ANNUAL REPORT

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INTRODUCTION

The Nuclear Physics Laboratory of the University of Washington has for over 40 years supported a broad program of experimental physics research. The current program includes "in-house" research using the local tandem Van de Graaff and superconducting linac accelerators and no-accelerator research in gravitation as well as "user-mode" research at large accelerator facilities around the world.

The most extensive upgrade of the tandem accelerator in its 29 years of operation has begun. The Department of Energy made funds available for installing a pelletron charging system and new spiral inclined field beam tubes. Installation of the pelletron, of a computer control system in the terminal, and of a new column resistor string has been completed and the tandem is operating superbly. Manufacture of the beam tubes has been delayed because of problems with the electrodes. The tubes are expected to be shipped in April 1994.

Our in-house studies of nuclear structure and reactions include nuclear astrophysics, giant resonance (GDR) studies, studies of fusion and high angular momentum phenomena in nucleus-nucleus collisions, investigations of weak interactions and test of the Equivalence Principle, AMS studies using the tandem as an ultra-precise mass spectrometer, and a variety of applied activities by outside users. There is an active program at the laboratory to develop instrumentation in support of the user-mode physics activities. The user-mode research includes work at TRIUMF, the CERN SPS, and the Michigan State NSCL facility. Below we present some of the highlights of the UW NPL research program.

We have completed our study of compound nuclear GDR decay at high spin in the A ~ 60 mass region, with evidence for the strongly deformed nuclear shapes that are predicted at high spin by the rotating liquid drop model. We have measured high energy gamma ray production in ^{12}C + Mg collisions, and found a substantial enhancement of the cross section for bremsstrahlung production on ^{26}Mg relative to the production on ^{24}Mg.

We have completed a new measurement of the radiative decays of the (16.6, 16.9 MeV) 2+ doublet in ^{8}Be, for the purpose of an improved CVC/second class current test. We have made a more precise determination of the M1 width, and we have shown that, in contrast to previously published results, the isovector E2/M1 mixing ratio is small.

Our involvement in the APEX experiment continues, with recent acquisition of over 600,000 positrons and 150,000 electron-positron pairs with the APEX spectrometer. It is now becoming possible to make specific comparisons with GSI results, including a careful analysis of the relative acceptances of the several experiments.

The analysis of an intermediate energy heavy ion reaction study is nearing completion and has yielded some quite interesting results. We find that the fusion cross section (fission plus evaporation residues) remains surprisingly high as the bombarding energy of the ^{14}N and ^{16}O projectiles vary from 25'A to 130 A MeV. We attribute this to contributions from partial waves beyond the angular momentum value for which the fission barrier of the composite system goes to zero. This occurs because the angular momentum finally appearing in the composite system is reduced by pre-equilibrium particle emission to values which the system can accommodate without instantly fissioning. The interpretation is supported by our linear momentum transfer and pre-equilibrium particle multiplicity measurements.

As part of this experiment we have also obtained information on the composite system lifetime from deuteron-deuteron intensity correlation. The lifetimes are in the few times 10^{-21} sec range. They vary with impact parameter and target mass as expected, lending confidence to their interpretation as originating from an equilibrated system.

The ultra-relativistic heavy ion (URHI) physics research program of the Nuclear Physics Laboratory has in the past year accepted major new responsibilities for CERN experiment NA49, including development of the overall slow-control console for the experiment and development of the tracking and data analysis software for the experiment's main time-projection chambers. In the analysis of NA35 data we have developed a new version of the tracking program that is now standard in the collaboration and have established momentum calibration procedures that should permit analysis of mixed-charge correlations. We have also made significant contributions to the STAR collaboration including development of a grouping pattern-recognition technique for the SVT. We have new STAR responsibilities for developing an electrostatic model of the TPC field cage and for developing a regulation and control system for the TPC high voltage. The technique discussed last year for bin-free maximum-likelihood HBT analysis has now been demonstrated with simulated data. We have also discovered a subtle error in a proposed technique that appeared to offer unexpected sensitivity to moments of HBT distribution functions.

The accelerator mass spectrometry (AMS) group has completed a study in which AMS radiocarbon (^{14}C) dates were obtained for samples of pollen extracted from segments of nine lake sediment and peat cores that contain an ash layer associated with the catastrophic eruption of Mt. Mazama, Oregon, about 7600 years ago. Pure pollen was extracted, using procedures recently developed here, from core segments just above and just below the Mazama Ash layer. The results are characterized by the striking internal consistency of the pollen dates, by the agreement of the date inferred from them for the Mazama eruption with the best consensus date derived from previous studies elsewhere, and by a number of serious discrepancies between the pollen dates and the "bulk carbon" dates, i.e., those obtained for material extracted from the same core segments using the traditional, much simpler procedures that yield essentially the total organic carbon component of the core material. Pollen is a widely used paleoclimate indicator, and pollen many thousands of years old can now be dated through our methods with an accuracy of ±50 years. This should lead to enhanced clarity and much more accurate time control in the reconstruction of paleoclimates through palynology.

The Laboratory provides beams for a range of uses outside of conventional nuclear physics. This year researchers from the Ball Aerospace Systems Group and the Boeing Defense and Space Groups used beams from the tandem and booster to investigate radiation damage in various electronic devices. Also the tandem was used to test the neutron response of a muon detector for the Visual Techniques Laboratory of the University of Washington Department of Physics.

As always, we welcome applications from outsiders for the use of our facilities. As a convenient reference for potential users, the table on the following page lists the vital statistics of our accelerators. For further information, please write or telephone Professor William G. Weitkamp, Technical Director, Nuclear Physics Laboratory, University of Washington, Seattle, WA 98195; (206) 543-4080 (e-mail; W@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 have been listed alphabetically, with the primary author underlined.

We thank Karin M. Hendrickson for her help in producing this report.

Robert Vandenbosch
Editor

Barbara Fulton
Assistant Editor

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1. NUCLEAR ASTROPHYSICS

1.1 β^+ decay of ^{37}Ca

E.G. Adelberger, A. Garcia,* P.V. Magnus, H.E. Swanson, F. Weitfeldt, the GSI group of E. Roeckl, the Göttingen group of W.-D. Schmidt-Ott and the ISOLDE group

We have made new studies of ^{37}Ca β^+ decay at GSI and ISOLDE. The main motivations for this work were:

1. to compare the $^{37}\mathrm{Ca} \rightarrow {}^{37}\mathrm{K}$ B(GT) values to the isospin-analog $^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar}$ values inferred from ^{37}Cl(p,n) data; and
2. to improve predictions of the efficiency of the Homestake Mine solar ν detector that depend upon relating the $^{37}\mathrm{Cl}(\nu,e)$ GT cross-section to the ^{37}Ca B(GT) values.

The GSI experiment was focused on obtaining absolute branching ratios for the $\beta-$delayed proton and $\gamma-$ray branches. We used an energetic ^{37}Ca beam from the GSI Fragment Recoil Separator. ^{37}Ca ions from the fragmentation of a ^{40}Ca beam were stopped in the central element of a stack of 3 Si counters and β's were detected in the outer two Si elements. The Si stack was surrounded by 2 large-area Ge counters that detected $\beta-$delayed γ's. We observed $\gamma-$rays of 1371, 2750, and 3241 keV; the latter two indicate that the B(GT) values of the particle-unstable levels at 2750 and 3241 keV need to be corrected for their non-zero values of Γ_γ / Γ_p. Preliminary analyses indicates that these corrections reduce, but do not eliminate, the previously noted[1] discrepancy between the $\beta-$decay and (p,n) B(GT) values.

We determined the ^{37}Ca lifetime by running with a short beam spill and observing the decay time of the intense and essentially background-free superallowed group in the delayed proton spectrum. This and other results are being analyzed by GSI.

The experiment at ISOLDE was an upgraded version of our earlier experiment[2] which featured the following improvements:

1. we ran on the $^{37}\mathrm{Ca}^{19}\mathrm{F}$ 'sideband' so that the beam had essentially no contamination of other activities (especially ^{37}K);
2. we used a high-efficiency annular NaI detector segmented into 8 channels to detect ^{37}Ca $\beta-$delayed proton decays feeding excited states of ^{36}Ar, as well as the $\beta-$delayed γ decays; and
3. we used a thicker Si detector that could count higher energy protons without 'punching through'.

Preliminary analysis of the delayed $\gamma-$ray data yields results consistent with our GSI experiment. The delayed proton data are largely consistent with our earlier work, but some small discrepancies are present. We are currently tracking these down.

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* Notre Dame University, South Bend, IN.

[1] E.G. Adelberger *et al.*, Phys. Rev. Lett. **67**, 3658 (1991).

[2] A. Garcia *et al.*, Phys. Rev. Lett. **67**, 3654 (1991).

1.2 Measurement of the beta-delayed alpha-particle decay of ^{16}N and the astrophysical E1 S-factor of the $^{12}C(\alpha,\gamma)^{16}O$ reaction

E.G. Adelberger, J.F. Amsbaugh, P. Chan, L. De Braeckeleer, P.V. Magnus, D.M. Markoff, D.W. Storm, H.E. Swanson, K.B. Swartz, D. Wright and Z. Zhao

The determination of the astrophysical reaction rate for the $^{12}C(\alpha,\gamma)^{16}O$ reaction is a problem of great importance in nuclear astrophysics, as it determines the evolution of massive stars and therefore the synthesis of heavier elements. This cross section at 300 keV is dominated by two subthreshold states, the 1^- state at 7.12 MeV and the 2^+ state at 6.92 MeV. It was demonstrated[1,2] that the beta-delayed alpha-particle emission of ^{16}N at low energy reveals an interference peak which is directly related to the reduced alpha-particle width of the subthreshold 1^- state. Therefore this spectrum provides information on the E1 cross section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at lower energies.

The two previous experiments on the beta-delayed alpha-particle emission suffer from various limitations. The Yale experiment[1] used a thick target, which complicated the interpretation of the results. The TRIUMF experiment[2] suffered from the difficulties in subtraction of the ^{17,18}N contamination in the spectrum, which appears in the position of the predicted minimum.

We have conducted initial tests on measuring the alpha-particle spectrum using the rotating arm apparatus built for the mass-8 beta-alpha correlation measurements. The deuteron beam (30μA at 3.5 MeV) from the FN tandem was incident on the rotating target which consisted of Ti^{15}N on a Ni backing. When the beam was on, the recoiling ^{16}N nuclei were collected by a carbon catcher foil, 10 $\mu g/cm^2$ or 20 $\mu g/cm^2$ respectively. When the beam was off, the catcher was transferred to the counting area. There are two silicon surface barrier detectors (100 mm^2 and 20 μm thickness, 50 mm^2 and 15 μm thickness) in the counting area. The energies of the alpha-particles and the carbon nuclei were detected simultaneously. The slow timing between the two particles was also determined at the same time, and was used in the software to reduce the random background. The lifetime of the decay was measured to be consistent with the known lifetime of the ^{16}N nuclei. In addition, the detector response to low energy carbon ions was also studied. In Fig. 1.2-1, we show the two-dimensional histogram of carbon energy versus alpha-particle energy. The contribution of the broad 1^- state at 9.6 MeV in ^{16}O is the dominant feature of the histogram, while the true low energy events are visible in a curved group roughly along the diagonal line. The proper gate (based on the foil thickness and the detector response effects) is then placed to the two-dimensional histogram to obtain the β-delayed α-particle spectrum over the range of the interest, shown in Fig. 1.2-2.

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[1]Z. Zhao, R.H. France III, K.S. Lai, S.L. Rugari, M. Gai and E.L. Wilds, Phys. Rev. Lett. **70**, 2066 (1993).
[2]L. Buchmann *et al.*, Phys. Rev. Lett. **70**, 726 (1993).

Fig. 1.2-1. Energy of C deposited in detector 1 vs. energy of alpha-particle deposited in detector 2.

Fig. 1.2-2. Beta-delayed alpha-particle spectrum of ^{16}N.

2. GIANT RESONANCES

2.1 Spin-induced shape transitions in Cu compound nuclei

A.W. Charlop, Z.M. Drebi, M.S. Kaplan, K.A. Snover, D.P. Wells and D. Ye

At very high spins a shape transition is expected, in medium mass nuclei, from oblate to triaxial, with a superdeformed major to minor axis ratio of 2:1 and larger. To search for this shape transition, we studied GDR decays of ^{59,63}Cu compound nuclei formed in ^{32}S+^{27}Al and ^{18}O+^{45}Sc reactions over a wide range of spin and excitation energy. Results of these measurements have been reported earlier.[1] In the top row of Figs. 2.1-1 and 2.1-2 the average cross sections $\sigma_{abs}(E_\gamma)$, inferred from statistical model analysis of the measured GDR spectral shapes, are plotted for ^{32}S+^{27}Al and ^{18}O+^{45}Sc systems respectively. In the highest two bombarding energy cases of ^{32}S+^{27}Al the high energy γ rays were measured in coincidence with the low energy γ multiplicity, and a fold ≥ 2 condition was required in the multiplicity filter. In the highest two bombarding energies of ^{18}O+^{45}Sc reaction, a non-statistical contribution at high $\gamma-$ray energies $E_\gamma \geq 22$MeV is observed in the emission spectra and in the measured angular distribution $a_1(E_\gamma)$ coefficients, and is attributed to nucleon-nucleon bremsstrahlung. The measured σ_{abs} were corrected for this background in a self-consistent procedure. The angular distributions in the CM frame were fitted with a second order Legendre polynomial expansion, and the extracted $a_2(E_\gamma)$ coefficients are plotted in the bottom row of Figs. 2.1-1 and 2.1-2.

In both systems, the width of the GDR strength function was found to increase smoothly with increasing bombarding energy. This broadening of the strength function is due to two effects: spin-induced equilibrium deformation of the nucleus, and temperature-induced fluctuations around this equilibrium configuration. Full thermal shape and orientation fluctuation calculations are needed to interpret the results. These calculations are performed[2] with liquid drop potential energy surfaces (PES) calculated at constant spin. Below a certain spin J_c ($=36\hbar$, and $39\hbar$ for ^{59}Cu and ^{63}Cu nuclei respectively) the minimum lies along the oblate non-collective axis. At $J = J_c$, a shape transition occurs, the equilibrium shape becomes triaxial, rapidly approaching the prolate collective-axis, and the deformation increases rapidly with spin. This is similar to the Jacobi transition in rotating stars. The calculations are averaged over the initial spin distribution which is approximated by three spins of roughly equal weight. The thermal fluctuation calculations are performed at each spin and then averaged; the results are shown as thick curves in Figs. 2.1-1 and 2.1-2.

The calculated cross sections for all cases agree very well with the experimental results in the region $E_\gamma \geq 12$ MeV. Below $E_\gamma \approx 12$ MeV, the disagreement between the calculated spectra and the data, for the high bombarding energy cases, is due to the low-energy background contamination. The calculated a_2 also agree with data in $E_\gamma \geq 12$ MeV region, particularly the observed negative dip on the low energy side of the resonance is well reproduced in all bombarding energies. The calculations predict that the a_2 coefficients should turn positive on the high energy side of the resonance. The statistics become increasingly poor above $E_\gamma = 20$ MeV, and the measured a_2 provides little information to test the theory in this region.

To investigate further the role played by the spin-induced Jacobi transition, full fluctuation calculations using parabolic potential energy surfaces in which this shape transition is removed were performed for ^{32}S+^{27}Al system. The results are shown as thin curves in Fig. 2.1-1, and are adequate only

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[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 3; (1992) p. 14; and (1991) p. 3.
[2]Y. Alhassid, private communication.

at the lowest two bombarding energies corresponding to low average spins. At higher bombarding energy (spin) cases, these calculations fail to reproduce the experimental cross sections, indicating the importance of the Jacobi phase transition to account for the experimental results.

Fig. 2.1-1. Absorption cross sections (top row), and angular distribution coefficients (bottom row) inferred from analysis of the $^{32}S + ^{27}Al$ data. Thick solid curves are the results of the full fluctuation calculations with the RLDM potential energy surfaces including the Jacobi phase transitions. Light solid curves are calculations with the phase transition removed.

Fig. 2.1-2. Same as Fig. 2.1-1, but for $^{18}O + ^{45}Sc$ data.

2.2 Bremsstrahlung and GDR decay in ^{12}C + $^{24,26}Mg$ collisions

Z. Drebi, M. Kicinska-Habior,[*] M. Kelly, A. Maj,[†] K.A. Snover, K. Swartz and D. Ye

As part of our effort toward a better understanding of heavy ion bremsstrahlung in the near-threshold region E/A < 15 MeV/nucleon, we have measured high energy gamma-ray emission in collisions of ^{12}C with ^{24}Mg and ^{26}Mg. Data were taken at five angles and at bombarding energies of 6.1, 8.6, and 11.2 MeV/nucleon. High energy gamma rays were detected in the large NaI spectrometer and low energy gamma rays were also measured in coincidence using the multiplicity filter.

The inclusive data for the four measured reactions are shown in Fig. 2.2-1. The top row displays the total cross section, together with the statistical (GDR) decay component calculated with Cascade using standard parameters. The bottom rows show the a_1 and a_2 coefficients extracted from fits to the measured angular distributions. The curves in these lower panels are illustrations of the behavior expected for nucleon-nucleon bremsstrahlung, assuming isotropic emission in the nucleon-nucleon center-of-mass with a cross section given by the solid curve in the second row. At high $E_\gamma \geq 30$ MeV, this bremsstrahlung estimate agrees well with the measured a_1 values in the highest three bombarding energy cases. In the region near 20 MeV in these cases (and for all E_γ in the 73 MeV data), the measured a_1 values lie below the curves, due presumably to the GDR contribution.

