains and rings in the n=4 to 10 range (and presumably for larger n) the energy required for binary fragmentation of even-n clusters favors breakup into two odd-n fragments. In all cases the most energetically favored breakup split is the one in which a C_3 is one of the partners.

Similar results to those shown in the figure have been obtained for the light fragment distribution in triple coincidence with the n=22,23 heavy fragment pair.



Figure 5.1-1. Relative yield of lighter coincident fragment when both an n=18 and an n=19 fragment has also been detected.

¹Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 67.

5.2 Search for gas phase dianions

R. Vandenbosch

A search for small molecular species which can bind two electrons has been continued. Briefly, our method¹ consists of producing by sputtering an anion with an electropositive alkali or alkaline earth metal attached to the species whose dianion one is seeking. This anion is accelerated and focused on to a gas target where the anion is fragmented into a positive metal ion and the dianion of interest. Tentative results from a search for the gas phase dianion $Si_2O_5^{2-}$ were reported last year.² It has not been possible to obtain statistically convincing results for this anion from the fragmentation of the NaSi₂O₅⁻ anion. The yield of the parent monoion from the sputtering of Na₂SiO₃ was rather low, and the upper limit of the dianion to monoanion yield was 2 x 10⁻⁴. This is greater than might be expected for production of the dianion on the basis of previous results for the fragmentation mechanism for producing dianions. Thus no definitive statement can be made regarding the existence of this dianion.

Boldyrev and Simons³ have performed a theoretical search for small linear dianions. Linear species are of particular interest since our fragmentation method for producing dianions was first demonstrated on the linear anion RbC_9^- . They suggested that the $Mg_2S_3^{2-}$ dianion might be the smallest linear dianion. An attempt has been made to produce this dianion by fragmentation of the $Mg_3S_3^-$ anion. A sputter source pellet made from mixed and finely ground Mg and S was sputtered with Cs in the usual way. Good yields of MgS and MgS₂ anions were produced, but the mass spectrum in the region of the hoped-for $Mg_3S_3^-$ anion was very complex and low in yield. It was not possible to cleanly identify and fragment the anion of interest. Further progress will require finding a more prolific source of a suitable precursor anion.

¹R. Vandenbosch, D. I. Will, C. Cooper, B. Henry, and J. F. Liang, Chem. Physics Lett. **274**, 112 (1997).

²Nuclear Physics Laboratory Annual Report, University of Washington (2000) p. 68.

³A. Boldyrev and J. Simons, J. Chem. Phys. **98**, 4745 (1993).

6 Electronics, Computing and Detector Infrastructure

6.1 Status of advanced object oriented real-time data acquisition system

M.A. Howe, F. McGirt,* L.P. Parazzoli and J.F. Wilkerson

We are developing an advanced object oriented real-time data acquisition (DAQ) system which will implement a multiple platform, fast, scaleable, distributed DAQ system suitable for both small and large experiments. By using a client/server model to totally separate the hardware controlling computers (the servers) from the user interface computers (the clients), we are building in the flexibility to have multiple server computers taking and processing data while being controlled and/or viewed by multiple remote clients. We will support both the common crate-based DAQ hardware systems (VME and CAMAC) as well as PC-based DAQ cards. The server and client frameworks are designed in such a way that it is easy to add support for new DAQ objects as the need arises. The framework is also suited for the inclusion of data analysis modules.

Both the client and the server are written in C++ using the gnu compiler running under the Linux operating system using the Qt widget set to provide a cross platform capability for both Windows and Unix. For communication between the client and server, we are using CORBA (Common Object Request Broker Architecture) which is an industry-wide standard for implementing client/server communication.

The client provides an easy-to-use graphic user interface to the hardware servers. To set up a hardware configuration, the user selects hardware or data processing modules from a list of available objects in a catalog and drags that module to a configuration window. The desired object is created on the server when the drag is completed, and appears in the configuration window as an icon. The data flow between objects is set up at run time by dragging lines from object to object. Double clicking on an icon brings up a dialog for controlling and/or viewing the status of the represented server object.

The servers, after being set up by a controlling client, do all data acquisition and processing. They have no external user interface at all, only a low-level programming interface. Objects existing at the server level implement all of the functionality of the hardware objects that they represent. All of the hardware objects that have been implemented so far are Vme modules and include the low-level PCI driver, the 617 controller, FIFO buffer card, 408 I/O card, and Emit/Ncd shaper adc cards. A Vme crate object contains and controls the interactions between the cards.

A well-developed run control system has been completed which allows the users to start and stop data runs. The length of a run and whether it is to be automatically repeated can also be specified. Multiple runs can be done at the same time using different sets of hardware. Data from a run can be sent to histogram objects that build catalogs of the existing histograms. Client-side plot objects can then select histograms to view from the data catalogs. A data storage object allows the user select where the data is to be stored.

In the near future we will be finalizing the details of the core framework in preparation for adding support for many more types of hardware modules.

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6.2 Shaper board electronics development

M. C. Browne,* A. W. Myers, R. G. H. Robertson, T. D. Van Wechel and J. F. Wilkerson

In previous annual reports,¹ we have discussed the UW Shaper/ADC Board. There are now two versions of this board. The "Standard Board" which will be used in the SNO and the emiT experiments and the "TimeTag" board, developed for use at Los Alamos National Laboratory.

The "Standard Board" Altera chip houses 8 independent scalers and an overall scaler. The benefit of these scalers is mitigated by the presence of TTL-level trigger outputs for each channel, enabling off-board scalers to be incorporated if necessary.

The "TimeTag" board Altera chip has 8 independent 32-bit timetag modules clocked by the VME bus clock, instead of the scalers. Los Alamos National Laboratory has used the "TimeTag" board in several new experiments for nuclear nonproliferation work. The timetagged data was used to recombine events distributed among arrays of detectors, to provide 2-dimensional analysis of pulse shape and total energy deposition in detectors, and to investigate geometrically correlated fission neutron emission.

 ^{*}Safeguards Science and Technology Group, Los Alamos National Laboratory, Los Alamos, NM 87545.
 ¹Nuclear Physics Lab Annual Report, University of Washington (1998) p. 55; (1999) p. 55; p. 73 (2000).

6.3 Laboratory computer systems

M. A. Howe, R. J. Seymour and J. F. Wilkerson

This year continued the replacement and addition of systems in the form of G4 Macintoshes for SNO/EWI/NCD tasks, generic PCs as Windows98-based normal desktop workstations, a Windows 2000 system, a 1.5GHz Pentium 4 Windows system, and three more dual-processor Linux systems. As described in Section 1.4, many of the systems are used to provide a loose "parallel" Mathematica computing matrix.