Comparing the two different targets at the highest bombarding energy (first two columns), it is puzzling that the Cascade calculations (top row) indicate the GDR is a bigger fraction of the total yield near $E_\gamma = 20$ MeV in the case of the ^{26}Mg target, whereas the a_1 coefficient implies the opposite. Another interesting feature of the data is that the cross section ratio for $^{26}Mg/^{24}Mg$ at high E_γ is approximately 1.7, independent of E_γ whereas the simple scaling factor for first chance n-p collisions is 1.03. This last observation is similar to previous results[1,2] in much heavier systems. More detailed calculations are in progress.

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[1]C.A. Gossett *et al.*, Phys Rev C **42**, R1800 (1990).
[2]N. Gan *et al*., Phys. Rev. C **49**, 298 (1994).

Fig. 2.2-1. Spectra and angular distribution coefficients for γ-rays produced in $^{12}C + ^{24}Mg$ and $^{12}C + ^{26}Mg$ collisions.

2.3 Bremsstrahlung and GDR decay in O + Mo reactions

Z.M. Drebi, F. Liang, M.P. Kelly, K.A. Snover and D. Ye

For nuclear reactions at beam energies of 30 MeV/A or above, high energy $\gamma - \text{ray}$ spectra ($E_\gamma \geq$ 30 MeV) are dominated by the nucleon-nucleon bremsstrahlung component. At beam energies below 5 MeV/A, GDR decay dominates the region. However, at 10 MeV/A, both components are evident. Understanding the interplay between the two components will extend our knowledge of nucleon-nucleon bremsstrahlung to lower beam energies and will also provide more reliable data on the GDR cross section in this bombarding energy region.

In our experiment, an isotopically enriched ^{92}Mo target of 3 mg/cm^2 was bombarded by a 150 MeV ^{16}O beam. The spectrum shape and angular distribution of high-energy γ rays were measured by a large NaI spectrometer. The multiplicity of low-energy γ rays was measured in coincidence with high-energy γ rays using the newly completed multiplicity detector array.[1]

High-energy $\gamma - \text{ray}$ yields were measured at five angles: 40°, 55°, 90°, 125°, 140°. The cross sections were transformed into the compound nucleus center of mass and fitted with $Y(\theta) = A_0[1+a_1P_1 + a_2P_2]$ where the P_i are Legendre Polynomials. Data have been analyzed with a multiplicity gating of $M_\gamma \geq 4$, and without multiplicity gating. In Fig. 2.3-1, the two sets of center-of-mass a_1 values are plotted as a function of $\gamma - \text{ray}$ energy. At the low energy end, smaller a_1 values can be seen for $M_\gamma \geq 4$, indicating a suppression of direct reaction contributions by the multiplicity gate. In high energy region ($E_\gamma \geq 20\text{MeV}$), a gradual increase in a_1 can be seen in both data sets. This increase results because both the forward folding of the bremsstrahlung component, and the fractional size of this component (relative to the GDR contribution) increase with E_γ. Also noticed is that in this region, the two sets of a_1's are in agreement with each other within statistics. This agreement indicates that the ratio between the bremsstrahlung and the GDR decay is insensitive to the gate on low-energy $\gamma - \text{ray}$ multiplicity (which is correlated to the impact parameter of the compound reaction). Statistical calculations are currently being carried out to understand the influence of multiplicity gating condition on the GDR cross section. Future analysis will be concentrated on decomposing the two components based on the measured angular distribution and spectrum shape.

In a similar measurement, a 73 MeV ^{16}O beam was incident on a ^{92}Mo target of thickness 1 mg/cm^2 to produce the compound nucleus ^{110}Sn at excitation energy of $\approx$60 MeV. The $\gamma - \text{ray}$ decay energy spectra with no multiplicity gating and with multiplicity gating $M_\gamma \geq 2$ are being analyzed using a CASCADE (statistical model) fitting routine. The extracted width of the GDR is of interest in light of present uncertainties as to the dependence of the GDR width on compound nucleus excitation energy.

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[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 83.

Fig. 2.3-1. Angular distribution coefficient a_1 as a function of $\gamma - \mathrm{ray}$ energy in center of mass coordinate of compound nuclear reaction. Both data with multiplicity ≥ 4 and data without multiplicity gate are plotted for comparison.

3. NUCLEUS-NUCLEUS REACTIONS

3.1 Distributions of fusion barriers extracted from cross section measurements on the systems ^{40}Ca + ^{192}Os, ^{194}Pt

J.D. Bierman, P. Chan, F. Liang, A.A. Sonzogni and R. Vandenbosch

The problem of subbarrier fusion enhancement over one-dimensional barrier penetration calculations has been attributed to coupling to other degrees of freedom which split the apparent barrier, resulting in a distribution of barriers instead of just one barrier. This explanation led to several attempts to determine this distribution by fitting the available cross section data. In recent years, it was suggested by Rowley[1] that information about the distribution of fusion barriers could instead be extracted directly from the cross section data rather than from a fit or simulation. This method was shown to work well when a more detailed study of the ^{16}O + ^{154}Sm system[2] was performed, yielding the expected distribution due to nuclear deformation effects.

We have decided to attempt a detailed study of the fusion cross section for two systems which, though similar in Z and A, should exhibit differences in the barrier distributions and see if these differences are present in the actual distributions extracted from the data. We have chosen ^{192}Os and ^{194}Pt as targets because the quadrapole deformation sign flips, ^{192}Os $\beta 2 = -0.17$ and ^{194}Pt $\beta 2 = +0.15$, indicating a shift from prolate or cigar shape deformation to oblate or pancake shaped deformation. Since the sought-after effect goes as dV/dr we could magnify it by going to a higher Z projectile. This resulted in our decision to use ^{40}Ca as our projectile. Fig. 3.1-1 shows a CCDEF calculation which includes the appropriate static quadrapole deformation and a small hexadecapole deformation for both targets. Coupling to the 3- inelastic state in ^{40}Ca and to the very positive Q valued 2n transfer for both systems is also included.

Since the fusion of ^{40}Ca with either target results in a compound nucleus which is very neutron deficient, the compound nucleus will always decay by fission so we can measure the fission cross sections and equate those to the fusion cross sections. We measure the fission products using E-ΔE telescope with an angle-defining collimator. A 4 cm high, 6.5 cm wide, seven segment silicon strip detector is placed at the proper angle to detect the complementary fragment to the fissions detected in the telescope. At present we have performed two test runs and are preparing to begin measurements on the ^{40}Ca + ^{192}Os system. Once the measurements have been made we will extract and compare the barrier distributions for the two systems.

Fig. 3.1-1. Fusion barrier distributions extracted from a CCDEF calculation of the cross sections for ^{40}Ca + ^{192}Os and ^{194}Pt.

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[1]N. Rowley *et al.*, Phys. Lett. B **254**, 25 (1991).
[2]J.X. Wei *et al.*, Phys. Rev. Lett. **67**, 3368 (1991).

3.2 Evaporation residue cross sections for ^{40}Ca + ^{46,50}Ti at energies close to the Coulomb barrier

J.D. Bierman, P. Chan, J.F. Liang, A.A. Sonzogni and R. Vandenbosch

A few years ago, the fusion excitation functions for ^{16}O on different isotopes of Sm were measured.[1,2,3] The targets ranged from the semi-magic ^{144}Sm to the well deformed ^{154}Sm, and it was observed that the larger the number of neutrons, the larger the fusion cross section. This enhancement could be attributed to both the increasing deformation and the decrease in the neutron binding energy with increasing mass number.

Our intention is to make a similar study, but with a system where the target becomes less deformed as it gets richer in neutrons. An ideal target for that purpose is Ti, for which the deformation decreases as we go from ^{46}Ti to ^{50}Ti. We decided to use the doubly magic ^{40}Ca as the projectile.

The experimental setup consisted of a telescope, made of two Si detectors, located at 64 cm from the target and free to change its angle with respect to the beam. The evaporation residues left most of their energy in the first element and the second one was used to veto the elastic scattering. Time of flight information was used to improve the identification of residues. Two Si detectors were placed at ± 25 degrees for normalization purposes. The ^{40}Ca beam, with energies from 121.4 MeV to 154.3 MeV, was first accelerated by the 9 MV UW-NPL Pelletron and post accelerated by the UW-NPL Linac. Special care was taken to collimate and focus the beam.

Angular distributions were taken for ^{46,50}Ti. Preliminary results are shown in Fig. 3.2-1. A double Gaussian function was fitted to the angular distributions and the total fusion cross section at a given energy is calculated by integrating this function over angle.

Further experiments will include the bombardment of ^{48}Ti as well as a larger number of energies.

Fig. 3.2-1. Evaporation residue angular distribution for ^{40}Ca(154.3 MeV) + ^{50}Ti.

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[1]R.G. Stokstad *et al.*, Phys. Rev. C **21**, 2427 (1980).
[2]D.E. DiGregorio *et al.*, Phys. Rev. C **39**, 516 (1989).
[3]D.E. DiGregorio *et al.*, Phys. Lett. B **176**, 322 (1986).

3.3 Evaporation residue and fission cross sections and linear momentum transfer for ^{14}N and ^{16}O induced reactions at energies ranging from 25 A MeV to 130 A MeV

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We report here the results of two experiments[1] performed at the National Superconducting Cyclotron Laboratory at Michigan State University using the miniball array.[2] The evaporation residue (**ER**) and fission fragment (**FF**) angular distributions were measured for ^{14}N at 35 and 100 on ^{154}Sm, ^{159}Tb, ^{197}Au and 130 A MeV on ^{154}Sm and ^{197}Au. Typical **ER** angular distributions are shown in Fig. 3.3-1. They were fitted and integrated over angle to get the total **ER** cross section. The total fission cross section at a given energy was obtained by transforming the angular distributions from the laboratory frame to the moving frame that yields a symmetric angular distribution, and then integrating it over angle. The transformation was made assuming that the target captures a fraction of the projectile (to simulate pre-equilibrium particle emission) and then undergoes symmetric fission. The ratio of the mass of the effective projectile captured to that of the projectile gives us an estimate of the average linear momentum transferred (LMT).

The fusion cross section, taken as the sum of the **FF** and **ER**, is somewhat large even at the highest energy. The critical ℓ values for fusion, ℓ_c^{fus}, determined from the sum of the **ER** and **FF** cross sections increase with bombarding energy and considerably exceed the ℓ value for which the fission barrier goes to zero ($\ell_{Bf=0} \sim 80$). This might be troubling at first but we must remember that the ℓ value here refers to the angular momentum of the incoming partial wave, not the angular momentum deposited in the composite nucleus. Pre-equilibrium particle emission increases with increasing bombarding energy and is responsible for loss of both linear and angular momentum. One simple way to look at this, although not correct in detail, is to ask what is the maximum angular momentum brought in by capture of that fraction of the projectile found to account for the missing LMT. This turns out to give ℓ_c^{fus} values which are always less than $\ell_{B_f} = 0$.

The fission fragment folding angles, ($\theta_f = \theta_{FF_1}^{lab} + \theta_{FF_2}^{lab}$) were measured for the reactions 25 A MeV ^{16}O and 35 and 100 A MeV ^{14}N on four targets ^{154}Sm, ^{159}Tb, ^{181}Ta and ^{197}Au. A Monte Carlo simulation, based on a minimization procedure, was developed to reproduce the experimental folding angle distributions and extract the mean LMT. Typical results for 25 A MeV ^{16}O on Ta are shown in Fig. 3.3-2.

The bombarding energy dependence of the LMT in fusion reactions, expressed as the ratio of the observed composite system velocity to that expected from complete fusion, is illustrated in Fig. 3.3-3, where Au is excluded because of its high fissionability. The present results are in good agreement with the systematics of Viola *et al.*[3] noted by a full line. A dashed line was used for higher values of E/A and it overestimates the experimental values. The LMT value for Au can be compared with the average LMT measured for highly fissionable targets reported by Viola[4] and a good agreement is observed. One can also estimate the LMT using the source velocity and multiplicities deduced from p, d, t, and alpha energy and

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[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 10.
[2]DeSouza *et al.*, Nucl. Instrum. Methods A **295**, 109 (1990).
[3]V.E. Viola, Jr., Phys. Rev C **26**, 178 (1982).
[4]V.E. Viola, Jr., Nucl. Phys. A **502**, 531c (1989).

angular distributions, obtained as part of this experiment (see Section 3.4). A preliminary calculation agrees with the other values.

Thus a consistent picture emerges, where as the bombarding energy increases, fusion-like processes can occur for an increasing number of partial waves with ℓ_c^{fus} well beyond the angular momentum value for which the fission barrier of the composite system goes to zero. This occurs because the angular momentum finally appearing in the composite system is reduced by pre-equilibrium particle emission to values which the system can accommodate without instantly fissioning. The relatively large fusion cross sections even at bombarding energies exceeding 100 A MeV make possible a number of interesting experiments using fusion products as tags for central collisions.

Fig. 3.3-1. Angular distributions of evaporation residues for ^{14}N + ^{154}Sm at three different bombarding energies.

Fig. 3.3-2. Experimental (circles) and simulated (full curve) FF folding angle distributions.

Fig. 3.3-3. Ratio of composite system velocity to velocity for complete fusion as a function of the square root of the bombarding energy per nucleon.

3.4 Properties of light charged particles produced by 25 A MeV ^{16}O on ${}^{159}_{65}$Tb, ${}^{181}_{72}$Ta, ${}^{197}_{79}$Au and 35 A MeV ^{14}N on ${}^{nat}_{62}$Sm, ${}^{181}_{72}$Ta

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As part of the experiment discussed in the previous article (see Section 3.3), we measured light charged particles (LCPs) in coincidence with fission fragments (FF tag) or evaporation residues (ER tag). The ER tagged events were from more central collisions than the FF tagged events and by varying the target mass we change the average impact parameter over a large range while changing the total fusion cross section only slightly.[1]

The FF, ER and LCP detection has been described previously.[2] Briefly, we measure the LCP type, energy and angle over about 70% of the solid angle with nearly complete coverage in ϕ. We expect no FF-LCP correlation but some ER-LCP correlation for which corrections must be made. We are in the process of using Monte Carlo techniques to verify that this correction works.

The tagged LCP energy and angular distribution are fitted to a sum of three Maxwell-Boltzmann distributions describing a projectile-like, a prompt and an equilibrium source. Each source is characterized by four parameters: multiplicity, temperature, Coulomb barrier and velocity. We fix the projectile source velocity at 85% of the beam velocity. The prompt source velocity varies between 30 and 40% of the beam velocity and the equilibrium source velocity varies between 1 and 7% of the beam velocity. The projectile source and prompt source Coulomb barriers are poorly determined by the data so are fixed at the equilibrium source Coulomb barrier. The latter is consistent with a simple calculation of the Coulomb barrier. The temperatures for protons, deuterons and tritons are plotted in Fig. 3.4-1. We find for the equilibrium component that $T_p < T_d < T_t$ which is consistent with the heavier particles being emitted earlier in the de-excitation chain. The values of the multiplicities are in reasonable agreement with other experiments. We see a substantial variation depending on the tag and we are currently trying to understand this.

Fig. 3.4-1. Temperatures for FF tagged proton, deuteron and triton data. The vertical axis is the temperature (or slope parameter) in MeV and the horizontal axis is the target and beam energy. The three left points are 25 A MeV ^{16}O data and the two right points are 35 A MeV ^{14}N data.

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[1]D. Prindle *et al.*, Phys. Rev. C **48,** 291 (1993).

[2]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p 10.

3.5 Disappearance of anisotropy in alpha-alpha azimuthal correlations at 100 A MeV

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Azimuthal correlations between light charged particles in intermediate energy heavy ion collisions can have at least two origins. For pre-equilibrium particles the correlation may reflect dynamical localization effects in the early stages of the collision. For evaporated particles the correlation function is generally reflection symmetric about ninety degrees and reflects centrifugal effects due to the rotation of the evaporating source. A previous study of azimuthal correlations between alpha particles and fission fragments showed that this correlation weakened as the bombarding energy was increased from 20 to 50 A MeV (see Section 3.3).

We have performed a preliminary analysis of azimuthal correlations for 25 A MeV ^{16}O and 35 and 100 A MeV ^{14}N bombardment of Ta. We have tagged the impact parameter range by requiring a coincidence with a fission fragment but have not yet used the direction of the fragment to help establish the reaction plane. The correlations shown in Fig. 3.5-1 are inclusive over alpha particle energy and alpha particle polar angle. It can be seen that the azimuthal correlation weakens with increasing bombarding energy and has essentially disappeared at 100 A MeV. We plan to further explore this result with cuts on alpha energy and angle to emphasize separately the pre-equilibrium and evaporation components.

Fig. 3.5-1. Alpha-alpha azimuthal correlations at 25, 35 and 100 A MeV bombardment of Ta.

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3.6 Lifetime study via momentum correlation function

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When two nuclei collide at bombarding energies over the Coulomb barrier but well below relativistic energies a compound nucleus can be formed via fusion. Some light charged particles (LCP) are emitted before (pre-equilibrium particle emission) and after equilibrium (evaporation). Studying the lifetime τ for particle or fragment emission produces information on the equilibrium and pre-equilibrium partially thermalized nucleus. In this energy range the expected lifetime is in the range of 10^{-22} to 10^{-20}s and is too short for any kind of direct measurement. Since when two particles are emitted from the nucleus, they can be very close to each other, the long range Coulomb repulsion and short range nuclear force can have an effect on their relative momentum which can be studied by the momentum correlation function.[1] At near barrier energies (≤ 10 MeV/u) many studies have shown that a thermalized compound nucleus is formed and decays via particle evaporation or fission. Several approaches have been developed to compare the measured correlation function to the ones calculated by a reaction simulation code. We adopted a classical approach.[2] We fix the size of the compound nucleus and use the time delay between the emissions as the driving force of the correlation. We used a customized version of MENEKA,[3] a statistical model using the 3-body Coulomb trajectory calculation to simulate the LCP emission. We formed the excited composite system as prescribed by projectile, target and linear momentum transfer and randomly chose E_i from the observed energy spectrum. The delay time between two emissions is selected randomly from a probability distribution of $P(t) \propto e^{-t/\tau}$. After both particles are emitted we calculate the 3-body Coulomb trajectory and use the detector geometry as the acceptance.

We have extracted the correlation function from the data we got in the MSU experiment (see Section 3.3). We report the results from analyzing the equilibrium deuteron-deuteron momentum correlations. We select the equilibrium deuterons by making cuts on their energies and polar angles. Fig. 3.6-1 shows that an example of a deuteron-deuteron correlation function. It is clear that the correlation function lies in between the two calculated lines and we can thus conclude that the average lifetime is between the times indicated by these lines. Fig. 3.6-2 summarizes the lifetimes for many systems and triggers. The estimated error here includes both systematic error and statistical error. Our results show that the average time delay between two deuteron emissions gets shorter when the bombarding energy increases. Also when the average impact parameter decreases [going from fission fragment trigger (FF) to evaporation residue trigger (ER)], we expect less energy goes into the rotation and the nucleus gets hotter. Thus the average lifetime becomes shorter. Also as the mass of the target goes up, we expect there will be more nucleons sharing the excitation energy and the average lifetime becomes longer.

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[1] S.E. Koonin, Phys. Lett. B **70**, 43 (1977).
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Fig. 3.6-1. A deuteron-deuteron momentum correlation function. The dotted line is a MENEKA calculation with $\tau = 1 \times 10^{-21}$ and the dashed line is a similar calculation with $\tau = 5 \times 10^{-22}$. The data points have energy cut of $E \leq 25$ MeV and polar angle cut of $\theta \geq 50°$.

Fig. 3.6-2. Lifetimes from different projectile and target combinations and different triggers. $\times$ has no specific trigger requirement, ◊ requires an ER trigger and requires a FF trigger.

3.7 APEX progress report

T.A. Trainor and the APEX Collaboration

During 1993 a series of diagnostic runs on the partially completed APEX spectrometer were carried out to determine efficiencies and resolutions. By late 1993 the second arm of the APEX spectrometer had been completed and tested. The second cold nitrogen cooling system constructed at the University of Washington was installed on this arm. During a run in December, with APEX operating in a fully symmetric mode, about 600,000 positrons and 150,000 positron-electron pairs were accumulated.

Uranium beams of up to 5 pna intensity and energies of 6.1 and 6.3 MeV/u were incident on tantalum targets.

Preliminary analyses of these data with various cuts on heavy ion kinematics have been carried out. Comparison of this analysis with GSI results poses significant questions with regard to the relative acceptances of the various experiments. As a result of detector calibration procedures it is unlikely that differences are due to trivial energy resolution considerations. Careful reanalysis of the relative acceptances is underway.

APEX was designed to investigate in a kinematically complete way the production mechanism for anomalous lepton-pair production in several very heavy ion collision systems, where the reported anomaly consisted of discrete components in the invariant mass spectra. The initial results from APEX shift the emphasis of this investigation to the task of confirmation or falsification of the reported anomaly.

For the case of falsification one is testing the assertion that in some subvolume of the complete parameter space of the heavy ion collision (heavy ion kinematics plus lepton pair kinematics) there are one or more localized excesses of lepton-pair yield above a smoothly-varying background distribution or null hypothesis. With finite statistical power (integrated beam-target luminosity) and limited a priori information on the location of the special subvolume(s) one must bin the space optimally, with a bin size comparable to the expected size of the special subvolume. Then the test becomes a sequence of comparisons of bin contents to the corresponding predictions from the null hypothesis. If there is no significant difference then the assertion of yield excess is falsified within some confidence limit.

Failure thus far to observe significant peak structure in the positron singles or lepton pair spectra may indicate that the binning is not yet optimized or that bins overlapping the special subvolume(s) have not yet been sufficiently illuminated because of limited acceptance. Or it may mean that the assertion of excess yield is falsified within some limit. At this time there is sufficient uncertainty on several methodological points to preclude a definitive statement.

4. FUNDAMENTAL SYMMETRIES AND WEAK INTERACTIONS

4.1 Measurement of the $\beta-\alpha$ angular correlation in the decay of ^{8}Li

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The measurement of the $\beta-\alpha$ correlation in ^{8}Li is part of a precision test of the Conserved Vector Current (CVC) hypothesis and a search for Second Class Currents (SCC) in the A=8 system, consisting of ^{8}Li, ^{8}Be and ^{8}B.[1] A high precision test of these fundamental symmetries is of interest due to the anticipated breaking of isospin symmetry created by the difference of the up and down quark masses. To test these symmetries requires the measurement of the $\beta-\alpha$ angular correlation in ^{8}Li and ^{8}B, and the $\gamma-$ray decay of the isobaric analog state in ^{8}Be. The $\gamma-$ray measurement is described elsewhere (see Section 4.2). During the past year the apparatus to measure the beta decays was completed. After numerous short test runs to debug the apparatus, a high-statistics measurement of the $\beta-\alpha$ correlation in ^{8}Li was undertaken. Data were taken during a one-week run in August and a three week run in November during which approximately 100 million decays were detected. The measurement of the $\beta-\alpha$ correlation in ^{8}B awaits the completion of a high intensity ^{3}He source which is planned for next year.

The apparatus design was optimized to reduce systematic errors, from β particles scattering and β detector response. The apparatus consists of a production chamber from which the activity is transported on the end of a 75 cm long rotating arm to the middle of the counting chamber. The ^{8}Li activity is produced via the reaction ^{7}Li(d,p) at an energy of 1 MeV. The target is a rotating wheel of 900'μg/cm^2 nickel onto which 200 μg/cm^2 ^{nat}LiF is evaporated. The recoiling activity is caught by a 100'μg/cm^2 natural carbon catcher foil that is located right behind the target and is attached to the end of the rotating arm. The arm rotates 180 degrees every two seconds, placing the activity in the counting chamber. The detector complement includes five beta detectors, three gas alpha counters and one silicon counter for alpha detection. The beta detectors lie in a plane with two of the alpha counters, the alpha counters are at 0 and 180 degrees and the beta counters at 30, 60, 90, 120 and 150 degrees. The other two alpha detectors are at points perpendicular to this plane. These alpha detectors are used to cross normalize and calibrate the beta counters. The 0 and 180 degree alpha counters are then used to measure the angular correlation. The beta detectors consist of a thin (1.5 mm) detector and E counter which is surrounded by a veto. All 3 components are NE104 plastic scintillator. The beta counter phototubes are stabilized with reference to a LED. The alpha counters are low pressure gas wire chambers based on a design by Breskin *et al.*[2] They are 20 cm in diameter and 62 cm from the catcher foil. Energy of the α particles is obtained by time of flight. Events which are coincidences between a beta and an alpha counter are recorded.

Due to the high statistics and large number of parameters for an event the offline data analysis sorting is performed on the NPL Digital Equipment Company Alpha computer, the only computer at NPL that can perform the task in a reasonable time. Preliminary analysis has been completed and results are encouraging. The error after the last data taking runs is dominated by statistical errors, the systematic errors are estimated to be three times smaller than the statistical errors. The calibration of the beta counters using a coincident alpha in the silicon detector which is used to obtain the endpoint energy works extremely well and gives a beta detector calibration accurate to 1%. The data analysis is expected to be completed by summer.

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[1]Nuclear Physics Annual Report, University of Washington (1991) p. 31.

[2]A. Breskin *et al*., Nucl. Instrum. Methods, **221**, 363 (1984).

4.2 Radiative decays of the 16.6, 16.9 MeV doublet in ^{8}Be

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As part of an improved test of CVC and a search for second class current contributions in the mass-8 (^{8}Li,^{8}Be,^{8}B) system, we have made an improved measurement of the radiative properties of the isospin-mixed 2^+(16.6, 16.9 MeV) analog doublet in the ^{4}He(α,γ)^{8}Be reaction. The motivation stems primarily from the possibility of observing a spurious second class current contribution due to the mass difference of the up and down quarks.

In our experiment, a 34 MeV alpha particle beam from the tandem-linac bombarded a small cylindrical ^{4}He gas cell with 0.3 mil Kapton entrance and exit windows. Gamma rays were detected in the large NaI spectrometer. Time-of-flight with respect to the linac RF was used to eliminate neutron background. In order to eliminate background gamma-ray contributions from the Kapton foils, difference spectra were computed by subtracting from the full target data runs in which the ^{4}He gas was replaced by H_2 gas at a pressure calculated to produce the same energy loss as the helium did. The beam energy was monitored by measuring the elastic scattering from a gold foil which was inserted into the beam in between gas cell runs. An excitation curve over the resonance doublet was measured at θ_γ = 90°, and angular distributions were measured at θ_γ = 45, 90, 140° near the peak of each resonance. The detector efficiency was determined from a measurement of the ^{12}C(p,γ) reaction. The combined data set (excitation curve plus angular distributions) for decay to the 2+(3.0 MeV) final state was fitted with an expression based on a two-level R-matrix formula of Barker.[1] In this fit, the energies and widths of the doublet together with the isospin mixing were fixed based on the results of previous experiments, and the only free parameters were the four radiative decay widths, corresponding to isovector and isoscalar M1 and E2 decay. The results of the fit are $\Gamma_\gamma(\mathrm{M1,T=1})$=2.8±0.2"eV, $\in = [\Gamma_\gamma(\mathrm{M1,T=0}) / [\Gamma_\gamma(\mathrm{M1,T=1})]^{1/2}$=+0.06±0.02, $\delta_1=[\Gamma_\gamma(\mathrm{E2,T=1})/\Gamma_\gamma(\mathrm{M1,T=1})]^{1/2}$=+0.01±0.03, and $\delta_0=[\Gamma_\gamma(\mathrm{E2,T=0})/\Gamma_\gamma(\mathrm{M1,T=1})]^{1/2}$=+0.22±0.04. Our observation of a weak E2 T=1 decay (δ_1) is in disagreement with earlier work,[2] and is in good agreement with theoretical calculations. Our value for δ_1 also implies that contributions to the ^{8}Li - ^{8}B beta-alpha correlation factor δ^- which are quadratic in the beta energy are small. Our value for Γ_γ(M1,T=1) is substantially smaller than the values 3.6±0.3 eV, 4.1±0.6 eV obtained from a reanalysis of the results of references 2 and 3, respectively, using our values for δ_1 and δ_0. Our value of Γ_γ(M1,T=1) together with CVC implies $(M_n/E_\beta)\delta^- \cong 7.0\pm0.2$, where M_n is the nucleon mass and E_β is the β energy. This value may be compared with the values deduced from the $\beta-\alpha$ correlation, of 7.0±0.5[3] and 6.5±0.2.[4] Ground-state (E2) decays were observed from both resonances, with relative strengths which imply a decay that is either mostly isoscalar or mostly isovector.

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[1]F.C. Barker, Aust. J. Phys. **20**, 341 (1967).
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[4]R.D. McKeown, G.T. Garvey and C.A. Gagliardi, Phys. Rev. C **22**, 738 (1980).

4.3 GT and M1 strengths in ^{8}Li, ^{8}Be and ^{8}B

L. De Braeckeleer and D. Wright

In order to extract CVC-violating terms due to second class currents from $\beta-\alpha$ angular correlation measurements undertaken by the mass-8 collaboration here, it is necessary to have independent measurements of the Gamow-Teller (GT) strength functions for the beta decays of the ground states of ^{8}Li and ^{8}B to ^{8}Be, and of the isovector M1 electromagnetic decay of the 16 MeV doublet in ^{8}Be.[1] We have undertaken experiments to measure these quantities and have developed data analysis software which allows us to interpret the results accurately.

The two GT strengths were measured in an approximately two week run. The mass-8 apparatus[2] was used to produce ^{8}Li and ^{8}B, whose decays were observed by a silicon counter in close geometry. The silicon counter measured the energy spectrum of alpha particles produced in the disintegration of the daughter nucleus ^{8}Be. From momentum and energy conservation, each alpha particle produced in a ^{8}Be disintegration must carry half the energy released (ignoring the recoil from beta decay). The alpha particle energy spectrum thus gives the relative probabilities of beta decays to different excitation energies in ^{8}Be. The time of each event relative to the apparatus arm rotation was also recorded. A decaying exponential fit to the time-of-event spectrum yielded half-lives for ^{8}Li and ^{8}B of 842 ± 3 ms and 767 ± 2 ms, respectively. These values agree with the accepted values[3] of 838 ± 6 ms and 770 ± 3 ms.

A sample alpha energy spectrum is shown in Fig. 4.3-1. The low-energy peak represents energy deposited in the silicon counter by electrons. To correct for this background, we subtracted from this raw spectrum a spectrum gated on late events and scaled by the relative widths of the two gates. This technique, which subtracts events due to decays with lifetimes long compared to those of the mass-8 nuclei, reduced the height of this low-energy peak by an order of magnitude.

We were able to extract the GT strength function from these alpha energy spectra with an accuracy of 0.5%. To achieve this accuracy, we first corrected the measured spectra for alpha energy loss in the foil.[4] We then divided out the integrated phase-space factor, corrected by accurately computed Fermi[5] and order-α radiative[6] correction factors, and for non-GT contributions.[7] The corrections for Fermi, radiative, and non-GT effects were found to alter the extracted GT strength by ~10%, ~1%, and ~1%, respectively. The extracted GT strength for ^{8}Li decay is shown in Fig. 4.3-2.

Employing a nonlinear least squares fitting routine, we performed an R-matrix fit[8] to the extracted GT strength. Allowing contributions from the 3 MeV 2^+ state and the 16 MeV 2^+ doublet with energy and width fixed by previous experiments,[3] and without an intruder state, we obtained fair agreement with the data: for ^{8}Li decay, $\chi^2/\nu = 2.9$ with 3 MeV state parameters $E_3 = 3.14 \pm 0.07$ MeV, and $\gamma_3 = 32.2 \pm 1.6$ KeV$^{1/2}$, and for ^{8}B decay, $\chi^2/\nu = 2.7$ with $E_3 = 3.18 \pm 0.04$ MeV, and $\gamma_3 = 32.8 \pm 0.7$ KeV$^{1/2}$. The best fit to the extracted GT strength is superimposed on Fig. 4.3-2.

We have also completed a preliminary run in which the photon spectrum from ^{4}He$(\alpha,\alpha\gamma)$ was observed as the first step in extracting the isovector M1 decay strength function of the 16 MeV 2^+ doublet

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[8]E. K. Warburton, Phys. Rev. C **33**, 303 (1986).

in ^{8}Be. Because the isotriplet part of this doublet is the analog of the 2^{+} ground states of ^{8}Li and ^{8}B, this strength is related to the GT strength discussed above by CVC. In these measurements, we employed a Compton-shielded 10" x 15" NaI spectrometer at 90° and a gas cell target with Kapton windows, sufficiently long (~ 35cm) that photons originating in the center of the gas cell could be distinguished from neutrons originating in the windows by employing a pulsed α beam and a time-of-event gate. Further background reduction was achieved by replacing the ^{4}He in the gas cell with ^{1}H at a pressure designed to match the α energy-loss in the helium, and subtracting the hydrogen-target photon spectrum from the helium-target spectrum. This technique significantly reduces background from α particle interactions with the walls of the gas cell at the high end of the photon energy spectrum, but was found to be insufficient for low photon energies.

Fig. 4.3-1. ^{8}Li raw α energy spectrum.

Fig. 4.3-2. ^{8}Li GT strength.

4.4 Construction of an apparatus to measure the PNC spin rotation of cold neutrons in a liquid helium target

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Our apparatus to measure the parity non-conserving (PNC) spin-rotation of transversely polarized neutrons through a liquid helium target is under construction. The goal of this experiment is to measure the predicted neutron spin rotation of ~$2 \cdot 10^{-7}$ radians[1,2] in our 46 cm long target chambers with an error of less than $3 \cdot 10^{-8}$ radians. This observable is sensitive to the isovector pion-exchange amplitude, F_π which is sensitive to the neutral current contribution to the weak interaction meson-exchange potential between hadrons. This experiment is motivated by the discrepancy between the experimental limits and the theoretical calculations of f_π which differ by a factor of three.[3]

Oxford Instruments Inc. has delivered a cryostat built to our specifications that contains a horizontal central cold bore at liquid helium temperatures into which we will mount our insert containing the liquid helium targets, the target-gas transfer system, and the single central $\pi-\text{coil}$. We have tested the cryostat at cryogenic temperatures with mostly favorable results; the few minor difficulties are being worked out in cooperation with Oxford Instruments.

The experiment has a split neutron beam and four target chambers. We will alternately fill two of the four chambers, so that each beam passes through one full and one empty target chamber. The target chambers will be cycled approximately 12 times per hour, using the liquid helium from a reservoir contained within our cold-bore insert. To achieve this, a valve and pump system have been designed. The valve is a two piece, tapered, stop-cock design with rotational settings which allow the filling and draining of each set of chambers. The valve is constructed of aluminum, with the mating surfaces coated with a 1 mil thick layer of teflon to assure a slippery surface at liquid helium temperatures. Prototype versions of the valve and pump have been built and will soon be tested for performance and longevity under cryogenic conditions.