Our computing and analysis facility consists of:

- Our principal central compute-server base: a pair of dual-CPU Digital AlphaServer 4000/466s running Digital Unix, each with a gigabyte of ram and a total of 260 gigabytes of disk space. Our dual-controller, 288 gigabyte RAID system had a drive failure, but the RAID and hot-swap features permitted seamless continued operation throughout the event. The lab's other Unix and VMS systems route their backup load through the RAID system, and from there they are backed up to our DLT4000 and DLT8000 tape drives.
- Our VMS cluster, holding at three VAXstation 3100s, three 3200s and a single Alpha 3000/400. The cluster shares 26 gigabytes of disk space. In addition, we have a standalone OpenVMS AlphaStation 433au with a dedicated 27 gigs.
- The Ultra-Relativistic Heavy Ion group's seven Hewlett Packard 9000 Unix systems, all running HP-UX v10.2, sharing 62 gigabytes of distributed disks. Three of the systems are serving as workstations at STAR. One of the HPs is the lab's World Wide Web server (www.npl.washington.edu).
- The SNO and emiT group have Macintoshes, Apple G3 and G4's, and Power Computing PowerPC Mac "clones. Many of the older Macs and clones are being retired and replaced with G4's. They also have a Sun SparcStation 20 running Solaris 2.5.1 to provide CADENCE circuit layout facilities to our electronics shop. The two Sun Ultras have been moved to the Sudbury site.
- Linux's presence continues to grow, from our first 233 MHz Pentium II system used for compatibility with RHIC's RCF facility, through a dual-processor 400MHz Pentium II system serving as the development platform for the NCD and our next data acquisition system (see Sec. 6.1), two 500-MHz dual Pentium II systems serving as NCD testbeds and slated to become our next DAQ system, and a gigahertz dual-PIII system for analysis. The two "future-DAQ" systems are taking over compute loads from the twin Alphas. Linux's development curve, 32-bit structure and utilities continue to create some minor inconveniences, but for the most part it provides the computing flexibility and value which has led to its widespread acceptance.
- Three MBD-11 equipped VMS VAXstation 3200s still serve as the Lab's primary data acquisition systems running acquisition software based upon TUNL's XSYS, with major modifications to their DISPLAY program. Another VAXstation is the Linac's control and display system, with three LSI-11/23s and six LSI-11/21s built into the Linac for cryogenics, vacuum

and resonator control. Four PCs are serving as controllers for the rest of the accelerator systems' interlocks, safety and vacuum system.

- Although not directly used by Lab personnel, we provide co-location services for Nuclear Theory and the Physics Nuclear Theory group in the form of two VMS VAXstation 3200s. The Astronomy Department is installing a 64-processor Xeon-based Beowulf cluster for simulation of galactic formation by performing N-body gravitational modeling.
- The Lab's network is a mixture of 100baseTX and 10baseT ethernet ports, and our existing legacy 10base2 net. We use HP 800T, Compex and Hawking switches to partition the network and provide full-duplex ports to the larger systems.

We have a full duplex 100baseFX fiber uplink to the campus routers, recently upgraded to gigabit capability in support of the Astronomy Linux cluster.

6.4 Electronic equipment

T.A. Anderson, G.C. Harper, A.W. Myers and <u>T.D. Van Wechel</u>

Along with the normal maintenance and repair of the Nuclear Physics Laboratory's electronic equipment, projects undertaken by the electronics shop included the following:

- The SNO NCD MUX boards, Shaper/ADC boards, Controller boards, and DAC boards have been completed and tested. A HV interface board was designed and constructed for interfacing the high voltage power supplies to the HV controller board and HV DAC board. A MUX voltage regulator board was constructed to provide power to each MUX board. The Altera chip program for the controller boards was modified for the HV control boards.
- 2. Three rack mounted systems are being constructed: the main underground system, a second above ground system at Sudbury, and a system at the University of Washington for software development and testing. Linear power supplies were constructed for each system. Also the VME crate power supplies were converted to linear power supplies. The two systems for Sudbury are nearly complete and will be shipped to site in May.
- 3. An AMP-TEK A250 charge sensitive preamplifier was set up and tested for use in the SNO tagged neutron source.
- 4. After testing of the prototype low power emiT pre amp modules constructed last year it was determined that the resolution was significantly worse than the original emiT pre amps. The open loop gain and bandwidth was much lower than required so we decided to redesign the low power pre amp module. The input stage was changed from a folded cascode to a configuration with the drain of the input FET driving a differential amplifier with an emitter follower output. The gain of the output stage was improved by using a cascode amplifier buffered with an double emitter follower. Also, the layout of the motherboard was improved by minimizing breaks in the ground plane which were causing undesired positive feedback.
- 5. An isolated power supply system for the emiT experiment was constructed. This consisted of a HV isolation transformer and power supplies for the emiT pre amps and fiber-optic drivers that are elevated to approximately 30KV.
- 6. A prototype laser diode driver was designed and constructed and is currently undergoing testing for the New-Wash torsion balance instrument. Also a two channel optical sensor preamplifier with sum and difference outputs has been designed and constructed.
- 7. The electronics shop assisted in the design and installation of the TIS gas manifold and control system for the Van de Graaff.
- 8. Eight photomultiplier tube bases were designed and constructed for the Be⁷ experiment.

7 Van de Graaff, Superconducting Booster and Ion Sources

7.1 Van de Graaff accelerator operations and development

J.F. Amsbaugh, <u>G.C. Harper</u>, C.E. Linder,* T.L. McGonagle, A.W. Myers, D.W. Storm, T.D. Van Wechel and D.I. Will

The tandem was entered 22 times this year. Two openings were for changing the terminal configuration from stripper to TIS, or for the reverse. Three openings were used to service the pelletron chains. A link was removed from the low energy chain which had stretched over time. A link in the same chain was located which had a bad pin and was replaced.

The following openings were for development or repair of the Terminal Ion Source (TIS). These are discussed in more detail in Section 7.3. Three tank openings were for the purpose of ascertaining the optimum distribution of ball bearing column section shorts to allow operation with very low terminal voltages. Seven openings were to change the gas and magnet for the production of different ion species. Two tank openings were for installation and testing of the spherical electrostatic deflector for the TIS. Three tank openings were used to install and test gas manifolds for the TIS. During three of the tank openings, two different einzel lens assemblies were installed and tested for the TIS. Power supplies for the TIS were repaired during 5 of the tank openings.

There was one tank opening for each of the following:

1) To install a flange with new, high voltage feed thrus for the terminal steerer and the electrostatic deflector voltages.

- 2) To install a KN van de Graaff accelerator tube in place of spiral tube #3.
- 3) To install transient suppression for the electrostatic deflector power supplies.

We replaced no chain idlers or pick-up pulleys this year.

During the 13 months from March 1, 2000 to March 31, 2001 the tandem pellet chains operated 1498 hours. The DEIS operated 252 hours, and the SpIS 132 hours. Additional statistics of accelerator operations are given in Table 7.1-1.

ACTIVITY	USAGE (DAYS)	PERCENT OF YEAR
Molecular research, deck ion sources only Nuclear physics research, TIS Nuclear physics research, ⁴ He or below, tandem only	$44 \\ 51 \\ +10$	$ \begin{array}{c} 11 \\ 13 \\ +3 \end{array} $
Subtotal, molecular or nuclear physics research	105	27
Machine development, maintenance, or crew training	+107	+27
Grand total	212	54

Table 7.1-1. Tandem accelerator operations March 1, 2000 to March 31, 2001.