A prototype detector, a segmented ionization chamber run in integration mode, has been built. Testing of this prototype will begin soon, to determine the optimum mixture of argon and helium-3 and the subsequent gas pressure, and physical dimensions to reduce the wall effects. Simultaneously, the supporting electronics will be tested for its capability to integrate the count rate (10^8 neutrons per second at the NIST reactor in Gaithersburg, Maryland) with a noise level of one part in 10^4, set by the goal of keeping systematic errors at the level of 10^{-8}.

Other parts of the apparatus under construction include the coaxial μ-metal magnetic shields with end-caps that surround the cryostat. The estimated axial shielding factor is better than 100, as determined by calculations and preliminary measurements before annealing and degaussing the material. The π-coil, described in a previous Annual Report,[4] is under construction. The complete apparatus should be built and tested by January 1995, when our scheduled beam time begins.

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*Department of Physics, University of Washington, Seattle, WA.

[1] Y. Avishai, Phys. Lett. B **112**, 311 (1982).

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4.5 The electron-neutrino correlation in pure Fermi transitions

E.G. Adelberger and B. Monteyne*

The electron-neutrino correlation in beta decay directly and unambiguously reflects the spin of the exchanged particle that mediated the decay. It is well known that this spin is one, and that the exchanged particle is the W. However, the very feebleness of the weak interaction makes it an interesting process to probe for new physics, such as possible ultra-massive, charged scalar particles that could be exchanged instead of the well-known W boson. We recently showed[1] that isospin-forbidden beta-delayed proton emission in pure Fermi decays provides a sensitive probe for the exchange of charged scalar bosons with masses up to three times the W mass. These decays probe the electron-neutrino correlation by measuring the effect of the lepton recoil on the energy of the subsequently emitted delayed proton.

In preparation for an approved experiment to study ^{32}Ar decay at ISOLDE, we have made improved calculations of the expected lineshapes of the delayed protons emitted in Fermi transitions. We have, for the first time, made predictions in which the recoiling nucleus and the subsequent delayed particle are treated relativistically and take correct account of events where the beta and the associated delayed particle are detected in the same counter. We also include a realistic response function for the delayed particle detector. A code running on IBM compatible PC's has been written that has an accuracy sufficient to see a 10^{-3} effect on the electron-neutrino correlation coefficient, which is more than adequate for our planned experiment.

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[1]E.G. Adelberger, Phys. Rev. Lett. **70**, 2856 (1993).

4.6 New tests of the Equivalence Principle

E.G. Adelberger, M.G. Harris, B.R. Heckel and Y. Su

We have tested the Weak Equivalence Principle using the Eöt-Wash rotating torsion balance. Our data analysis method has been modified to give better treatment of tilt and turntable imperfections. With this analysis and additional data, we have improved our Be/Al and Be/Cu results to

$$\frac{\Delta a(\mathrm{Be}-\mathrm{Al})}{a} = (-0.2 \pm 2.8)\times 10^{-12} \text{ and } \frac{\Delta a(\mathrm{Be}-\mathrm{Cu})}{a} = (-1.9 \pm 2.5)\times 10^{-12}$$

where $\Delta a(\mathrm{A-B})$ represents the horizontal differential acceleration of bodies A and B in the northerly direction.

During last year, we also took data with a Cu and Si/Al test body pair. The Si/Al test bodies consisted of perfect single-crystal Si cylinders inside Al shells. The composition of these test bodies is similar to that of the moon, while the composition of Cu is similar to that of the earth's core, so by comparing the accelerations of the Cu and Si/Al bodies toward the sun, we set an upper limit on the differential earth-moon acceleration toward the sun due to composition-dependent interactions:

$$\frac{\Delta a_{\mathrm{comp}}}{a_{\mathrm{sun}}} = (-1.6 \pm 2.2)\times 10^{-12}$$

This result, together with the latest lunar ranging results,[1] tested the Equivalence Principle for gravitational binding energy at the level of 5 parts in 1000.

Cu--Si/Al results also tested Weber's claim[2] that solar neutrinos scattered coherently from single crystals with cross-sections ~10^{23} times larger than the accepted values. We place a 2σ upper limit on the neutrino scattering cross-section that is 530 times below Weber's claim.

We demonstrated our sensitivity to small signals by creating a weak Q_{44} field (see our previous publication[3] for definition) that should produce a 4ω signal with an amplitude of 38 nrad. A 1ω signal of this amplitude would correspond to an Equivalence Principle violation of $|\eta| = 2.1\times 10^{-11}$, consistent with the null result of Roll, Krotkov and Dicke.[4] We extracted a 4ω signal of (44±8) nrad (Fig. 4.6-1), in excellent agreement with the expected value.

A paper reporting our latest results has been submitted to Phys. Rev. D.

[1]J.O. Dickey *et al.*, Science, to be published.
[2]J. Weber, Phys. Rev. D **38**, 32 (1988).
[3]E.G. Adelberger, Phys. Rev. D **42**, 3267 (1990).
[4]P.G. Roll, R. Krotkov, and R.H. Dicke, Ann. Phys. (N.Y.) **26**, 442 (1964).

Fig. 4.6-3. Demonstration of our experimental sensitivity using a Q_{44} source. The plot was made by subtracting source-out data from source-in data and binning the results in ϕ. Fiber drift has been subtracted. The curve shows the best fit 4ω signal which agreed well with the expected amplitude and phase.

4.7 Design of a new Eöt-Wash rotating torsion balance

E.G. Adelberger, J.H. Gundlach, M. Harris, B.R. Heckel, Y. Su and H.E. Swanson

With the Equivalence Principle results reported elsewhere in this report we have essentially reached the sensitivity limits of our current rotating balance. We are now designing a new rotating torsion balance that we expect will have 100 times higher sensitivity. We are attempting to improve systematic errors by a similar factor, but can only tell if this latter goal is successful after we operate the new instrument.

The sensitivity improvement will come from increasing the fiber length by a factor of three, and increasing the Q of the torsion oscillator by more than a factor of 1000 by operating at a vacuum of 10^{-7} Torr. The instrument will be placed in a new site in the cyclotron vault that has a stronger source strength for Yukawa interactions with ranges up to 10 m.

Systematic errors will be minimized by a very high-quality air-bearing turntable with an eddy-current motor fed back to an Inductosyn angle measuring device. The instrument will be attached to the turntable with a gimbal so that it will hang freely. These improvements should greatly reduce systematic errors from turntable imperfections and tilt. The gravity-gradient errors will be minimized by new pendulum design that gives better reproducibility of the test-body placements and new gravity-gradient compensators that are farther from the pendulum and have improved design and tolerances. In addition, the site for the new balance is well below the soil surface; this will reduce the variations in the Q_{21} gravity gradient from rainwater soaking into the ground that were observed with our existing Eöt-Wash balance.

This project involves a substantial engineering effort because the size of the instrument (total height of over 3.5 m) and its location (to minimize the laboratory gravity-gradient and maximize the source strength the instrument will be placed near the hill-facing wall of the cyclotron vault with the upper fiber attachment point about 5 m above the floor).

4.8 New constraints on composition-dependent interactions with ranges down to 1 cm

E.G. Adelberger, J.H. Gundlach, M.G. Harris, B.R. Heckel, G.L. Smith and H.E. Swanson

Another measurement cycle with our rotating-source torsion-balance[1] was completed to set new limits on fundamental, composition-dependent interactions with ranges, λ, down to 1 cm ($m_b = 20 \mu eV$). We compared differential accelerations of Pb and Cu test bodies towards a three ton uranium mass that rotates slowly about the torsion pendulum. The choice of test bodies and source make our measurement particularly sensitive to interactions coupled to the third component of isospin, I_3, but establish new limits for couplings to baryon number, B and lepton number, L as well.

Since our results reported in last year's annual report we have reduced the thermal statistical noise drastically by operating at a higher vacuum of 10^{-6} torr. We also reduced the detector noise of the autocollimator by using a laser diode. The pendulum body was modified with eight small trim screws that allowed us to tune out stray gravitational q_{21} and q_{31} moments.

Data were taken for about one month, during which we oriented the composition dipole in two different directions with respect to the pendulum tray, rotated the source mass 180° with respect to the turntable, and reversed the pendulum with respect to the vacuum can. A pendulum deflection at the rotation frequency of the source with the proper phase for a new interaction was observed with an amplitude $7.5 \pm 2.6 \pm 4.0$ nrad. The first error is statistical and presents a threefold improvement over our previous measurements. The systematic error reflects uncertainties arising from a slight radial misplacement of the test bodies after a test mass interchange. These change the stray q_{31} and q_{51} moments of the pendulum which couple to the Q_{31} and Q_{51} same order source fields. We also observed a signal of 11 nrad that was uncorrelated with the composition dipole flip. We attribute this "offset" to gravitational coupling between residual imperfections in the pendulum body (q_{31} and q_{51}) which couple to stray Q_{31} and Q_{51} fields of the source.

We have now rebuilt our source mass to eliminate the Q_{51} field by design; this allows us to accurately tune out the stray q_{31} field. With this improvement we hope to reduce our sensitivity to the test-body placement errors. Furthermore we expect this to reduce the "offset".

Our limit on the strength[2] of an interaction coupled to a charge $q_5 = (B - 2L)/\sqrt{5}$ is $\alpha_5 = -0.9 \pm 0.3 \pm 0.5$ for λ = 1 cm and α_5 = $(-9 \pm 3 \pm 5) \times 10^{-6}$ for λ > 1 m. We interpret them as null results.

With the improvements mentioned above we hope to ultimately achieve a sensitivity 10 times better than the results reported here.

[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 26.
[2]q_5 and α_5 are defined in Phys. Rev. D **42**, 3267 (1990).

4.9 Study of an isospin-forbidden $0^+ \rightarrow 0^+$ transition in ^{38m}K decay

E.G. Adelberger, A. Garcia, H.E. Swanson, the Strasbourg group of G. Walter and the ISOLDE group

The least-studied correction that must be applied to infer the vector coupling constant from the rates of $0^+ \rightarrow 0^+$ Fermi transitions is the reduction of the nuclear overlap because of charge-dependent configuration mixing. The reduced overlap diverts some of the Fermi strength from the superallowed transition into isospin-forbidden $0^+ \rightarrow 0^+$ branches. We are studying the isospin-forbidden Fermi decay of ^{38m}K to the 3377 keV level in ^{38}Ar because ^{38m}K decay is expected to have the largest or second-largest charge-dependent mixing correction of any of the decays used in determining Gv. Charge-dependent shell-model calculations by Alex Brown[1] predict that the strength of the superallowed transition is diminished by 0.11%, and that the isospin-forbidden transition has a branching ratio of 6×10^{-6}. Towner, Hardy and Harvey[2] predict a larger value of $\approx 10^{-5}$.

We used the Strasbourg tape-transport system and the ISOLDE isotope separator on the PS/BOOSTER at CERN to produce a source of ^{38m}K and ^{38}K. The pulsed nature of the proton beam allowed us to optimize the yield of the 925 ms ^{38m}K activity compared to the 7.63 min ^{38}K activity that generated a background of 2168 keV $\gamma-$rays. 1209 keV gamma rays from the decay of the 3377 keV level of ^{38}Ar were detected in a large-volume Ge detector. The Ge detector was gated by a coincidence with a thin plastic scintillator that required the positron to travel away from the Ge detector and vetoed by a second plastic scintillator that rejected events where the positron scattered back into the Ge detector.

A preliminary analysis of the data gives an upper limit of 1×10^{-5} on the isospin-forbidden branch. Our result is limited by a background from the Compton tails of the 2168 keV γ's. We hope to repeat this measurement with a Compton-suppressed detector.

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[1]B.A. Brown, private communications (1993).

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

5. ACCELERATOR MASS SPECTROMETRY

T.A. Brown, G.W. Farwell, and P.M. Grootes

5.1 Performance of the FN tandem-based AMS system

We reported last year[1] that the typical measurement uncertainty for a routine determination of the $^{14}C/^{13}C$ ratio of an approximately modern sample is ±0.7%, and that less than ±0.3% of the 1σ uncertainty in such determinations cannot be accounted for by counting statistics. The absolute accuracy of the measurements to better than ±0.5% is borne out by measurements on secondary standards for which consensus data are available from both β-counting and AMS laboratories. Recent measurements on samples 5000 to 8000 years old have exhibited typical 1σ uncertainties of ±50 to 100 years (±0.6 to 1.3%). Further details are given elsewhere.[2,3]

5.2 Coral studies

Results of our study of the intra-annual variability of the radiocarbon content of corals from the Galapogos Islands, in which we observed an ENSO (El Niño/Southern Oscillation) effect, have been published.[4]

5.3 AMS ^{14}C dating of pollen from lake sediments and peat deposits

A very brief preliminary discussion was given in last year's Annual Report. We have now completed the measurement of purified pollen samples and certain other samples from lake sediment and peat cores taken from lakes and bogs in northern California, the Puget lowlands, the east side of the Cascade mountain range, and southern Vancouver Island (Canada).

Samples were taken from both above and below the "Mazama ash layer", a well-known chronostratigraphic marker resulting from the catastrophic eruption of Mount Mazama that formed Crater Lake, Oregon, about 7000 years ago. In preparation for the extension of our study to the Arctic regions, where the organic content of lakes is typically lower, we have also measured samples from a core taken from Lake Minakokosa, Alaska. Our principal efforts will now be directed toward a study of the migration of alder and spruce in Alaska following the recent glacial period (the early Holocene).

The results of the Mazama ash study demonstrate the reliability and reproducibility of ^{14}C dates determined by AMS analysis of samples of pollen extracted from sediment cores using the procedures developed here over the past several years.[3,5] Excellent agreement is obtained between ages determined from pairs of samples developed from the material, and between ages of different pollen (size) fractions from the same material. Our best date for the Mazama eruption, determined from cores from the four similar lakes where an intact Mazama ash layer exists, is 6898±35 BP (radiocarbon years before present). This is to be compared with 6840±50 BP from what is generally regarded as the most credible previous determination, and with the general range of prior determinations (6600 to 7100 BP).

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[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) pp. 32-35.
[2]T.A. Brown, G.W. Farwell, and P.M. Grootes, Proceedings of the 6th International Conference on Accelerator Mass Spectrometry (1993), Nucl. Instrum. Methods B (in press).
[3]T.A. Brown, Ph.D Dissertation, University of Washington (1994), in preparation.
[4]T.A. Brown, G.W. Farwell, P.M. Grootes, F.H. Schmidt, and M. Stuiver, Radiocarbon **35(2),** 245 (1993).
[5]T.A. Brown, G.W. Farwell, and P.M. Grootes, research paper presented at the NSF-sponsored 1st Annual PALE (Paleoclimate from Arctic Lakes and Estuaries) Research Meeting, Boulder, CO, Feb. 3-4, 1994.

Systematic apparent age differences (up to several hundred years) are observed between samples derived from sediments just above and those just below the ash layer; these can be largely understood in terms of a model that allows for bioturbation effects in the sediments following deposition. AMS measurements made (as a part of this study) on samples prepared by the simple method traditionally used for ^{14}C dating by β-counting demonstrate that such "bulk carbon" samples may yield dates that are in error (usually too young) by as much as 1000 years at an age of 6000 to 8000 years. These results raise strong doubts as to the reliability of many β-counting dates and, as well, of AMS dates obtained for "bulk carbon" samples. The pollen extraction procedure used here also evidently eliminates one traditional and quite serious problem, the "hard water" effect of dissolved carbonates that can lead to erroneously old age determinations. The Mazama ash results also suggest caution in the interpretation of ^{14}C dates from peat cores as well as from macrofossils, which may sometimes be displaced stratigraphically by post-depositional processes.

Finally, the results obtained for the Lake Minakokosa study show that essentially pure pollen fractions can be extracted from the low-organic-carbon sediments of Alaskan cores. The AMS ^{14}C dates obtained for such pollen fractions have allowed an accurate determination of the ages at which alder and spruce first appeared in the Lake Minakokosa area; thus, we have completed the first stage of our efforts to determine the pattern and the timing of the migration of alder and spruce across Alaska in the early Holocene (about 10,000 to 5,000 years BP).

This research is funded in part by an NSF grant to P.M. Grootes and G.W. Farwell under the Paleoclimate from Arctic Lakes and Estuaries Initiative of the ARCSS Program (Grant No. ATM 91-23963).

6. MEDIUM ENERGY

6.1 Search for narrow resonances in p,2p scattering

The E627 Collaboration[*] and W.G. Weitkamp

Many previous experiments have provided some evidence for narrow resonances in the p-p system.[1] A plethora of resonances have been reported, but few have been particularly well established. The present experiment is a search for narrow resonances in p,2p scattering on nuclei, using the 500 MeV polarized proton beam at TRIUMF.

The set up is shown in Fig. 6.1-1 below. A total of 16 NaI detectors 150 mm thick view a line of four targets of CH_2, Al, Cu and Cu. Plastic scintillator delta detectors 10 mm thick, a pair of X-Y wire chambers near the NaI detectors and a pair of wire chambers near the target provide good background rejection with large solid angles and high counting rates.