7.2 Superconducting Linac

J.F. Amsbaugh, G.C. Harper, M.A. Howe, <u>D.W. Storm</u> and D.I. Will

There were no requests for beams from the superconducting linac during the past year. Consequently we have put the linac in a "mothballed" status. The helium refrigerator is off and the helium gas has been stored. The liquid nitrogen supply to the linac was turned off and the cryostats carefully warmed up while maintaining pumping. After an outgassing period of a few days, vacua have returned to ranges of 10^{-6} to 10^{-8} Torr in the 14 cryostats.

During the year the vacuum system has been maintained.

If there is need for linac beams in the future, we will be able to run it after several weeks of work re-conditioning resonators, starting the cryogenics, and doing general troubleshooting.

7.3 Tandem terminal ion source

G. C. Harper, C. E. Linder,* A. W. Myers and T. D. Van Wechel

The terminal ion source (TIS) was used for the ${}^{7}Be(p,\gamma){}^{8}B$ and ${}^{7}Li(d,p){}^{8}Li$ experiments during this reporting period. The ions used were ${}^{1}H^{+}$ at terminal voltages from 0.22 MV to 1.5 MV, ${}^{2}H^{+}$ at terminal voltages from 0.77 MV to 1.4 MV and ${}^{4}He^{+}$ at a terminal voltage of 1.37 MV. The list of experiments run with the TIS to date is given in Table 7.3-1 below.

Development for this year included modeling and testing of the spherical electrostatic deflector. It was determined that the spherical deflector would have optical properties similar to those of a double focusing magnet if the electrodes were run unbalanced. Electrostatic deflectors differ from dipole magnets in that the vertical and horizontal image points closely track each other if the vertical and horizontal object points are coincident, regardless of the longitudinal position of the object points. An additional benefit is that the electrode balance adds a quadrupole control element that is not available with the fixed field dipole magnet.

Two new einzel lens assemblies were built and tested this year. Both of these were designed to produce a real object point in front of the electrostatic deflector as opposed to the system that produced a virtual object point in front of the double focusing magnet. One of these einzels was a 5 cm diameter lens placed 5 cm closer to the source than the one used with the magnet. The other was a 2.5 cm diameter lens placed 7 cm closer. When tested it was found that an adequate, stable beam could be transported with either lens assembly in place but that the 5 cm diameter lens produced fewer aberrations and therefore a stable and more intense beam over a broader range of terminal voltages.

A three bottle gas manifold with a high voltage break between the bottles and the gas needle valve was developed for the TIS. This eliminated tank entries previously required to change the gas bottle and magnet for each ion species. Digital output channels in the terminal computer were used to control the manifold valves. Several software interlocks were added to the CSX control system to prevent improper gas handling. Two to four hours are now required to pump out the manifold through the gas needle valve in order to change gases. This is a substantial reduction in time from the 48 hours required for ion species changes when a tank opening was necessary.

A KN van de Graaff tube was procured from the Wright Nuclear Structure Lab at Yale University. This tube has non-inclined accelerating planes which makes it desirable for the initial acceleration of the extremely low energy (10-13 keV) ion beams from the TIS in that there is no transverse electric field component to steer the beam. It also has plane apertures that are 10 cm in diameter as opposed to the 2.5 cm diameter apertures in the spiral inclined field tube. This makes ion collisions with the tube much less likely. End adapters were manufactured for the KN tube to precisely match its length and end connections to those of spiral tube #3. We then replaced spiral tube #3 with the KN tube. We have successfully transported ion beams as low as 82 keV using the new tube. We have observed the onset of x-rays from the backstreaming of electrons in the tube produced from ions striking the first plane of spiral tube #4 when the KN tube is supporting 1 MV or more. The electron loading becomes significant enough that it is difficult to maintain charge on the terminal when the KN tube is supporting 1.4 MV and transporting a beam. We intend to add magnetic electron suppression in the bellows section between the KN tube and spiral tube #4 to

eliminate this problem for an upcoming run requiring 5.5 MeV ${}^{3}\text{He}^{+}$ for ${}^{6}\text{Li}({}^{3}\text{He},n){}^{8}\text{B}$. A slowly increasing gradient made by reducing the resistor values of the first 25 planes in the KN tube by 80% will also be implemented for this run. The KN tube, the manifold system, the spherical electrostatic deflector, and the new einzel lens assemblies were all used successfully during the last ${}^{7}\text{Be}$ and ${}^{7}\text{Li}(d,p){}^{8}\text{Li}$ experimental runs.

With the KN tube, we have continued our practice of using 0.5 inch diameter chrome-plated steel ball bearings inserted between the anti-corona rings of the column to short out various planes of the beam tube. We have found this to be an extremely fast way to alter the gradient for optimum beam transmission at low energies. With the straight KN tube, continuous sections of the gradient may be shorted because there is no compensation required to balance the transverse steering component.

ION	ENERGY RANGE (kev)	EXPERIMENT	$\begin{array}{c} \text{BEAM CURRENT} \\ (\mu \text{amps}) \end{array}$
$^{1}\mathrm{H}^{+}$	220-1400	$^{7}\mathrm{Be}(\mathrm{p},\gamma)$	10-20
$^{2}\mathrm{H}^{+}$	770-1400	⁷ Li(d,p)	15-20
³ He ⁺	5500	⁶ Li(³ He,n)	28
$^{4}\mathrm{He^{+}}$	1370	$^{7}\mathrm{Be}(lpha,\gamma)$	15

Table 7.3-1. Table of ion species and TIS experiments.

7.4 Cryogenic operations

J.H. Elms, G.C. Harper, M.A. Howe, D.W. Storm, <u>D.I. Will</u> and J.A. Wootress^{*}

As we mothball our booster and cryogenic system, it is again appropriate to thank those who were instrumental in our success. While planning the booster cryogenic system in 1983 we received invaluable advice from Jack Nixon,¹ John Hulbert², and Tom Peterson³ Among the authors John Wootress, our long-time technician, contributed greatly through his mechanical intuition, skill, and labor. The reliability of the system was in large part due to the advice, knowledge, and skills of these four. Also key to the cryogenic operation were the mix and scheduling flexibility of available personnel, a technician assigned $\approx 50\%$, an engineer $\approx 40\%$, and an instrument maker $\approx 10\%$, all of whom could be utilized at once in crisis. During heavy use periods the helium refrigerator was available for booster runs more than nine months per year (easily exceeding booster demand) and produced sufficient liquid helium for quiescent periods more than 98% of the average year.

By turning off rotating machinery and warming the booster to room temperature we are able to save on maintenance and on helium and liquid nitrogen costs. Nitrogen use has decreased by 500 gallons of liquid per day⁴ to 100 gallons per day, now used mostly as gas. This still exceeds boiloff from our 9000 gallon MVE^5 Vertical Customer Station, so no gas is lost from the tank. Helium gas lost in venting and purging has been eliminated. Since the helium refrigerator⁶ could hold the quiescent booster at liquid helium temperature with only one of the three expansion engines turning at low speed, engine rebuild frequency depended strongly on both hours of booster use and resonator cooling demands (which affect engine rotational speed.) At peak booster use the top two engines required three rebuilds each per year, and the wet engine, one. Eliminating rebuilds saves at least two months per year of technician's time and associated shop time.⁷

With all RS screw compressors off, RS history includes five pump cores used on three skids, #1, #2, #3. One original core, RS-1, has run 119,350 hours; the medium brown color of its coolant and decreasing output pressure indicate moderate mechanical wear. RS-2 shorted phase-to-phase in 1993 at 57,547 hours. Its replacement, RS-2a, has run 59,413 hours and shows little wear. RS-3 shorted to ground in 1990 at 22,752 hours. This core was stopped and restarted as often as once a week to adjust capacity in a power-efficient manner: staggered starting of split-phase windings may also have contributed to its rather early demise. To minimize further compressor failures we changed (in 1990) to loading/unloading compressors to adjust capacity⁸ and switched to across-the-line starting (which produces less surge heating at starts and spreads that heat over both split windings). Replacement core RS-3a has run 82,484 hours, and the brown-black color of its coolant indicates severe metal wear.

^{*}Retired.

¹Argonne National Laboratory, Argonne, IL retired.

²Chalk River Laboratory, Atomic Energy of Canada, Ltd., Chalk River, Ontario, retired.

³Fermi National Accelerator Laboratory, Batavia, IL.

 $^{^{4}}$ This year the cost of liquid nitrogen has jumped from the historic 0.20/gallon of the last 15 years to 0.37/gallon. 5 MVE, Inc. Burnsville, MN.

⁶Built by Koch Process Systems, Inc., Westborough, MA.

⁷See Cryogenic Operations in Nuclear Physics Laboratory Annual Report, University of Washington (1984 through 2000) for further information.

⁸Since an unloaded compressor uses 60% of full load power but produces only 25% of full output, this method of operation is less power-efficient.

Nuclear Physics Laboratory Personnel 8

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George W. Farwell	Professor Emeritus	
Jens H. Gundlach	Research Associate P	rofessor
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Predoctoral Research Associates

Qazi Rushdy Ahmad ⁴	Minesh Bacrania
Theresa Bullard	Ki-Young Choi
G. Adam Cox	Charles Duba
Robert Fardon ⁵	Karsten Heeger
Charles David Hoyle	$ m Qilung \ Huang^5$
Dan Kapner	Kareen Kazkaz
Erik Mohrmann	Hans Pieter Mumm
Christian Neumann	John Orrell
Jeffrey Reid	Kathryn Schaffer
Miles Smith	Laura Stonehill
Jeremy Thomas ⁵	Seth Van $Liew^5$
Sarah Veatch ⁵	Heather Zorn

Research Experience for Undergraduates participants

Angela Kopp⁶

Deborah Spain⁷

Professional staff

The professional staff are listed with a description of their recent major efforts.

Research Engineer	Mechanical design, Vacuum systems
Research Engineer	Construction SNO NCD's
Research Engineer	Construction SNO NCD's
Research Engineer	Electronic and mechanical design
	Accelerator upgrades and operation
Research Engineer	Software for DAQ, control systems
Research Engineer	Electrical systems, Tandem operations
Research Engineer	
Research Scientist	Heavy Ion software
Computer Systems Manager	
Research Physicist	Precision experimental equipment
Electronics Engineer	Electronic design, construction, maintenance
Research Engineer	Cryogenics, Ion sources
	Research Engineer Research Engineer Research Engineer Research Engineer Research Engineer Research Engineer Research Engineer Research Scientist Computer Systems Ma Research Physicist Electronics Engineer Research Engineer

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Technical staff

James Elms David Hyde Allan Myers Hendrik Simons

Administrative staff

Instrument Maker Instrument Maker Electronics Technician Instrument Maker, Shop Supervisor

Barbara J. Fulton	Administrator
Karin M. Hendrickson ⁹	Fiscal Specialist
Kate J. Higgins	Fiscal Specialist

Part Time Staff

Daniel B Allred¹⁰ David Beard¹⁰ Nathan Collins¹⁰ Ellen Eames¹⁰ Adam Elias Mikel Grezner¹⁰ Elvsa Kuznetz¹⁰ Nels Lindberg¹⁰ Tami McGonagle Bhasker Moorthy 10 Cheth Ouch¹⁰ Edwin Penniman¹⁰ Christopher Scannell Tina Stremick Lincoln Webbeking Matthew White

Tuesday Anderson Jon Bumgardner¹⁰ Paul Duffell Clara Eberhardy Adrian Fehr¹⁰ Laura Grout¹⁰ Joshua Leingang¹⁰ Jeff Manor Christy McKinley Robert O'Neill¹⁰ Lambert Paul Parazolli Annika Peter¹⁰ David Stone¹⁰ Kyle Sundqvist Jeff West

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9 List of Publications from 2000-2001

Published papers:

"Results on the Strong Equivalence Principle, dark matter, and new forces," B. Heckel *et al.*, Adv. Space Res. **25**, 1225 (2000).

"Positron-neutrino correlations in ³²Ar and ³³Ar decays: searches for scalar currents and measurements of isospin mixing," A. García, E.G. Adelberger, C.O. Ortiz, H.E. Swanson, M. Beck, O. Tengblad, M.J.G. Borge, I. Martel, H. Bichsel and the Isolde Collaboration, Hyperfine Interactions **129**, 237 (2000).

"High-voltage microdischarge in ultra-low-background ³He proportional counters," K.M. Heeger, S.R. Elliott, R.G.H. Robertson, M.W.E. Smith, T.D. Steiger and J.F. Wilkerson, IEEE Transactions of Nucl. Sci 47, 1829 (2000).

"A low-noise ³He ionization chamber for measuring the energy spectrum of a cold neutron beam," S.D. Penn, E.G. Adelberger, B.R. Heckel, D.M. Markoff and H.E. Swanson, Nucl. Instrum. Methods in Phys. Res. A **457**, 332 (2001).

"The Sudbury Neutrino Observatory," J. Boger and the SNO Collaborators (including Q.R. Ahmad, T.H. Burritt, P.J. Doe, C.A. Duba, S.R. Elliott, J.E. Franklin, A.A. Hamian, K.M. Heeger, M. Howe, A. Meyers, R.G.H. Robertson, M.W.E. Smith, T.D. Steiger, T. Van Wechel and J.F. Wilkerson), Nucl. Instrum. Methods in Phys. Res. A **449**, 172 (2000).