An initial data taking run was held in 1991[2] and the data were subsequently analyzed. Several factors made this data somewhat unreliable, however. Air scattering contributed significantly to the background. Consequently, a large number of non-significant events were included on the data tapes. Also, gain shifts in the photomultipliers made energy calibration of the detectors problematical. Peaks did appear in some detectors, but the precision was inadequate. TRIUMF made an additional three weeks of beam time available in February 1994. The apparatus was reassembled with several important modifications. First, the targets were placed in a vacuum chamber to reduce the effects of air scattering. Second, hodoscopes in the vicinity of the targets was replaced with position sensitive wire chambers and third, light emitting diodes were installed on the phototubes to enable drifts in gain to be monitored and corrected for. In addition, the detectors were calibrated using elastic proton scattering from deuterons in CD_2 targets.

During the February 1994 run, approximately 10^8 triggers were recorded, an order of magnitude more than during the previous run. The efficiency of the detection system appears to be substantially improved. These data are presently being analyzed.

Fig. 6.1-1. Detector array for the E627 experiment.

[*]Dubna, Tashkent, TRIUMF and the University of Washington. Spokespersons: V.A. Nikitin, Dubna and B.S. Yuldashev, Tashkent.

[1]See for example, Yu.A. Troyan, Phys. Part. Nucl. **24**, 294 (1993).

[2]Nuclear Physics Laboratory Annual Report, University of Washington (1992) p. 42.

6.2 Photoproduction of π^+ on targets with masses spanning the periodic table

H. Caplan,[*] K. Fissum,[*] I. Halpern, D.P. Rosenzweig,[†] D.W. Storm and J. Vogt[*]

As reported previously,[1] we have measured spectra of π^+ photoproduced on H, C, Ca, Sn, and Pb. Tagged photons were used, with energies from 179 to 217 MeV. The measurements were made at four angles using plastic scintillator telescopes, and positive pions were identified by detecting the muon from the pion decay.

Last year we reported that we were having difficulty obtaining a sensible absolute normalization for the cross sections that we obtained from our pion photoproduction data. Subsequently we found an error in part of the efficiency determination. This error had little impact on the results presented previously, because they were given as ratios of cross sections for nuclear pion photoproduction to that on a nucleon. We measured both these quantities, and the efficiency error largely canceled out in the ratio determination. Also, our calculations of nuclear cross sections involved quasi-free models which were based on a particular formulation for the free pion photoproduction cross section, and by taking ratios we were able to minimize our dependence on this particular model. Nevertheless, it is indeed possible to obtain absolute cross sections using tagged photons, and it is reassuring to find that with careful attention to the efficiencies we obtain cross sections for π^+ photoproduction on the proton that generally agree with an existing parameterization[2] which has been found to represent various measurements at the 10 to 20% level. Our revised results for $H(\gamma,\pi^+)$ are shown along with these predictions in Fig. 6.2-1.

Fig. 6.2-1. Differential cross sections for $H(\gamma,\pi^+)$ for a photon energy of 213 MeV. The curve is the Blomqvist-Laget prediction.

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[*]University of Saskatchewan.
†Department of Radiation Oncology, University of Rochester, Rochester, NY.
[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 36.
[2]I. Blomqvist and J. M. Laget, Nucl. Phys. A **280**, 405 (1977).

6.3 Fermi gas calculations for photoproduction of π^+ on nuclei

D.W. Storm

Last year[1] we described an implementation of a Fermi gas calculation[2] for pion photoproduction. This calculation should account, in a reasonable way, for the effects of Fermi motion and Pauli blocking on the pion photoproduction process in nuclei. In order to better understand the effects, besides those due to Pauli blocking and Fermi motion, of nuclear matter on the pions, we consider ratios of differential cross sections from nuclear targets to those from proton targets. This removes sensitivity to the Blomqvist-Laget amplitude[3] used as the basis of the Fermi gas calculation.

Because the photons penetrate the entire nucleus, the pion sources are uniformly distributed. Consequently, in a quasi-free picture of the pion photoproduction, the angular distribution of the pions from a nuclear target are determined: 1) by the elementary angular distribution (smeared out by Fermi motion), 2) by Pauli blocking, especially of the forward pions, 3) by refraction at the nuclear surface, and 4) by differences in absorption at different angles. The last effect follows because the pion absorption in nuclei is strongly dependent on the pion energy, and kinematics and Pauli blocking produce higher average energy pions at forward angles than at backward ones. In our calculations, we do not consider effects of velocity dependent nucleon optical model potentials nor of the effects of the pion optical potential on pion production. In Reference 2, these two effects are shown to be of similar magnitude and opposite sign, for energies below the Δ resonance.

The differential cross section given by the Fermi gas calculation is fairly flat with angle for angles of 50° or more.[1] Because the main effect of refraction will be to smear out the angular distribution, which is expected to be and is observed to be fairly flat, it is reasonable to ignore refraction.

For the protons, we use Fermi momenta of 220, 250, 260, and 265 MeV/c for C, Ca, Sn, and Pb respectively. For the neutrons in the heavier two targets the Fermi momenta are higher, 289 and 306 MeV/c for Sn and Pb, respectively.

We define R_m to be the ratio of the measured differential cross section from a nuclear target to the measured differential cross section for a proton; R_F is the ratio for the nuclear differential cross section resulting from the Fermi gas calculation to the differential cross section calculated for the proton. Then if we consider the ratio of these ratios and neglect refraction, R_m/R_F should reflect the absorption of pions. This ratio is plotted in Fig. 6.3-1, as a function of angle, for several targets. It has typical values around 0.3 to 0.4, it decreases with angle, and it exhibits remarkably little dependence on target. Because the dependence of pion energy on angle leads to an angle dependent absorption, one might expect the quantity R_m/R_F to be smaller at forward angles, where the average pion energy is higher, but the opposite angular dependence is observed..

The fact that R_m/R_F is 0.3 to 0.4 implies that less than half the pions that are initially produced escape. The reason this ratio exhibits such little A dependence remains a mystery. The larger value at forward than backward angles may be a result of an over estimate of Pauli blocking, which is expected to be largest at forward angles.

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[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 38.
[2]W.M. MacDonald, E.T. Dressler, and J.S. O'Connell, Phys. Rev. **19**, 455 (1979).
[3]I. Blomqvist and J.M. Laget, Nucl. Phys. A **280**, 405 (1977).

Fig. 6.3-1. Angular dependence of the quantity R_m/R_F for photon energy of 213 MeV. As argued in the text, this quantity should be related to the fraction of pions absorbed by the nuclear material.

7. ULTRA-RELATIVISTIC HEAVY ION COLLISIONS

7.1 NA35 momentum calibration and calculation

P. Chan and T. A. Trainor

This work involved minimization of systematic error in particle momenta derived from tracking information from the NA35 TPC. The problems included determining the relative positions of the momentum dispersal magnet system, the beam-target system and the moveable TPC. A priori information from professional surveys was available as a starting point. However, errors in the survey numbers and uncertainties deriving from imperfect rigidity, TPC motion during the runs, changes in the beam phase space resulting from transport adjustments and incomplete monitoring produced significant systematic uncertainties in the inclusive spectra.

We, therefore, developed techniques by which internal properties of the data were used to improve the system geometry information and minimize the systematic momentum error. As an example we observed that there was a small but significant population of electron pairs in the data from conversion of pi-zero decay photons in the TPC front wall. These pairs essentially pointed back exactly to the beam-target intersection point, even with the magnet on. This provided an important internal fiducial for the beam-target-TPC system relative geometry.

Another technique consisted of demanding that the inferred transverse particle momentum distribution be symmetric about the beam direction. This revealed systematic offsets due to relative beam-magnet-TPC geometry errors which could then be minimized. Carrying out a systematic study of these effects over the whole set of Spring 1992 runs made possible a run-number dependent statement of TPC angle and position and beam-target angle and position to within 1 mm and 0.1 mrad. This brought the systematic error in momentum down to the level of the random error due to multiple scattering of particles after exiting the magnet field and before entering the TPC (5 MeV/c). Uncertainties prior to this analysis were on the level of several mm and 0.5 mrad or 10-30 MeV/c.

An outgrowth of this analysis was a simulation study of particle transport in the momentum dispersing magnetic field and resulting improvement of the momentum calculation algorithm which increased both speed and accuracy. This study is described in the next article.

7.2 Momentum determination for NA35 TPC

P. Chan and T.A. Trainor

In CERN experiment NA35, a 1.5 Tesla superconducting dipole analyzing magnet was used to obtain momentum information for charged particles produced in collisions of 200 GeV/u S nuclei with stationary S, Au, or Ag targets. For a hard-edged model magnet with constant field strength, this is a simple and straightforward task. However, in the stray-field region of the real magnet the trajectory of the particle is not the same as that for a hard-edged magnet. For CERN experiment NA35 the TPC is located 5.6 m from the center of the magnet. Momentum information for these particles can only be inferred from their trajectories after the effect of the stray field has been included. In an attempt to simplify the analysis chain and reduce the computational time, we have used a hard-edged magnet to model the real magnet. The model is good if it produces the same particle trajectories inside the TPC as the real magnet. A GEANT simulation was used to test the quality of the model.

The original GEANT simulation package GNA49 was written by Peter Jacobs of LBL for CERN experiment NA49. It has been modified by us to suit the NA35 geometry, and a separate magnetic field routine has been adopted. The real magnetic field had been measured and parameterized as a function of radius (Fig. 7.2-1). For the present simple model only the vertical component of the magnetic field is used.

The testing of the model was done in two steps. First, the parameterized field profile was used to simulate the trajectories of a set of particles of known momenta using GEANT. The particle trajectory inside the TPC, which is outside the magnet, is a straight line and, therefore, can be described by slope and intercept parameters in the TPC coordinate system. The second step was to find an equivalent model hard-edged magnet with certain field strength, field radius, and magnet position. Then the momentum of the particles could be calculated analytically from the slope and intercept parameters of the particle trajectory using the geometry of the model hard-edge magnet.

For the optimum model magnet the center of the magnet coincides with the center of the real magnet. The field radius r_0 of the model is given by:

$$r_0 = (x_{\text{magnet}} - x_0) + (x_{\text{target}} - x_0),$$

where x_{magnet} and x_{target} are the distances between the center of the TPC and the center of the magnet and the target respectively. The intersection of the straight-line extrapolations of the particle trajectories in the TPC with the beam axis (in particular for particles with high momenta emitted near 0°) define a focal point (Barber's rule). The distance from the center of the TPC to that point is x_0.

Ideally, the field strength B_o of the model magnet should satisfy

$$\int_{x_{\text{target}}}^{r_0} B_0 \bullet d1 = \int_{x_{\text{target}}}^{\infty} B(r)dr,$$

B(r) is the parameterized field profile of the real magnet and x_{target} is the position of the target. In the present implementation the path is simply chosen to be a straight line from the target and parallel to beam axis.

Fig. 7.2-2. shows the input data (circles) as a function of inverse momentum and emission angle with respect to the beam. Plotted on the same figure are the inferred momentum and angle (stars) using a 1.448 Tesla hard-edged model magnet with field radius 161.6 cm.

This simple algorithm is used to obtain momentum information for the particles detected in the TPC using a hard-edged magnet model. The result from the GEANT simulation shows that such modeling produces results that are quite satisfactory. The errors in inferred momenta are comparable to multiple scattering errors. The success of this modeling method greatly simplifies the method to obtain momentum information from the TPC track data. Moreover, the algorithm improves the speed of the analysis chain.

Fig. 7.2-1. NA35 magnetic field profile. Circles are measured values of the vertical component of the magnetic field strength; solid line is the parameterization of the measured values.

Fig. 7.2-2. Input momenta (circles) and inferred momenta (stars).

7.3 NA35 TPC pad-to-pad relative response calibration

P. Chan and T.A. Trainor

A Time Projection Chamber (TPC) was used in CERN experiment NA35 to detect particles resulting from collisions of 200 GeV/u S ions on Au, Ag and S targets. Ionization caused by the charged particles traveling through the sensitive volume of the TPC was sampled by an array of pads. The trajectories of the particles were reconstructed from the inferred spatial positions at which the ionization occurred. Due to the coarse sampling size of the array of individual pads, it is important to measure the pad-to-pad relative response. Otherwise, any particular pad with relatively large or small response could cause a distortion in the inferred position of the ionization. Originally, such calibration was done by sending an electronic pulse through the gating grid wires of the TPC. However, the condition of the electronics can change after the calibration has been made. Furthermore, there is evidence that during the experiment the pad response changed over time. While some of the pads were turned off because of known problems, pads that showed occasional malfunction needed to be removed by software before going through the analysis chain. Hence, an independent calibration was done not only to show that the original calibration was not effective, but also to provide a way to find out the correct pad relative response on a run-by-run basis.

The method used to obtain relative pad response was based on a simple assumption: that the total amount of ionization detected by a pad over a long period of time varies smoothly across neighboring pads, provided that the geometry remains unchanged during that period. Therefore, by calculating the average ADC counts per time unit on each pad, one can estimate the relative response of the pads. On the other hand, if any particular pad on the average recorded excessive/insufficient ADC counts, it is quite likely that the pad has some history of malfunction during that period. Fig. 7.3-1 shows result from one of the eight sectors of the NA35 TPC. Each sector has 15 rows, and each row has 128 pads. The average ADC count per time channel is about 90. Several channels have over 150 ADC counts per time channel, indicated by the peaks, while some have almost zero which correspond to valleys. Including those pads in obtaining position information of the ionization would obviously produce error. However, by this analysis they can easily be distinguished from the others as shown in the figure.

In order to see if the two calibration methods, grid pulse and average ADC counts, are consistent, one can apply the original grid pulse calibration to the raw averaged ADC counts on the pads. If the calibration reduces the fluctuations on the averaged ADC counts relative to neighboring pads, then both methods would be consistent. However, the result was contrary. The variation of the average ADC counts among neighbors only gets worse after applying the original calibration.

Fig. 7.3-1 shows the raw average ADC counts per time channel (left). Comparing this with the figure for the same data after applying the grid pulse calibration (right), we see that the pulser calibration does not smooth out the distribution. It makes it rougher. Also there are valleys which are not on the previous figure. Some of the valleys are pads that were turned off because there were known problems with them. Others were turned off by this calibration because they had poor performance at the time that the calibration data were taken. However, those pads did not show any significant bad behavior during the time period in question.

This small exercise shows that the calibration using the wire pulse signal does not work well for the TPC because of changes in the electronics between the time real data were taken and the time the calibration was done. This averaged ADC count calibration method still needs tuning to be more robust. For example, the energy loss for particles may need to be included to account for the variation between the front and the back of the TPC. Once all the fine tuning is done, this method should provide a way of obtaining pad-to-pad relative response dynamically.

Fig. 7.3-1. Raw average ADC counts (left) and average ADC counts with grid pulse calibration applied (right) per time channel as function pad and row number in a sector of NA35 TPC.

7.4 NA35 momentum error systematics and variance analysis

S.J. Bailey, H. Bichsel, P. Chan, J.G. Cramer, D. Prindle, T. A. Trainor and X. Zhu

This was a lengthy error analysis program carried out on the NA35 TPC data from the Spring 1992 sulfur beam run on sulfur, silver and gold targets. The analysis had two components: an analysis of systematic momentum error, and an analysis of variance in the TPC tracking process and the random error in inferred momentum which results.

The systematic error analysis involved a detailed study of the relationship between all TPC geometry parameters, such as positions, angles, drift speeds, timing, magnetic field parameters, etc., and the consequent systematic distortions in the inclusive momentum spectra.

The result of this study, in addition to a detailed statement of the error propagation, was a reduction of the total systematic error due to improved knowledge of the system geometry from requirements of symmetry and internal consistency. A statement of the error system consisted of descriptions of the topological mappings (distortions) in momentum space resulting from various offsets in system geometry parameters, with estimates of the uncertainties in the geometry parameters.

Such systematic distortion analyses become especially important when attempting to carry out 'mixed charge' HBT analysis, in which case relative registration of widely separated regions of momentum space (for oppositely charged particles) becomes critical. This places far more stringent requirements on momentum accuracy than have been routinely achieved in the past.

The momentum variance analysis began with a detailed study of the energy loss process in the TPC and the recording and digitization of the resulting charge distributions by the data acquisition system. This involved both analysis of real track data from the Spring 1992 run and microscopic simulation of energy loss and electron drift in the TPC.

Careful study of the tracking analysis process on both simulated and real data revealed ways to modify the tracking algorithms to reduce significantly the random error (in some cases by more than 50%). The tracking analysis software was modified to take advantage of these findings.

Analysis of the consequences of random error in TPC tracking, especially to Hanbury-Brown-Twiss (HBT) interferometry used to reconstruct the space-time geometry of the collision event, revealed that the error structure in the reconstructed event space-time is highly asymmetric and momentum dependent when the tracking device is a significant distance from the target, as was the case with the NA35 TPC. This finding does not mean that HBT interferometry would be ineffective at such reconstruction, but rather that any statement about collision system space-time using this technique must include corrections for the asymmetric random error effects noted here.

The NA35 data have served as a test bed for development of these analysis techniques, which will now be extended during the NA49 data analysis.

7.5 Energy loss straggling functions needed in NA49 and STAR

H. Bichsel

The choice of a gas for the time projection chambers depends on several properties: ionization per cm, electron drift parameters, chemical hazards. The ionization is derived from the energy loss Δ of the charged particles. Since Δ is a stochastic variable, we need to know the distribution function $f(\Delta)$, usually called the straggling function. It can be characterized by its most probable value Δ_p and the full-width-at-half maximum, w. The ionization J is given in a first approximation by $J = \Delta/W$, where W is the energy needed for creation of an ion-electron pair. It consists of two parts: J_1 representing the number of primary ion pairs produced, $J_1 = n_p \cdot t$, where t is the thickness of the gas layer traversed by the particles, and J_2 produced by the secondary electrons (δ rays) from the primary collisions. The total ionization is $J = J_1 + J_2$. The stopping power S = dE/dx does not represent a useful parameter for characterizing $f(\Delta)$.

Energy loss parameters have been calculated for helium, argon, ethane and butane with the Weizsäcker-Williams method. They are given in the table for particles with $\beta\gamma = 4$.

Table 7.5-1. Number of collisions per cm, n_p; W(eV); stopping power S keV/cm; most probable energy loss Δ_p (keV) and fwhm w (keV) for two thicknesses t of gas: 1 cm and 4 cm. Uncertainties of the values are several percent.

gas	n_p	*W*	*S*	Δ_p 1 *cm*	*w* 1 *cm*	Δ_p 4 *cm*	*w*	w / Δ_p
He	5.2	30	0.33	0.15	0.21	0.74	0.53	0.72
Ar	26	26	2.47	1.0	1.24	5.2	3.4	0.65
C_2H_6	69	25	3.02	1.65	1.05	7.7	3.0	0.39
C_4H_{10}	128	23.4	6.1	3.84	2.01	16.8	5.4	0.32

Values for *W* are those for electrons.[1] For He, an estimate is given which takes into account the Jesse effect, which accounts for the ionization of impurities by highly excited states of helium atoms. There is no doubt that *W* depends on particle speed. Since at present there is no reliable theory permitting the calculation of *W* with an uncertainty of, say, 1%, we do not know how much *W* depends on speed. At small speeds (e.g., 1 MeV protons) *W* depends on particle type. It is unlikely that *W* depends on particle type at relativistic speeds, so I gave the values for electrons.

Data for n_p for the organic gases are much higher than those given by Sauli.[2] This is due to the large photo absorption cross sections for these gases. Note especially that Δ_p is much less than the mean energy loss $< \Delta > = t \cdot S$. Thus it is inappropriate to talk about "dE/dx" when straggling functions are discussed. Also note that Δ_p increases approximately as $t^{1.1}$. The resolution for particle identification will be proportional to w/Δ_p. From this aspect, butane would be the best choice for the TPC gas.

[1] "Average energy required to produce an ion pair" Report No. 31, Int. Comm. Radiation Units, Bethesda, MD, 1979.

[2] "Principles of operation of multiwire proportional and drift chambers," F. Sauli, CERN 77-09, Geneva, 1977.

7.6 Projective tracking in NA35 and NA49 TPCs

H. Babcock, S. Bailey, P. Chan, J.G. Cramer, D.J. Prindle and T.A. Trainor

NA35 and NA49 are fixed target heavy ion experiments at CERN. In both experiments there is a target in a magnetic field so that particles produced in heavy ion collisions follow curved trajectories until they emerge from the magnetic field. The trajectories are then measured by TPCs. NA35, which has finished data taking, had a single external TPC. NA49, which is being constructed now, has two large external TPCs (the so called Main TPCs) as well as TPCs inside the magnetic fields (the Vertex TPCs).

The NA35 track finding program TRAC is a traditional "follow your nose" approach in which a hypothesis or previously determined points are used to predict where the next measured point on the track should be. This involves a substantial amount of calculation, even for straight lines. We have developed an alternative pattern recognition algorithm which involves projecting all points to the TPC mid-plane based on a point-of-origin hypothesis. This allows us to search the two dimensional mid-plane for peaks. All the points within a peak are assumed to belong to a track.

We project all TPC points to the mid-plane by assuming all tracks from the target were emitted at small angles and then curved in the magnetic field. For NA35, with a single magnet, this means that in one dimension the tracks extrapolate to the beam-target intersection while in the other dimension they extrapolate to the center of the magnet (Barber's rule). For NA49, with two magnets, the projection is more difficult to describe but still possible.

We have tested the projection using NA35 raw data. Here we project all the pad-time bins containing charge, as opposed to applying a cluster finding algorithm and projecting the space points. Shown in Fig. 7.6-1 is the high density part of an NA35 event. The charge density contours represent the projected raw data, and the crosses are the mid-plane intersection of the tracks found by TRAC.

Fig. 7.6-1. Raw data from an NA35 event projected to the TPC mid-plane. The charge density contours represent the projected raw data, and the crosses are the mid-plane intersection of the tracks found by TRAC.

7.7 MTRAC tracking analysis code

S.J. Bailey, T.A. Trainor and P. Venable

The Pb beams program at the SPS at CERN will commence in Fall of this year. NA49 will be one of the leading experiments in this program, with data rates for 200 GeV/u Pb on heavy targets expected to be in the neighborhood of 8 Mbytes/s. Particle tracking will be shared among four TPCs, of which the two 'main' or MTPCs are 3.5 m square and located downstream of the momentum dispersing double magnet system. Data analysis of the very substantial final data package will be performed at a distribution of analysis centers around the world, including CERN, IKF-Frankfurt, MPI-Munich, Birmingham-UK, Seattle and LBL, and will represent a major step in the development of distributed data analysis systems.

The MTPC tracking task involves a lengthy sequence of computational steps to find track correlations within the deposited charge in a TPC for each collision event, and then to interpret the found tracks in terms of specific particle types and momenta. This must be done with the highest possible speed and efficiency in view of the large amount of data produced and the relatively low incidence of the most interesting events, those that would reveal evidence of QCD color deconfinement. The task of generating the tracking software for the main or MTPCs has been undertaken by our group at the University of Washington.

This task has two components. A software environment for overall NA49 data analysis is currently being developed by our European colleagues under the coordination of IKF in Frankfurt, in which all analysis subsystems will eventually reside. During this environment development a standalone version of the MTPC tracking code is being developed here by SJB which will also be used for hardware tests at CERN in the near future. This code is being developed with contributions from personnel at MPI-Munich and LBL.

As more detailed versions of the software environment become available working elements of the standalone code are being transferred to this environment by PV. This parallel development program insures optimum schedule security and matching to various simulation and hardware testing requirements.

7.8 NA35 and NA49 tracking analysis software

S.J. Bailey, P. Chan, D. Prindle, S. Schönfelder,* T.A. Trainor and P. Venable

TRAC[1] is an analysis software package for NA35 time projection chamber (TPC) tracking. We have been updating this program for use as NA49 tracking software. To facilitate this process, the following changes were made.

The code was modularized so that each module had a clearly defined set of input and output parameters, and the purpose of each module was clearly known. This modularization enabled each module to be updated separately without affecting other modules. The code was also reorganized to make it clearer and easier to understand. Unused portions of the code were removed and the existing code was reorganized to disentangle different portions of the analysis chain from each other. During this process the code was upgraded to ANSI-C compliance. Complete documentation was also written, both for using the program as a whole and for the specifics of individual modules.

The modularization, reorganization, and documentation has allowed users to be able to change one portion of the TRAC code without having to understand all of it. This has reduced initial learning time and has made the process of trying new modules and algorithms more efficient.

The ultimate goal of the changes was the eventual use of the code as NA49 tracking software, but there have also been side benefits directly applicable to NA35 data analysis. The detailed understanding of the entire program allowed several small bugs to be identified and corrected as well as improved algorithms to be implemented. The latest NA35 version, released as TRAC version 1.2, had significantly improved data quality.

TRAC is being updated to do the tracking analysis for the two NA49 main TPCs which are significantly larger and more complicated than the NA35 TPC. The internal geometry variables and functions have been entirely rewritten to reflect this new geometry. The NA49 specific code is also being streamlined from the original TRAC code. Several modules have been entirely rewritten and the process and data flow have been reorganized. The INIT file format has also been entirely redesigned. The current code, TNT[2] version 0.05, is much easier to understand and update because it is specifically designed to be modular and easy to work with.

The NA49 analysis system will use a daemon server for memory management and I/O. Under this system each major module of the TNT program will become a separate stand-alone executable. The geometry functions have been converted into a library to which other modules link to gain access to those functions. The new modularization has greatly facilitated this process of creating entirely stand-alone modules.

There are currently two major versions of the tracking analysis code being developed. One is the stand-alone program TNT, designed to allow current code development while the daemon is being finished and to serve as a backup analysis tool in case overhead or other unanticipated factors cause the daemon environment to be impractical. At the same time, modules from within TNT are being converted into stand-alone executables to work with the prototype daemon. We have had good success with integrating these two parallel efforts.

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*MPI, Munich.
[1]TPC Reconstruction and Analysis Code, Gunther Roland, IKF Frankfurt.
[2]TNT stands for "TNT, Not TRAC".

7.9 Improvements to cluster finding software

S.J. Bailey, P. Chan, D. Prindle and T.A. Trainor

As part of the upgrade of the NA35 tracking software TRAC[1] a significant amount of time was spent analyzing the methods used in the cluster finder, especially regarding the usage of bad pads. In the NA35 time projection chamber (TPC), there are effectively 60 vertical pixel planes divided up into 256 pads by 512 time bins each. Within each plane contiguous islands of charge with a single peak in both the pad and time directions are formed into clusters. These clusters are eventually used for track finding.

To study anomalies in the cluster finding process, the clusters from fitted tracks were analyzed. For each cluster, its distance from the fitted track was correlated to its position in the TPC. In the time direction, nothing unusual was found. In the pad direction however, certain areas of the TPC had unusually high numbers of clusters that were much further from the track than average (see Fig. 7.9-1, representing sector three of the TPC). We noticed that these areas of the TPC corresponded to pads that a calibration file had already marked as "bad". It was already known that these pads were bad but they were not being properly handled and were thus distorting the final results.

It was discovered that the cluster finder was using bad pads in the cluster reconstruction process, and was merely flagging them as being invalid for use with dE/dx calculations because their charge values were inaccurate. But the inaccurate charge values were being used in moment calculations when finding the cluster centroids and were thus causing inaccurate cluster positions to be reported. If the pad was bad because it was permanently off or reading low, the centroid was shifted away from that pad. If the pad was permanently stuck on or was reading high, the centroid was shifted toward that pad.

Options were considered to attempt gaussian fits to the data on good pads surrounding bad pads, but it was decided that simply throwing out clusters involving bad pads was a more efficient method of achieving improved data quality without sacrificing a significant amount of statistical power. Even this was simplistic and most of the problematic areas remained (see Fig. 7.9-2). The cluster finding algorithm was studied in detail and it was found that the determination of cluster peaks was faulty, and that the cluster finder was erroneously using half-clusters along boundaries where part of the cluster had been chopped off.

After these flaws were corrected, there were still a few areas of the TPC which showed problems (see Fig. 7.9-3). These were traced to errors in the distortion correction parameters for certain portions of the TPC. The final results are shown in Fig. 7.9-4 (note the scale change).

The problematic pads in the TPC found by this method closely matched the bad pads identified by the calibration parameter analysis program.[2]

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[1]TPC Reconstruction and Analysis Code, Gunther Roland, IKF Frankfurt.
[2]Pakkin Chan, *NA35 TPC Pad-to-Pad Relative Response Calibration*, Section 7.3 in this report.

Fig. 7.9-1. Original cluster position analysis.

Fig. 7.9-2. No bad pads used.

Fig. 7.9-3. Improved algorithms.

Fig. 7.9-4. Final results.

7.10 Higher moment sensitivity/insensitivity in multiparticle HBT interferometry

J.G. Cramer

It is well known that two-particle Bose-Einstein correlations using Hanbury-Brown-Twiss (HBT) interferometry with pions provide information on the 2nd moment (radius) of the source distribution producing the pions. Zajc[1] has presented a comparison of 2-particle and 3-particle HBT interferometry on the same system which seemed to show sensitivity to the 3rd moment (asymmetry) of the source distribution. He compared the analytical Fourier transforms producing 2-particle and 3-particle correlations for a hard-edged spherical source and a hard-edged hemispherical source. The hemisphere was adjusted in size so that the 2-particle correlations functions of sphere and hemisphere matched. Zajc's calculation indicated that the 3-particle correlation functions were markedly different, with the hemisphere correlation function a factor of two narrower in momentum space. This was taken as evidence that the high-order HBT correlations have sensitivity to the asymmetry of the source distribution.

We have attempted to reproduce this result for more general (and realistic) source distributions by performing multidimensional numerical Monte Carlo integration over the space-time coordinates of the source distribution $\rho(r_1,\vec{k}_1)$. The integral evaluated to obtain the *n*th order correlation function $C_n(\vec{k}_1,\ldots,\vec{k}_n)$ is

$$C_n(\vec{k}_1,\ldots,\vec{k}_n) = \int \rho(r_1,\vec{k}_1)d^4r_1 \ldots \int \rho(r_n,\vec{k}_n)d^4r_n |\psi(r_1,\ldots,r_n;\vec{k}_1,\ldots,\vec{k}_n)|^2$$

where the multiparticle wave function is

$$\psi(r_1,\ldots,r_n;\vec{k}_1,\ldots,\vec{k}_n) = \frac{1}{\sqrt{n!}}\sum_{i=1}^{n!}\psi(r_1,\vec{k}_{\pi_{1(i)}})\ldots\psi(r_n,\vec{k}_{\pi_{n(i)}})$$

and $\pi_j(i)$ is the *j*th element of the *i*th permutation of the sequence 1,2,3,...,*n*. The FORTRAN code written to do these calculations was inspired by the 2-particle HBT correlation program PIPICORR written by Scott Pratt. The present program, HBT_MC, is very general and is capable of evaluating up to *n*=6 correlation functions for bosons or fermions.

We have used this code to examine the following four source shapes: sharp-edge sphere, sharp-edge hemisphere, hollow spherical shell and Gaussian distribution, with each source adjusted in size so that it has the same momentum space width in its 2-particle correlation function. Fig. 7.10-1 shows an example of these calculations for 2- 3- and 4-particle correlation functions plotted against longitudinal invariant mass difference Q_{long}. As can be seen the 3- and 4-particle correlation functions are essentially identical, except for some small (~ 5%) "ringing" oscillations in the high-Q region of the distribution. We conclude that the higher-moment sensitivity that Zajc ascribed to multiparticle HBT correlations is absent.

This disappointing numerical result prompted us to re-examine the analytic Fourier transform relations that Zajc used to calculate the 3-particle correlations for a hemispherical source. On doing so, we discovered that including the momentum separations of particle pairs in cyclic order, i.e., $(k_1 - k_2, k_2 - k_3, k_3 - k_1)$, introduces a sign change from Zajc's result which cancels out the imaginary part of the Fourier transform, the part produced by the source asymmetry. In the properly symmetrized Fourier transform there is no remaining strong sensitivity to the 3rd (or higher) moments of the source distribution.

We note, however, that the small "ringing" oscillations mentioned above are different for each source shape and are produced by the higher source moments. It is possible that, with ultra-precise HBT

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[1]W.A. Zajc, "A Pedestrian's Guide to Interferometry" in the Proceedings of the NATO Advanced Study Institute on Particle Production in Highly Excited Matter, Lucca, Italy, Gutbrod and Rafelski, eds. (July, 1992).

correlation measurements performed with very high statistics, it may be possible to "decode" these oscillations and gain information about higher moments of the source. We are presently investigating this phenomenon.

Fig. 7.10-1. Calculation of two-particle (R2), three-particle (R3) and four-particle (R4) HBT correlation functions plotted as a function of longitudinal invariant mass differences (Q_{long}) using four different distribution shapes: sharp-edge sphere, sharp-edge hemisphere, spherical shell, and Gaussian. No significant shape-dependences are found in the correlation functions.

7.11 The onset of multiparticle effects in HBT interferometry

J. G. Cramer and V. Sacksteder IV

The particle momentum distribution analyzed in HBT is like the spatial distribution of an ordinary gas. There is a density, the "phase space density:" $n = N (R / (2\pi h))^3$, where N is the total number of like-charge pions produced by the collision and R is the source radius. In an ordinary gas, particle interactions are governed by a potential, which induces correlations between particle positions. Likewise, in HBT interferometry the particles exhibit boson interference, which can be characterized by an effective potential and induces correlations between particle momenta. The experimental method is to observe the momentum correlations, deduce the phase space density, and then find the source size from the above equation.

The deductive leap from the observed momentum correlations to the phase space density is nontrivial. At low densities, pairs of particles with similar momenta are rare, and triplets of such particles are much rarer; the interaction becomes effectively pairwise. The gas with a pairwise potential is the tried-and-true statistical mechanics problem; for low densities, the dependence of the correlation function on n is trivial. However, for higher phase space densities, the potential begins to manifest its true multiparticle nature and the traditional methods of statistical mechanics fail. Computation of the correlation function's behavior also becomes impossible, because the potential becomes impossible to compute.

Therefore, we would like to know if the planned HBT experiments will have the desired low phase space densities, or if they will exhibit the mathematical intractibility associated with high densities. This problem is nontrivial, because particle momenta are concentrated in certain regions of phase space, and also because its solution would involve calculating all of the effects of the potential and comparing these with the effects predicted by a pairwise interaction potential. We attacked this problem by ignoring the interaction potential entirely, and finding out when large numbers of particles are near two or more other particles. This method produces a lower limit to the critical density, since the potential is attractive.

Since the source size to be seen in future experiments is not precisely known, we give our results in terms of a critical source size. Because of our approximation, this is a lower limit on the permissible source size. Our results confirmed the experimental finding that present HBT experiments are in the low density regime. At RHIC, however, the source size must be considerably bigger: our lower bound is around 9 fm, and the real critical radius is probably more like 12 fm. At the ALICE experiment, our lower bound gives a source size around 12 fm, and the real result is likely around 16 or 17 fm.