"A compact ${}^{3}H(p,\gamma){}^{4}He$ 19.8-MeV gamma-ray source for energy calibration of the Sudbury Neutrino Observatory," A.W.P. Poon, R.J. Komar, C.E. Waltham, M.C. Browne, R.G.H. Robertson, N.P. Kherani and H.B. Mak, Nucl. Instrum. Methods in Phys. Res. A **452**, 115 (2000).

"Data analysis techniques for extracting Gamow-Teller strengths from 0° (p,n) data," C.D. Goodman, M. Bhattacharya, M.B. Aufderheide, S.D. Bloom and P. Zuprawski, Nucl. Instru. Methods A, **462**, 545 (2001).

"Relativistic radioactive beams: a new access to nuclear-fission studies," K.-H. Schmidt, S. Steinhauser, C. Bockstiegel, A. Grewe, A. Heinz, A.R. Junghans, J. Benlliure, H.-G. Clerc, M. de Jong, J. Muller, M. Pfutzne and B. Voss, Nucl. Phys. A. **665**, 221 (2000).

"Pair breaking and even-odd structure in fission-fragment yields," F. Rejmund, A.V. Ignatyuk, A.R. Junghans and K.-H. Schmidt, Nucl. Phys. A **678**, 215 (2000).

"Dark matter search with CAF-2 scintillators in Osaka," I. Ogawa, T. Kishimoto, R. Hazama, S. Ajimura, K. Matsuoka, N. Suzuki, T. Nitta, H. Miyawaki, S. Shiomi, Y. Tanaka, H. Ejiri, N. Kudomi, K. Kume, H. Ohsumi and K. Fushimi, Nucl. Phys. A **663**, 869 (2000).

"Double beta decays of Mo-100 by ELEGANT V at Oto Cosmo Observatory," N. Kudomi, H. Ejiri, K. Fushimi, K. Hayashi, R. Hazama, T. Kishimoto, K. Kume, H. Kuramoto, T. Matsuoka, H. Ohsumi, K. Takahisa, Y. Tsujimoto and S. Yoshida Nucl. Phys. B (Proc. Suppl.) **87**, 301 (2000).

"Background studies for the Neutral Current Detector Array in the Sudbury Neutrino Observatory," K.M. Heeger, P.J. Doe, S.R. Elliott, R.G.H. Robertson, M.W.E. Smith, T.D. Steiger and J.F. Wilkerson, Nucl. Phys. B (Proc. Suppl.) 87, 502 (2000).

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"Solar-neutrino results from SAGE," J.N. Abdurashitov and the SAGE Collaborators (including J.F. Wilkerson and S.R. Elliott), Phys. Atomic Nuclei **63**, 943 (2000).

"Deuteron production in central Pb+Pb collisions at 158A GeV," S.V. Afanasev and the NA49 Collaborators (including J.G. Cramer, D.J. Prindle, J.G. Reid and T.A. Trainor), Phys. Lett. B **486**, 22 (2000).

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"Measuring supernova neutrino temperatures using lead percholate," S.R. Elliott, Phys. Rev. C 62, 065802 (2000).

"New limit on the *D* coefficient in polarized neutron decay," L.J. Lising and emiT the Collaborators (including H.P. Mumm, R.G.H. Robertson, T.S. Steiger and J.F. Wilkerson), Phys. Rev. C 62, 055501 (2000).

"Isoscalar, isovector, orbital, and spin contributions in M1 transitions in mirror nuclei," Y. Fujita, B.A. Brown, H. Ejiri, K. Katori and H. Ueno, Phys. Rev. C **62**, 044314 (2000).

"Short-range tests of the Equivalence Principle," G.L. Smith, C.D. Hoyle, J.H. Gundlach, E.G. Adelberger, B.R. Heckel and H.E. Swanson, Phys. Rev. D **61**, 022001 (2000).

"Measurement of Newton's Constant using a torsion balance with angular acceleration feedback," J.H. Gundlach and S.M. Merkowitz, Phys. Rev. Lett. 85, 2869 (2000).

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"Spectroscopy of double-beta and inverse-beta decays from ¹⁰⁰Mo for neutrinos," H. Ejiri, J. Engel, R. Hazama, P. Krastev, N. Kudomi and R.G.H. Robertson, Phys. Rev. Lett. **85**, 2917 (2000).

"A measurement of Gamow-Teller Strength for ${}^{176}\text{Tb} \rightarrow {}^{176}\text{Lu}$ and the efficiency of a solar neutrino detector," M. Bhattacharya, C.D. Goodman, R.S. Raghavan, M. Palarczyk, A. Garcia, J. Rapaport, I.J. van Heerden and P. Zupranski, Phys. Rev. Lett. **85**, 4446 (2000).

"Elliptic flow in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV," K.H. Ackermann and the STAR Collaborators (including H. Bichsel, J.G. Cramer, Q. Li, D.J. Prindle, J.G. Reid and T.A. Trainor), Phys. Rev. Lett. **86**, 402 (2001).

"Submillimeter test of the gravitational inverse-square law: A search for "large" extra dimensions," C.D. Hoyle, U. Schmidt, B.R. Heckel, E.G. Adelberger, J.H. Gundlach, D.J. Kapner and H.E. Swanson, Phys. Rev. Lett. **86**, 1418 (2001).

"Event-by-event fluctuations of the kaon to pion ratio in central Pb+Pb collisions at 158 GeV per nucleon," S.V. Afanasev and the NA49 Collaborators (including J.G. Cramer, D.J. Prindle, J.G. Reid and T.A. Trainor), Phys. Rev. Lett. **86**, 1965 (2001).

"Nuclear spin isospin responses for low energy neutrinos," H. Ejiri, Physics Reports, **338**, 265 (2000).

"Measurement of Newton's Constant using a torsion balance with angular accelertion feedback," J.H. Gundlach and S.M. Merkowitz, *Proceedings of the XI Marcel Grossmann Meeting General Relativity*.

"In-target chemistry during the production of ¹⁵O and ¹¹C using ³He reactions," K.A. Krohn, J.M. Link and W.G. Weitkamp, Radiochim. Acta. **88**, 193 (2000).

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"The plane of the present and the new transactional paradigm of time," J.G. Cramer, *Time and the Instant*, ch. 9, ed. Robin Drurie, Clinamen Press, UK (2001).

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Papers submitted or to be published:

"Scintillation efficiency of nuclear recoils in a $CaF_2(Eu)$ crystal for dark matter search," R. Hazama, S. Ajimura, H. Hayakawa, K. Matsuoka, H. Miyawaki, K. Morikubo, N. Suzuki and T. Kishimoto, submitted to Nucl. Instrum. Methods.

"ft value of the $0^+ \rightarrow 0^+ \beta$ decay of ³²Ar: A measurement of isospin breaking in superallowed decay," A. Komives, M. Bhattacharya, A. Garcia, E.G. Adelberger, B.A. Brown, M.W. Cooper, T. Glasonacher, V. Gulmanaraes, P.F. Mantica, A. Oros, J.J. Pricinadaro, H.E. Swanson, S.L. Tabor and M. Wiedeking, to be submitted to Phys Rev. C.