7.12 Bin-free maximum likelihood analysis of HBT interferometry

J.G. Cramer, D. Ferenc,* M. Gazdzicki,* and V. Sacksteder IV

As mentioned last year,[1] the extraction of source radii from particle momentum data through HBT interferometry can be difficult if there are low statistics or large errors in momentum measurements. The traditional method, which involves binning of data, exacerbates the problem of low statistics and totally ignores the problem of experimental errors. Therefore, we are working on implementing another data analysis method, maximum likelihood analysis. It is not limited to the regime of high statistics, but extracts all the information available in the data. We have elaborated on the maximum likelihood method by including integrals which allow the method to adjust perfectly for experimental resolution. Using this method, we are able to extract as much information from an experiment with a momentum resolution that is known perfectly as we are from an experiment with exact momentum measurements. Both of these strengths should make maximum likelihood analysis invaluable in upcoming experiments.

We have implemented this method in C in order to test it on simulated data. Our program runs quickly, finishing in a minute or two. We will shortly complete a complete demonstration of this method's capabilities and a quantitative comparison of its results with the binned method's results.

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[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 47.

7.13 Simulation of the STAR TPC field cage

J.F. Amsbaugh and J.G. Cramer

Contribution to the drift distortions of a track in the STAR TPC due to the electric and magnetic fields should be kept to a value less than the charge position resolution. Given both this resolution and the magnetic field of the designed solenoid, the quality of the electric field is constrained. Consideration of the Langevin equation implies that the radial component of the electric field is the most important. Electric field quality is evaluated by the integral of the ratio of the radial to axial electric field over the track drift length. For simplicity, we use the maximum drift length at constant ρ. Evaluation of design choices, e.g., bias resistor tolerances or construction position accuracy, should consider the design goal that this integral be less than 0.7 mm.

The code RELAX[1] assumes azimuthal symmetry, then solves Laplace's equation in ρ and *z* for the potential, on an evenly spaced grid, using an over relaxation method. Irregular boundary points use interpolation of degree two. We have modified the code for off axis use, increased the grid density to better approximate the electrode geometry, and added code to evaluate the integral of merit. The input boundary is in the form of connected line segment coordinates and their voltages.

Two cylindrical field cages bound the drift region in the STAR TPC and define the electric field along the *z* axis. The high voltage plane is at the center (z=0) with charge collection pad planes at each end. Each field cage has 365 electrodes 1.0 cm wide with a 1.15 cm pitch. The inner cage has ρ=50 cm, the outer, ρ=200 cm. The HV plane to pad plane distance is 210 cm. The innermost pad edge is at ρ=59.43 cm, the outermost ρ=196.1 cm. We model half the TPC with 183 inner and 183 outer electrodes at a grid density of 10 per electrode pitch. This density matches the electrode gap to the grid spacing, for studying the field near the boundary.

Separate series resistor chains bias the electrodes of the inner and outer field cages from high voltage to ground, and we want to know the effect of resistor tolerances on field quality. The effect of leakage currents to ground through composite electrode support structures are also of interest. Sets of input boundary voltage values are calculated using a set of resistors normally distributed with σ's of 0.0%, 0.1%, 0.2%, 0.5%, 1.0% for each case. Input boundary sets were then calculated with the effect of leakage paths added to the resistor sets. We conclude from this study that 0.5% resistors or better are required for the STAR TPC. Also 10 GΩ leakage paths from each electrode to ground completely destroy field quality for 1 MΩ bias resistors.

The field cages are assembled from 6 inch wide Cu/Kapton strips with 13 photo etched electrodes on each. To simulate a placement error of 0.115 cm we shift the 13 central electrodes by one grid point in *z*. Equivalently, these 13 electrodes can be shifted in voltage, and both methods agree to 0.5%. Voltage shifts are continuous while the *z* positions can only be shifted by an integer number of grid points. Shifting a strip in the field cage only effects the field near the shift, thus the position error of 14 strips are independent. The limit on the integral of merit becomes 0.7 mm/$\sqrt{14}$ or 0.19 mm per strip shift. Preliminary results indicate that this corresponds to position errors of 0.36 mm. Electrode strip position error studies continue.

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[1]Written and supplied by John Southon, Tandem Accelerator Laboratory, McMaster University, Hamilton, Ontario, CANADA LS8 4K1.

7.14 Pattern recognition in the STAR SVT for high density events

J.G. Cramer, P. Jones,* D.J. Prindle and T.A. Trainor

We have developed a pattern recognition algorithm (Grouper) which is useful for finding tracks that originate near the primary vertex and pass through the STAR SVT. The Solenoidal Tracker At RHIC (STAR) is one of two large detectors which will be installed in RHIC at turn-on. RHIC is a heavy ion collider capable of storing beams ranging from protons at 300 GeV to Au at 100 GeV/A. [The physics program at RHIC will emphasize central Au-Au collisions.] The Silicon Vertex Tracker (SVT) is a detector component of STAR and consists of three 'cylinders' of silicon drift detectors surrounding the interaction point at radii ranging from five to 14 cm.

The Grouper groups SVT hits that are close to each other in $\phi - \theta$. Its efficiency for reconstructing central Au-Au events has been described previously.[1] In a typical central Au-Au collision simulated by Fritiof or Hijing only a few percent of the beam energy goes into particle production at mid-rapidity. Thus there is a concern that these event generators could grossly under-estimate the particle flux passing through our detectors, in which case our detectors might not be useful.

To test our SVT pattern recognition algorithm in higher density events we merged the output of a number of Hijing events, creating events that had one, two and four times the number of tracks compared to normal Hijing events. These were then processed through the simulated STAR detector using the GEANT Monte Carlo code and presented to the analysis modules as single large events. The SVT pattern recognition code, developed for single central Au-Au events, was used without modification (except for increasing a few array dimensions).

We plot the track finding efficiency in Fig. 7.14-1. We plot efficiency as a function of $p_\perp$ since the lower momentum tracks are harder to find due to increased curvature and increased multiple Coulomb scattering. We see that as the track density increases the high $p_\perp$ efficiency decreases slightly, and the low $p_\perp$ cutoff increases. It is clear that even for four times the predicted Hijing track densities we do well at finding tracks in the SVT. There are optimizations that can be done to make it even better for high track densities if that becomes necessary.

Fig. 7.14-1. Pattern recognition efficiency in STAR SVT. The vertical axis is the efficiency and the horizontal axis is $p_\perp$. The three panels are for one, two and four Hijing events merged together to simulate higher track densities.

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*Lawrence Berkeley Laboratory, Present address: University of Birmingham, England.

[1] Nuclear Physics Laboratory Annual Report. University of Washington (1993) p. 66.

7.15 Trigger overview

T. A. Trainor

During 1993 the STAR trigger system development has included detailed specification of hardware, development of trigger algorithms and elaboration and testing of the trigger simulation chain. Our work here has concentrated on the last two areas.

Fast inputs for the STAR trigger in the baseline detector configuration include charged particle multiplicity coverage over the pseudo rapidity range [-2,2] using a scintillator barrel (CTB) within the pseudo rapidity range [-1,1] and the TPC endcap wire chambers (MWC) in the ranges [-2,-1] and [1,2]. In addition there are fast scintillator vertex position detectors (VPD) and spectator calorimeters at very high pseudo rapidity.

There are four trigger levels spanning the time range from 100 ns (RHIC clock period) to 100 ms (taping bandwidth limit). Level 0 is based on a minimum bias condition, valid collision vertex and total multiplicity as a measure of collision centrality to determine whether to open the TPC gate grid and begin collecting deposited charge at 1 us. Level 1, based on coarse analysis of the 1-D multiplicity distribution, determines whether to begin to digitize the TPC and SVT charge distributions at 100 us. Level 2, based on fine analysis of the 1-D distribution, and possibly a coarse 2-D analysis of this distribution, decides whether to begin higher-level (level 3) analysis of tracking data at 10 ms. Level 3 uses fast-tracking algorithms to analyze a fraction of the digitized drift detector data and to determine whether to write to tape at 100 ms to 1 s.

We have developed here a system of powerful algorithms for the level 1 and level 2 trigger processes based on power spectrum analysis of charged-particle multiplicity distributions. This method promises to extract the maximum possible information from the multiplicity distribution for the purpose of determining quickly whether an event has unusual properties and should be processed in preference to 'standard' events. It is especially important to extract all available information because of the limited trigger detector complement and uncertainty at present as to the details of QGP formation and other high-energy-density QCD phenomena.

In addition to trigger algorithm formulation we have participated in establishment and testing of a trigger simulation chain including QCD collision event generators such as FRITIF, HIJET and HIJING, and the particle propagation Monte Carlo code GEANT using detailed trigger detector specifications. This chain must be examined carefully to determine both that the detectors have been modeled realistically, and to calibrate the trigger algorithms by modifying the event generator outputs in known ways.

7.16 Optimum bin structures for trigger detectors

T.A. Trainor

In many cases it is necessary to divide a continuous index manifold into bins in order to represent some phenomenon. This includes voltage sampling, vision, formation of opinion and counting of hits. Depending on circumstance there is often an optimum binning structure which minimizes some cost while maximizing extracted information.

For the purpose of trigger detector design for STAR I have considered the method of determining the optimum binning for a system consisting of nominally random hits on a manifold, with some modulation of the hit density. The modulation or signal containing the information is a function of the index manifold with some power spectrum and finite band width. The question to be answered is: for some total multiplicity distributed on the domain, and for some power distribution in the signal, what is the optimum number of bins on the manifold which does not lose information either by limiting the signal or adding excess Poisson noise? This has obvious application for triggering with a multiplicity detector.

The problem is represented archetypally by shot noise in electrical current signals. The term 'shot noise' evokes an analogy with shot falling on a metal plate (or rain on a tin roof). There is a complete analogy between this standard time-domain problem and the somewhat more general problem of Poisson noise in multiplicity distributions as considered above. The essential feature of these problems is that some signal is carried in the density distribution of hits on some continuous domain. In the case of shot noise as used in the electrical engineering field the distribution of electrons on a current-carrying conductor is represented in the time domain.

In the analysis of collision events the signal is a matter of speculation because of incomplete knowledge about QCD aspects of relativistic nuclear collisions. However, we can make some general arguments to estimate the form of the power spectrum for the likely signal in the multiplicity distribution. We can also determine the Poisson noise exactly, once the total multiplicity is specified, which again is estimated from models.

As a simple 1-D example, the STAR trigger detectors span a pseudo rapidity range [-2,2] or 4 units. Based on rather general kinematic arguments it is not expected that structures on a scale less than 1/3 unit will be important. This would indicate 3 x 4 = 12 bins as nearly optimum. But because of the symmetry of the power spectrum for real values of multiplicity one must add an additional factor of two (Nyquist criterion) to avoid aliasing. Thus, for the conditions given 24 bins will just admit the largest anticipated signal bandwidth. However, the optimum bin number is also contingent on comparison between the Poisson noise background determined only by the total multiplicity, and the true amplitude distribution in the signal power spectrum, which latter is presently a matter for conjecture. Therefore, one should attempt to provide a 24-bin detector with the understanding that further bandwidth limitation (bin summing) may be required if the multiplicity and/or the signal are lower than anticipated.

7.17 TPC high voltage control system

G. C. Harper and T. A. Trainor

The drift speed of electrons in the gas volume of a time projection chamber depends mainly on the gas temperature and composition which are subject to small variations during operation. Inference of the point of creation of charge by fast charged particles from a nuclear collision, and hence the track geometry, depends on accurate knowledge of the drift speed. It is therefore very important to maintain the electron drift speed as nearly constant as possible and at a known value. This can be achieved by creating a servo stabilization loop which has as input the periodically measured drift times of known populations of electrons and which in turn controls the TPC drift field high voltage to maintain this 'time of flight' at a constant value.

The STAR TPC field cage high voltage servo system consists of a correction signal derived from the time of flight of electrons photo ejected from the cathode (midplane HV membrane) of the TPC by periodic laser pulses. This is the known electron population. Each time-of-flight measurement represents a time sample of the effective drift speed (with some Poisson and other noise included).

At each sample time the drift speed is calculated from the drift time of the ejected electrons. An error signal update is derived from some linear combination of the present and previous samples. The weighted sample combination determines in part the transfer function of the regulation system. From the error signal a correction is made to the TPC HV. One wants to design a system which minimizes the drift speed noise consistent with the limitations of the fundamental processes involved.

The system will include a 100 kV TPC cathode power supply, a time digitizer, an EPICS VME-based control system and a SUN workstation. This system, in addition to the servo control capability, will also serve as the interface for the TPC high voltage system to the overall STAR slow controls system. A schematic of the system is shown in Fig. 7.17-1.

Fig. 7.17-1. STAR TPC HV control system.

7.16 Particle multiplicity power spectrum analysis

P.B. Cramer and T.A. Trainor

In previous work one of us (T.A.T.) developed the technique of power spectrum analysis of charged particle multiplicity distributions in order to provide model-independent sensitivity to departures from some nominal distribution or null hypothesis for triggering purposes. A one-dimensional version of the analysis was more recently applied to twenty HIJET events, of which ten were 'normal' events and ten were 'special' events to which were added one or two additional energy concentrations (van Hove 'plasma bubbles') at specific points in rapidity. The placements amounted to a total of 1-5 TeV at one or two rapidity points out of a total collision system energy of about 40 TeV at RHIC. We found a strong 2-D relationship between certain features of the power spectra and rapidity moments of the added energy distributions. These features (total power and phase) can be used to form a 'pattern space' in which there is excellent separation between normal and special events.

We show here the twenty events on a pattern space derived from aspects of the power spectrum. For comparison, I also show a representation of the special events in terms of moments of the added energies on rapidity. The results indicate that such analysis provides important, model-independent information on the nature of the QCD energy transport process in nucleus-nucleus collisions and may serve as a powerful trigger algorithm.

The quantities used here to define a pattern space are not exhaustive, and different pattern spaces or higher-dimensional spaces may be preferable. The details of the space are not as important as the degree of independence of the various defined quantities. As in the design of a polygraph one wants a number of independent degrees of freedom defining a space which can be explored by simulations or by reactions to known inputs (truths and falsehoods or known anomalies). Once the space is defined in this manner it can be used to select events in a relatively bias-free way.

We have also extended this work to two dimensions, mainly for application to jet/minijet analysis in the event of an electromagnetic calorimeter upgrade to the STAR baseline system. The intermediate two-dimensional autocorrelation in this analysis provides a convenient way to include kinematic cuts in the trigger. The power spectrum shows excellent sensitivity even to jet structures not visibly distinguishable from background.

We show the case of a simulated two-jet distribution at one sigma. Since this is a differential technique the power spectrum for a uniform or non-jet event would have a negligible power density distribution by comparison.

Fig. 7.16-1. Bubble moments and pattern space.

Fig. 7.16-2 Two jet 2-D simulation.

Fig. 7.16-3 2-D analysis of two-jet simulation

8. CLUSTER IMPACT PHENOMENA

8.1 Cluster impact fusion using D_2O ice targets

J.F. Liang, R. Vandenbosch and D.I. Will

A technique of making deuterated ice targets was developed to study the d-d nuclear fusion induced by the impact of cluster ions. The advantage of using ice targets is that they are more stable than the deuterated polyethylene targets, which were used in early experiments.[1] Recently, Bae *et al.* studied d-d fusion reactions with small H_2O clusters impacting deuterated ice targets.[2] They observed that the fusion yields increased with cluster sizes of n = 2 to 4. This disagrees with a theoretical calculation[3] which shows no enhancement in the fusion yields for small clusters. In this report, the results of studying d-d fusion induced by impacting oxygen clusters on heavy ice targets will be presented.

The ice target was made with a copper backing which has an area of 2.5 cm x 2.5 cm and thickness of 0.4 cm. The copper backing was cooled to 100 K in the target chamber under vacuum. The cooling of the target was achieved by attaching a 0.48 cm diameter copper rod to the copper backing and a liquid nitrogen dewar mounted on the top of the copper rod as shown in Fig. 8.1-1. When the copper backing was cold, it was inserted into an isolated chamber to get exposed to heavy water vapors for approximately ten minutes. The uniformity and thickness of the ice target was checked by measuring the d-d fusion yield using a 172.5 keV deuteron beam incident on different parts of the target.

The oxygen atomic and molecular anions were produced by the DEIS ion source. In this experiment, 172.5 keV O^- and 345 keV O_2^- (172.5 keV per O^-), respectively, beams were used. A 5.6 mm aperture was installed to collimate the beam. The size of the beam on the target was about 2 mm. The beam current was read from the target by a current integrator and monitored by an upstream beam scanner. In order to avoid melting the ice, the beam current was maintained at less than 18 enA. Additionally, the target position was changed by 3.2 mm every 10 minutes to vary the spot irradiated.

The d-d fusion events were measured by collecting the 3 MeV protons from $d(d,p)^3H$ in a 300 mm^2 surface barrier silicon detector which was placed 3 cm away from the center of the target. A diffusion pump was used to pump on the target chamber such that the vacuum was 10^{-6} Torr or better during the experiment.

The fusion yields induced by the two different beams were compared by the number of 3 MeV protons measured per incident cluster per Oxygen atom in the cluster. The results are $(3.92\pm0.06) \times 10^{-13}$ protons/Oxygen for 172.5 keV O^- and $(4.45\pm0.86) \times 10^{-13}$ protons/Oxygen for 345 keV O_2^-. No enhancement in the fusion yield induced by O_2^- was observed within the experimental uncertainties. Further studies using beams of larger oxygen clusters and water clusters are underway.