"Reanalyses of $\alpha + \alpha$ scattering and β -delayed α spectra from ⁸Li and ⁸B decays," M. Bhattacharya and E.G. Adelberger, to be submitted to Phys. Rev. C.

"Details on the shape of ⁸B alpha and neutrino spectra," C.E.Ortiz, A. Garcia, M. Bhattacharya, R.A. Waltz and A.K. Komives, to be submitted to Phys. Rev. C.

"Direct measurements of neutrino mass," J.F. Wilkerson and R.G.H. Robertson, in *Current Aspects of Neutrino Physics*, ed. by D.O. Caldwell, (Springer, to be published), Springer-Verlag, Heidelberg, Germany.

"Lead perchlorate as a neutrino detection medium," S.R. Elliott, P.J. Doe, R.G. H. Robertson and C. Paul, *Proceeding of the Carolina Symposium on Neutrino Physics*, Columbia, SC, March 2000, (World Scientific), to be published, presented by P.J. Doe.

"New tests of Einstein's Equivalence Principle and Newton's Inverse Square Law," E.G. Adelberger, to be published, *Classical and Quantum Gravity*.

Invited talks, abstracts and other conference presentations:

"Status of the Sudbury Neutrino Observatory," P.J. Doe, NNN2000, Irvine, CA, February 2000.

"A measurement of Newton's constant using a torsion balance in acceleration feedback," J. Gundlach, American Physical Society, Long Beach, CA, April/May 2000, Bull. Am. Phys. Soc. 45, No. 5, 46 (2000).

"A transactional analysis of quantum interaction-free measurements," J.G. Cramer, American Physical Society, Long Beach, CA, April/May 2000, Bull. Am. Phys. Soc. **45**, No. 2, 62 (2000).

"The Seattle ${}^{7}\text{Be}(p,\gamma){}^{8}\text{B}$, experiment," A. Junghans, Invited talk, NorthWest Section of the APS, Eugene OR, May 2000.

"emiT - A test of time reversal invariance," J.F. Wilkerson, Invited talk, *Fundamental Physics with Pulsed Neutron Beams*, Durham, NC, June 2000.

"Experimental neutrino physics," J.F. Wilkerson, Invited lecture presented at the Theoretical Advanced Study Institute Summer School, Boulder, CO, June 2000.

"Probing small length scales in heavy ion collisons with event-by-event correlation analysis," T.A. Trainor, *New Frontiers in Soft Physics and Correlations on the Threshold of the Third Millenium*, Torino, Italy, June 2000, eds. A. Giovannini and R. Ugoccioni, Nucl. Phys. B. (Proc. Suppl.) **92** (2001).

"The giant dipole resonance strength and width at high temperature," K.A. Snover, Invited talk, Giant Resonances GR 2000, Osaka, Japan, June 2000, Proceedings of the Seventh International Topical Conference on Giant Resonance GR 2000, eds. M. Fujiwara, H. Ejiri, M. Nomachi and T. Wakasa, North-Holland, Nucl. Phys. A 687, 337c (2001).

"Nuclear responses for neutrinos and spin isospin giant resonances," H. Ejiri, Invited talk, *Giant Resonances GR 2000*, Osaka, Japan, June 2000, *Proceedings of the Seventh International Topical Conference on Giant Resonance GR 2000*, eds. M. Fujiwara, H. Ejiri, M. Nomachi and T. Wakasa, North-Holland, Nucl. Phys. A **687**, 350c (2001).

"Double beta decays and neutrinos," H. Ejiri, XIXth International Conference on Neutrino Physics and Astrophysics (Neutrino 2000), June 2000, Nucl. Phys. B (Proc. Suppl.) **91**, 255 (2001).

"Lead perchlorate as a neutrino detection medium," S.R. Elliott, P.J. Doe, R.G.H. Robertson, T.

Steiger and J.F. Wilkerson, XIXth International Conference on Neutrino Physics and Astrophysics (Neutrino 2000), Sudbury, Ontario, Canada, June 2000, Poster presented by S.R. Elliott.

"Measuring the neutral current event rate in SNO using ³He(n,p)t," R.G.H. Robertson and the SNO Collaborators (including T.V. Bullard, P.J. Doe, C.A. Duba, S.R. Elliott, R. Hazama, K.M. Heeger, K.K. Schaffer, M.W.E. Smith, T.D. Steiger and J.F. Wilkerson), XIXth International Conference on Neutrino Physics and Astrophysics (Neutrino 2000), Sudbury, Ontario, Canada, June 2000, Poster presented by M.W.E. Smith and K.M. Heeger.

"Spectroscopy of inverse-beta decays from ¹⁰⁰Mo for solar neutrinos and neutrino masses," H. Ejiri, J. Engel, R. Hazama, P. Krstev, N. Kudoni, T. McGonagle, and R.G.H. Robertson, XIXth International Conference on Neutrino Physics and Astrophysics (Neutrino 2000), Sudbury, Ontario, Canada, June 2000, Poster presented by H. Ejiri.

"Solar-neutrino studies by inverse-beta decays of ¹⁰⁰Mo," R. Hazama, *LowNu: Solar Neutrino Experiments below 1 MeV*, Sudbury, Ontario, Canada, June 2000.

"Precision measurement of the gravitational constant," G.H. Gundlach, IX Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Gravitation and Relativistic Field Theories, Rome, Italy, July 2000.

"Short range test of Newton $1/r^2$ -law," G.H. Gundlach, IX Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Gravitation and Relativistic Field Theories, Rome, Italy, July 2000.

"The ${}^{7}\text{Be}(p,\gamma){}^{8}\text{B}$ reaction," K.A. Snover, Invited talk, *Nucleosynthesis 2000* held in conjunction with the 220th National American Chemical Society Meeting in Washington, DC, August 2000.

"Solar neutrinos," J.F. Wilkerson, presented at the SLAC Summer Institute, Stanford, CA, August 2000.

"A $^{100}{\rm Mo}$ detector for low energy solar neutrinos," R.G.H. Robertson, Nuclear Physics Neutrino Workshop, Seattle WA, September 2000.

"Big G and gravity close up," J.H. Gundlach, Deutsches Elektronen Synchrotron, Hamburg, Germany and Berlin, Germany, September, 2000.

"PQCD structure and hadronization in jets and heavy ion collisions," T.A. Trainor, *Proceeding of the 30th International Symposium on Multiparticle Dynamics, (ISMD 2000)*, Tihany, Lake Baleton, Hungary, October, 2000.

"Engaging students and teachers in forefront high energy research," H.M. Zorn, Washington American Association of Physics Teachers Annual Meeting, Ellensburg, WA, October 2000.

"Molybdenum observatory of neutrinos (MOON) and intense neutrino sources," H. Ejiri, New Initiatives in Lepton Flavor Violation and Neutrino Oscillations with Very Intense Muon and Neutrino Sources, Hawaii, October 2000.

"The emiT experiment," K. Sundqvist and the emiT Collaborators, (including J. Wilkerson, H.P. Mumm, R.G.H. Robertson and T.D. Steiger) American Physical Society, Williamsburg, VA, October, 2000, Bull. Am. Phys. Soc. **45**, No. 5, 28 (2000).

"Progress in the ${}^{7}Be(p,\gamma){}^{8}B$," A.R. Junghans and the ${}^{7}Be$ Collaborators (including K.A. Snover, T.D. Steiger, E.G. Adelberger and H.E. Swanson), American Physical Society, Williamsburg, VA, October, 2000, Bull. Am. Phys. Soc. **45**, No. 5, 44 (2000).

"The first results from HBT interferometry with STAR data from RHIC," J.G. Cramer, American Physical Society, Williamsburg, VA, October, 2000, Bull. Am. Phys. Soc. 45, No. 5, 46 (2000).

"Limits on T violation from a search for a permanent EDM of ¹⁹⁹Hg," M.V. Romalis, W.C. Griffith, B.R. Heckel and E.N. Fortson, American Physical Society, Williamsburg, VA, October, 2000, Bull. Am. Phys. Soc. **45**, No. 5, 49 (2000).

"First results from Event-by-Event analysis with STAR," J.G. Reid, American Physical Society, Williamsburg, VA, October, 2000, Bull. Am. Phys. Soc. 45, No. 5, 71 (2000).

"Background studies for the Neutral Current Detector Array in SNO," K.M. Heeger and the SNO Collaborators (including T.V. Bullard, T.H. Burrit, P.J. Doe, C.A. Duba, S.R. Elliott, R. Fardon, R. Hazama, R.G.H. Robertson, K.K. Schaffer, M.W.E. Smith, T.D. Steiger and J.F. Wilkerson), American Physical Society, Williamsburg, VA, October, 2000, Bull. Am. Phys. Soc. **45**, No. 5, 50 (2000).

"Tandem terminal ion source and studies of the toroidal deflector," G.C. Harper, *Symposium for* Northeastern Accelerator Personnel, New Haven, CT, October 2000.

"University of Washington Lab Report to SNEAP 2000," G.C. Harper, J.F. Amsbaugh, D.I. Will, A.T. Myers, T.D. Van Wechel, C.E. Linder and D.W. Storm, *Symposium for Northeastern Accelerator Personnel*, New Haven, CT, October 2000.

"Summary of neutrino physics and astrophysics," J.F. Wilkerson, DNP Long Planning Meeting, Oakland, CA, November, 2000.

"Solar neutrinos," R.G.H. Robertson, Invited Review, Town Meeting on Neutrinos, Astrophysics, and Fundamental Symmetries, Oakland, CA, November 2000.

"Physics with radioactive beams: key experiments and requirements," A. Junghans, *European Center for Theoretical Studies in Nuclear Physics and Related Areas*, Trento, Italy, November/December 2000.

"MOON (inc. short Rev. of double beta)," H. Ejiri, International Workshop on Low Energy Solar Neutrinos, Tokyo, December 2000.

"Pion phase space density from STAR HBT analysis," J.G. Cramer and the STAR Collaborators (including Q. Liu, D.J. Prindle, J.G. Reid and T.A. Trainor), Poster presented at the *Quark Matter* 2001, SUNY, Stony Brook, NY, January 2001.

"MOON for supernova neutrino detection," H. Ejiri, *Physics Potential of Supernova II neutrino Detection*, California, February 2001.

"About the neutrino," R.G.H. Robertson, Invited lectures, Lake Louise Winter Institute, Alberta, Canada, February 2001, to be published.

"The WALTA project: Engaging students and teachers in forefront high energy research," H.M. Zorn, the 38th Conference of the Pacific Northwest Association of College Physics, Seattle, WA, March 2001.

"Fusion: Old puzzles and new probes," R. Vandenbosch, *American Chemical Society Meeting*, San Diego, CA April (2001).

Conference presentations by collaborators of NPL personnel:

"Giant dipole resonance in hot Se nuclei, and bremsstrahlung emission in $^{12}C + ^{58,64}Ni$ experiments at 6-11 MeV/u," Z. Trznadel, M. Kicinska-Habior, M.P. Kelly, K.A. Snover and J.P.S. van Schagen, *Giant Resonances GR 2000*, Osaka, Japan, June 2000, *Proceedings of the Seventh International Topical Conference on Giant Resonance GR 2000*, eds. M. Fujiwara, H. Ejiri, M. Nomachi and T. Wakasa, North-Holland, Nucl. Phys. A **687**, 198c (2001).

"Temperature dependence of the GDR width in ¹²⁰Sn," P. Heckman, D. Bazin, J.R. Beene, Y.

Blumenfeld, M.J. Chromik, M.L. Halbert, J.F. Liang, E.C. Mohrmann, T. Nakamura, A. Navin, B.M. Sherrill, K.A. Snover, M. Thoennessen, E. Tryggestad and R.L. Varner, *Giant Resonances GR 2000*, Osaka, Japan, June 2000, *Proceedings of the Seventh International Topical Conference on Giant Resonance GR 2000*, eds. M. Fujiwara, H. Ejiri, M. Nomachi and T. Wakasa, North-Holland, Nucl. Phys. A **687**, 225c (2001) and Am. Phys. Soc. **45**, 36 (2000).

"Sudbury Neutrino Observatory," A.B. McDonald and the SNO Collaborators (including T.V Bullard, P.J. Doe, C.A. Duba, S.R. Elliott, R. Hazama, K.M. Heeger, R.G.H. Robertson, K.K. Schaffer, M.W.E. Smith, T.D. Steiger and J.F. Wilkerson), XIXth International Conference on Neutrino Physics and Astrophysics (Neutrino 2000), June 2000, Nucl. Phys. B (Proc. Suppl.) **91**, 21 (2001).

"Solar neutrino results from SAGE," V.N. Gavrin and the SAGE Collaborators (including J.F. Wilkerson and S.R. Elliott), XIXth International Conference on Neutrino Physics and Astrophysics (Neutrino 2000), June 2000, Nucl. Phys. B (Proc. Suppl.) **91**, 36 (2001).

"Measurement of the solar neutrino capture rate with Gallium metal," J.N. Abdurashitov and the SAGE Collaborators (including S.R. Elliott and J.F. Wilkerson) it XIXth International Conference on Neutrino Physics and Astrophysics (Neutrino 2000), Sudbury, Ontario, Canada, June 2000, Poster presented by V.N. Gavrin.

"Overview of the status and strangeness capabilities of STAR," P.G. Jones and the STAR Collaborators (including J.G. Cramer, D.J. Prindle, J.G. Reid and T.A. Trainor), 5th International Conference on Strangeness in Quark Matter (Strangeness 2000), Berkeley, CA, July 2000, J. Phys. G 27, 651 (2001).

"Stopping and strangeness production in nuclear collisions at the CERN SPS," D. Rohrich and the NA49 Collaborators, (including J.G. Cramer, D.J. Prindle, J.G. Reid and T.A. Trainor), 15th International Conference on Particle and Nuclei (PANIC 99), Uppsala, Sweden, June, 1999, Nucl. Phys. A, 663,713 (2000).

"Temperature dependence of GDR width in ¹²⁰Sn," P. Heckman and the GDR Collaborators (including K.A. Snover and E.C. Mohrmann), American Physical Society, Williamsburg, VA, October, 2000, Bull. Am. Phys. Soc. **45**, No. 5, 37 (2000).

ANNUAL REPORT

Nuclear Physics Laboratory University of Washington May, 2001

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Cover photos, clockwise from upper left: Minesh Bacrania and Laura Stonehill preparing lead perchlorate for optical tests; the CHIME array; Greg Harper and Tami McGonagle installing the straight tube; the torsion pendulum for short range gravity measurements.

INTRODUCTION

Last year the Nuclear Physics Laboratory (NPL) officially became the Center for Experimental Nuclear Physics and Astrophysics (CENPA), with an expanded mandate. CENPA includes the activities of the former NPL and in addition fosters collaborative work among the members of the NPL and others in the University of Washington Physics Department and elsewhere. CENPA pursues a broad program of research in nuclear physics, astrophysics and related fields. Research activities are conducted locally and at remote sites. The current program includes "in-house" research on nuclear collisions and fundamental interactions using the local tandem Van de Graaff and superconducting linac accelerators, as well as local and remote non-accelerator research on fundamental interactions and user-mode research on relativistic heavy ions at large accelerator facilities in the U.S. and Europe.

A good ${}^{7}\text{Be}(p,\gamma){}^{8}\text{B}$ Phase I data taking run has been completed and the data are being analyzed. We used a 100 mCi target fabricated on a newly designed post backing with a breakaway washer, eliminating unwanted target tails. All important sources of systematic error were measured, including loss of ${}^{8}\text{B}$ due to backscattering out of the target. We expect to meet our goal of $\pm 5\%$ precision on the cross section and the astrophysical S-factor.

The SNO detector has been running in a production mode with pure heavy water in the acrylic vessel since November 1999. Analysis of the data taken since that time has been directed towards a measurement of the rate of charged-current interactions of ⁸B neutrinos, and will be completed soon. Both the SNO collaboration and the scientific community await this milestone with interest.

A new collaboration of CENPA members with the University of Mainz, Kernforschungszentrum Karlsruhe, and other institutions to carry out a large-scale experiment on tritium beta decay has formed. The objective is a direct kinematic measurement of the mass of the electron antineutrino with 0.5-eV sensitivity.

The notion of "large extra dimensions" has recently attracted a great deal of attention, particularly as a solution of the gravitational hierarchy problem. For example, the "true" Planck mass could be lowered to about 1 TeV if two of the extra 7 dimensions of string theory had sizes of around 1 mm. This would show up as a violation of the gravitational inverse-square law for separations less than a milimeter. We recently used a novel torsion balance instrument to test the inverse-square law down to 0.2 mm and found no evidence for anomalies, which implies an unification mass of > 3.5 TeV.

The big news in ultrarelativistic heavy ion physics this year is first data from the RHIC collider. Experimental results have been pouring in from all four experiments. The UW event-by-event program has pioneered a number of novel analysis techniques that are now being brought to bear on the first batch of STAR data. We have seen for the first time substantial dynamical fluctuations in event-wise mean transverse momentum, possibly signaling new QCD effects in Au-Au collisions, and charge- or isospin-dependent correlation structures possibly connected to novel structure on the hadronic freezeout surface formed during rapid traversal of the QCD phase boundary.

A study of collision-induced multifragmentation of C_{60} has been completed. Multifragmentation into three or more fragments each with three or more carbons in each fragment is found to be an important reaction channel for large deposition energies. An odd-even dependence of fragment yields implies sequential decay of chain or ring multifragmentation products. As always, we encourage outside applications for the use of our facilities. As a convenient reference for potential users, the table on the following page lists the capabilities of our accelerators. For further information, please contact Prof. Derek W. Storm, Executive Director, Nuclear Phyics Laboratory, Box 354290, University of Washington, Seattle, WA 98195; (206) 543-4080, or storm@npl.washington.edu. Further information is also available on our web page: http://www.npl.washington.edu.

We close this introduction with a reminder that the articles in this report describe work in progress and are not to be regarded as publications or to be quoted without permission of the authors. In each article the names of the investigators are listed alphabetically, with the primary author, to whom inquires should be addressed, underlined.

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Barbara Fulton, Assistant Editor

TANDEM VAN DE GRAAFF ACCELERATOR

A High Voltage Engineering Corporation Model FN purchased in 1966 with NSF funds, operation funded primarily by the U.S. Department of Energy. See W. G. Weitkamp and F. H. Schmidt, "The University of Washington Three Stage Van de Graaff Accelerator," Nucl. Instrum. Meth. **122**, 65 (1974). Recently adapted to an (optional) terminal ion source and a non-inclined tube #3, which enables the accelerator to produce high intensity beams of helium and hydrogen isotopes at energies from 100 keV to 5.5 MeV.

A 1 1 D

Some Available Energy Analyzed Beams					
Ion	Max. Current	Max. Energy	Ion Source		
	(particle μA)	(MeV)			
$^{1}\mathrm{H}$ or $^{2}\mathrm{H}$	50	18	DEIS or 860		
3 He or 4 He	2	27	Double Charge-Exchange Source		
3 He or 4 He	30	7.5	Tandem Terminal Source		
6 Li or 7 Li	1	36	860		
$^{11}\mathrm{B}$	5	54	860		
^{12}C or ^{13}C	10	63	860		
$^{*14}N$	1	63	DEIS or 860		
$^{16}O \text{ or } ^{18}O$	10	72	DEIS or 860		
\mathbf{F}	10	72	DEIS or 860		
* Ca	0.5	99	860		
Ni	0.2	99	860		
Ι	0.001	108	860		

*Negative ion is the hydride, dihydride, or trihydride.

Additional ion species available including the following: Mg, Al, Si, P, S, Cl, Fe, Cu, Ge, Se, Br and Ag. Less common isotopes are generated from enriched material.

BOOSTER ACCELERATOR

We give in the following table maximum beam energies and expected intensities for several representative ions. "Status of and Operating Experience with the University of Washington Superconducting Booster Linac," D. W. Storm *et al.*, Nucl. Instrum. Meth. A **287**, 247 (1990). The Booster is presently in a "mothballed" state.

	Some Available Energy Analyzed Beam			
	Ion	Max. Current	Max. Practical	
		$(p\mu A)$	Energy (MeV)	
	р	>1	35	
	He	0.5	65	
	Li	0.3	94	
	С	0.6	170	
	0	0.1	220	
	Si	0.1	300	
	$^{35}\mathrm{Cl}$	0.02	358	
_	Ni	0.001	395	

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