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[1] R. Vandenbosch, D. Ye, J. Neubauer, D. I. Will, and T. Trainor, Phys. Rev. A **46**, 5741 (1992).
[2] Y.K. Bae, R.J. Beuhler, Y.Y. Chu, G. Friedlander, and L. Friedman, Phys. Rev. A **48**, 4461 (1993).
[3] C. Carraro, B.Q. Chen, S. Schramm, and S.E. Koonin, Phys. Rev. A **42**, 1379 (1990).

Fig. 8.1-1. Apparatus for the ice target experiment.

8.2 Stopping powers of atoms and atomic clusters

F. Liang, S. Moskowitz, R. Vandenbosch and W. Weitkamp

Cluster impacts with solids are of increasing interest for a variety of reasons. Simulations[1] indicate that local densities exceed those achievable in a conventional high pressure apparatus. Such calculations also indicate that nuclear reaction rates can be increased in such an environment, although convincing experimental evidence for this is lacking. Relatively little information is available on the difference between the stopping powers for clusters and single atoms, an effect known as vicinage. The stopping power for molecular H_2 is about 20% higher than for atomic H at energies between 100 and 1,000 keV/atom, as is also the case for molecular O_2 compared to O at 2-3 MeV/atom.[2] For large C_n clusters (n = 13) at 1 keV/atom the opposite effect is predicted.[3] We have initiated a study of vicinage effects for carbon clusters losing energy in thin carbon foils. Thin carbon foils are inserted between a silicon surface barrier detector and an atomic or cluster beam from a Cs sputter source followed by an electrostatic accelerator. Our preliminary results are shown in Fig. 8.2-1. The absolute values of the atomic stopping powers are in reasonable agreement with the TRIM parameterization[4] and with the experimental results of Ormrod *et al.*[5] We plan to repeat and extend these measurements with a detector with a better response function in this energy domain.

Fig. 8.2-1. Atomic stopping powers measured for a carbon foil.

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[2]J.W. Tape *et al.*, Nucl. Instrum. Methods **132**, 75 (1976).
[3]V.I. Shulga, Nucl. Instrum. Methods B **58**, 422 (1991).
[4]J.F. Ziegler, J.P. Biersack, and U. Littmark "The Stopping and Range of Ions in Solids" Pergamon Press, New York, 1985.
[5]J.H. Ormrod and H.E. Duckworth, Can. J. Phys. **41**, 1424 (1963).

9. EXTERNAL USERS

9.1 Summary of single event effects testing by BPSRC

P.P. Majewski,* J.D. Ness,* E. Normand,* D.L. Oberg* and J.L. Wert*

The Boeing Physical Science Research Center (BPSRC) has conducted Single Event Effects (SEE) testing for the Space Station at the University of Washington Nuclear Physics Laboratory. The NASA/Boeing SEE test chamber, described previously,[1] was used in the dual configuration for tests using the superconducting LINAC booster. Part of the system was then transported to the Lawrence Berkeley Laboratory for use with their 88-inch cyclotron to gain access to high energy beams with ions heavier than nickel.

The remaining system at the NPL was modified to permit direct beam experiments. A perforated plate beam attenuator was designed to reduce the direct beam current to the level required for direct beam exposure. A scattering foil was then used to spread the beam. Tests indicated that the intensity and beam spread were adequate to test devices properly. With the present setup, the test system is ideal for testing power MOSFET's and has been used for this purpose on several occasions.

Several papers have been submitted to the 9th Single Event Effects Symposium as well as the 31st IEEE Nuclear and Space Radiation Effects Conference representing work done at the NPL and other facilities.

9.2 Radiation effects on opto-electronic devices

G.A. Geissinger† and E.W. Smith†

Improvements in opto-electronic devices for operation in radiation environments were suggested by previous experiments on optical materials performed last year with the University of Washington Van de Graaff accelerator.[2] In this year's experiments, specific optical components were subjected to a range of energies, particle types and total dose levels. These components were then used in various opto-electronic circuits in our lab at Ball Aerospace in order to evaluate the effect of radiation on the individual elements of a given design. With the results of such tests, it is possible to model the response of a given circuit design to the kind of radiation encountered by spacecraft in high or low altitude orbits or by sensors operating within a nuclear reactor.

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[1]University of Washington, Nuclear Physics Laboratory Annual Report (1993) p. 78.
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[2]University of Washington, Nuclear Physics Laboratory Annual Report (1993) p. 78.

9.3 Effects of fast neutrons on proportional drift tubes

W.M. Dougherty,* Z. Jin,* R.S. Terry,* W.G. Weitkamp and T.C. Zhao*

The University of Washington Physics Department Visual Techniques Lab was awarded prime responsibility for development of the Solenoid Detector Collaboration (SDC) muon detector of the Superconducting Super Collider detector system. One problem with that detector was that the neutron response of the detector was unknown. The neutron flux in SDC experiments was expected to be high. Monte Carlo studies indicated that at 10^{33}/cm^2/sec luminosity in the SDC detector, the neutron flux could have been as high as 10^3-10^4/cm^2/sec behind the calorimeter, which was to have been 10 nuclear absorption lengths thick where the central muon tracking chambers were located. The neutron flux was to have been one to two orders of magnitude higher in the forward region.

The basic tracking elements of the SDC muon detector were aluminum drift tubes with an inner diameter of 9 cm and a maximum length of 9 meters. A drift tube had two simple field shaping electrodes which were supported by extruded Noryl plastic insulators. An Ar-CO_2 gas mixture was used.

The neutrons which affect these muon drift tubes were expected to have a very broad energy spectrum. Because of the large drift tube cross section, the neutron hit rate per tube in the forward region and at certain locations of the central region was expected to be high. Neutrons which penetrate the drift tubes can interact with the chamber gas, aluminum wall and the Noryl insulator in several ways. The products of these interactions, recoil nuclei or secondary particles from a nuclear interaction, can produce signals in the proportional tubes. A fraction of the neutron induced signals will have amplitudes much larger than the signals produced by minimum ionizing particles. Background hits generated by neutrons can have a strong impact on the muon triggering and tracking.

The neutron response of these tubes was measured at the Nuclear Physics Laboratory. Neutrons were produced by a pulsed beam of deuterons (1 nsec pulses) on a beryllium target. The flux and energy spectra of these neutrons is well known[1] and the spectrum is similar to the higher energy part of the spectrum expected in the SDC detector. The neutron flux was monitored by a Bonner sphere and a 6 inch diameter plastic scintillator. The accompanying gamma flux was monitored by a 4x6 inch NaI scintillator. The effects of gamma rays and neutron reactions in the muon detector were separated by using time of flight techniques.

An array of short drift tubes was exposed to the neutron beam. The shape and pulse height spectrum of the signals produced by neutrons was studied. The intensity of the neutron beam could be adjusted by changing the deuteron beam current and by changing the relative position between the target and the drift tubes. The effect of different neutron background levels on charged particle tracking was investigated. The SDC muon drift tube gas mixture Ar-CO_2 was used in this study. For comparison, the same measurements were also made using an Ar-CH_4 gas mixture.

The results of this measurement indicate that the muon drift tube sensitivity is 10^{-3}/neutron.

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10. ELECTRONICS AND COMPUTER SYSTEMS

10.1 Electronic equipment

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

Projects undertaken by the electronics shop this year included the following:

a. An ion gauge translator was constructed which inputs two signals, the mantissa and exponent of a vacuum reading, and outputs a monotonic function readable by a single ADC. Two channels of translator were built.

b. A vertical slit control system for the Injector deck that provides independent control of the position of the top and bottom slits. The slit mechanism is coupled through a chain drive to a DC motor. A ten turn potentiometer coupled to the DC motor provides a voltage that is proportional to the slit position, This voltage is compared by a servo loop to the position setpoint voltage to control the slit position. Slit position can be set locally on the deck with a knob or remotely from the touch screen in the control room.

c. A log amp circuit was constructed for use with the Keithley digital picoammeter on the Injector deck. This provides a logarithmic output voltage to drive a chart recorder. Noise and offset voltage drift on the output of the Keithley limits the range provided by the log amp to less than four decades.

d. A microcomputer based controller system was designed, constructed, and installed in the tandem terminal as a part of the tandem upgrade (See Sections 11.3, 11.4 and 11.5).

e. We have changed the procedure for making circuit boards. We now use AUTOCAD to layout the circuit board, then plot this layout to a postscript file. We invert the video of this postscript file and use a Laser printer to print the negative on transparency material. This procedure gives a higher resolution and an easier to handle negative. We also changed to pre-sensitized circuit board material and a 1% sodium carbonate solution to develop this circuit board material. This change has decreased the amount of chemicals required to make a circuit board, decreased the amount of time to make a circuit board and has increased the quality and sharpness of the circuit board so that double sided circuit boards are as easy to make as a single sided board.

f. Construction of a 150 MHz preamplifier to replace a unit from one of the RF Power Labs 200 watt amplifiers that had burned up and was not repairable. A new circuit board was laid out and inductors and transformers constructed to replace non standard parts used in the original unit.

g. The Ortec 710 Quad 1-Kv Bias supply used in the Mass 8 apparatus was modified so that the output voltage ramps up slower without overshooting, when recovering from sparks on the output. A high voltage shutdown alarm was also constructed.

h. A vacuum sensor system to provide readout from four Moducell Model 325 pirani vacuum sensor/pressure switches. The meters can display actual pressure or the vacuum switch setpoint.

10.2 VAX-based acquisition systems

M.A. Howe, R.J. Seymour, D.W. Storm and T.A. Trainor

Our principal data acquisition system ("Quark") consists of a Digital VAXStation 3200/NTX running VMS v4.7a. We use VWS/UIS as the "windowing" software. The VAXstation supports a BiRa MBD-11 controlled CAMAC crate. The VAXStation's BA-23 cabinet is cabled into a BA-23 CC expansion cabinet, with a MDB DWQ11 Qbus to Unibus converter driving our old PDP 11/60's Unibus expansion bay. Our Qbus peripherals include a CMD CQD-220/TM SCSI adapter, a Seagate ST41650 1.38 gigabyte disk, a TTI CTS-8210 8mm tape drive, a DEC IEQ11 IEEE-488 bus controller, and a DEC DRV11-J. The Unibus bay contains a DR11-C, our Printronix lineprinter controller and a Unibus cable to the MBD-11.

This main CAMAC system contains interface modules for our dozen Tracor Northern TN-1213 ADCs. Those ADCs and other CAMAC modules are controlled by an in-house built coincidence interface, which includes routing-Or capabilities, and 32 10-digit 75 MHz scalers.

Additional CAMAC space is available for our LeCroy 2249s, 2228s and 2551s. We have two FERA 4300B ADCs, and two Phillips 7186 TDCs.

Our acquisition software is based upon TUNL's XSYS, with major modifications to their DISPLAY program.

We have two additional VAX-based acquisition systems. They run the same software as Quark. Each consists of a VAXstation 3200 with an Able Qniverter directly connecting to an MBD-11 with no Unibus "drawer" required. One has a 630 megabyte disk drive, and the other has two. They are both mounted in roll-around rack cabinets, and can be moved throughout the building as needed. Neither has the main system's complex external interfacing equipment.

The acquisition systems remained relatively stable throughout the year, with the primary software activity being minor performance enhancements and improvement of operator error messages. Many changes required by the migration of the analysis package to the Alpha (see next section) were folded back into the original source directories maintained on "Quark".

10.3 Analysis and support system developments

J.G. Cramer, M.A. Howe, R.J. Seymour, D.W. Storm and T.A. Trainor

Most of this year's analysis software activity was concentrated upon the migration of many of our packages to a Digital AXP 3000/400 (an "Alpha").

All of our offline analysis VAXes are running VMS v5.5-2. Five VAXstation 3100s and one VAXstation 3200 form a VAXCluster with the 150 megaHertz Alpha.

The 3000/400 has 96 megabytes of memory, two 1.0 gigabyte disks, a CDrom, a 19 inch color display, and occasional 8mm Exabyte tape drives attached to its external SCSI port. It is currently running OpenVMS v1.5. As members of the Digital's Campus Software License Grant program, we have implemented Digital's Fortran, C and C++ as its principal languages, and we have made heavy use of the DECMigrate package.

The migration of most Fortran and C packages was simple: recompile and relink. The expected speed improvements (roughly three times faster than the HP 9000/710s, and up to forty times faster than our VAXstations) were usually realized. Large Monte Carlo programs, such as Cascade, occasionally exhibited model-related performance variations as we exceeded the Alpha's cache sizes or sized data arrays in manners which "fought" its cache addressing methods. We're still tuning and adjusting programs to further improve their performance on the Alpha. One of the usual consequences of installing a faster machine is that people change their programs to stretch its capabilities. One user (J. Amsbaugh, see Section 7.13) now commonly runs a 100 megabyte virtual space model, with occasional runs requiring 300 megabytes of virtual space. Simply retuning for that application required that the system disk be cleaned and defragmented to allow creation of a 680,000 block pagefile.

Most of the XSYS analysis package simply moved to the Alpha via recompile and relink. Some of the shared COMMON areas had to be rearranged to provide quad-word alignment as required to allow the Alpha to run at full speed. The Alpha uses an 8192-byte "page" (as compared to the VAX's 512-byte "page"), and the shared-space "create and map" directives and XSYS's memory allocation routines had to be slightly modified to take that into account. Since VMS's mapping works with one physical page as the smallest quantum, the histogram allotment and placement routines were changed to interrogate the system for the page size, and then to choose mapping sizes based upon that.

On the VAXs we use VWS/UIS routines for our XSYS displays. That package has not been migrated by Digital to the Alpha platform. Therefore we modified our version of XSYS's display package to use DECWindows, Digital's implementation of X windows. All of the functionality of our VWS multi-window and mouse-interactive display has been achieved, despite X's greater layers of filtering between the program and the hardware interface. Digital's Migration package includes an Alpha cross-compiler for VAX Macro code. This allowed us to easily move some low-level VAX machine language routines. These were later recoded in higher level languages after the major packages were running and tested.

The final stage of XSYS migration is the rewriting of the Eval compiler to generate AXP instructions instead of VAX instructions. The initial syntax analyzer has been completed, the code generator is in process.

We still have our 8 megabyte VAX 11/780, with connections to thirty-odd local terminals. Our in-house VAX complement now includes the 11/780, four VAXstation 3100/30s, a VAXstation 3100/38, five VAXstation 3200s, and a VAXstation 2000. There are three additional 3200s serving the Nuclear Theory group. Three of the 3200s form the Online Acquisition systems described above. Another serves as the Linac's control and display system. Those four machines are all still running VMS v4.7a. TGV's Multinet provides our cluster with TCP/IP access to Internet. Our primary Internet address is npl.washington.edu (128.95.100.10). Bitnet access is via the campus central site's VAXes and IBM 3090 system.

We purchased a used VAXstation 3100/30 for use as an 19 inch color X terminal. It is being run with a Digital-supplied VAX Eln image for that purpose.

Our work with NA35, NA49 and STAR relies upon our two HP 9000/710s, running HP-UX v9.01. These are providing world-visible World Wide Web (WWW) service of programs and data related to those projects, as well as a growing library of other NPL documents, including our annual reports.

We provide some system management services for the Institute for Nuclear Theory. That remote site has three DECstation 5000/200's running Ultrix, each with 32 Mbytes of memory, color displays, a total of 5 gigabytes of disk, two 4mm DAT drives and a CDrom. These are currently being upgraded to three Alpha 3000/600s, two of which will become OpenVMS machines, and one shall be an OSF/1 platform. The Nuclear Theory division of the Physics department has installed two OpenVMS Alphas. Those two machines, and the management responsibility therefore, has been transferred to Physics.

11. VAN DE GRAAFF, SUPERCONDUCTING BOOSTER AND ION SOURCES

11.1 Van de Graaff accelerator operations and development

L.L. Geissel, G.C. Harper, M.A. Howe, C.E. Linder, A.M. Myers, T.D. Van Wechel and W.G. Weitkamp

The most significant upgrade of the tandem accelerator in the 29 years it has been operating has begun. As mentioned last year[1] we requested and obtained D.O.E. funding for installation of a pelletron charging system and a set of spiral inclined field beam tubes in the tandem.

The installation of the pelletron began in late November 1993. Two problems complicated this otherwise straight-forward installation. First, it was necessary to install new column resistors. There were three reasons for this: First, the pelletron manufacturer[2] only guarantees 250 μA of upcharge; we often run more than 300 μA for heavy ion beams. Replacing our 400 MΩ resistors with 800 MΩ resistors reduces the required upcharge and solves this problem. Second, our existing resistors[3] have been decreasing in value at a rate of 4.8 %/year, with the rms spread in values increasing by 3.6%/year. These changes are unacceptable. And third, other tandem labs have reported much improved stability for resistors shielded in metal tubes.[4] The design for the new column resistors is discussed in Section 11.2.

The second problem which complicated the installation of the pelletron was that the pelletron was to take space along the column occupied by six lucite rods used to control functions in the terminal. We replaced the lucite rod control system with an in-terminal computer. The pelletron installation also made it impossible to use our terminal ripple remover system.[5] A pelletron is supposed to deliver charge to the terminal much more evenly than a belt so we did not retain the terminal ripple remover. However, we did leave the capability in place to add the ripple remover later if needed. The computer installed in the terminal is described further in Sections 11.3, 11.4 and 11.5.

The accelerator was first run with the pelletron charging system in mid December, 1993. It was immediately clear that pelletron charging is superior to belt charging. Ripple on the beam decreased by an order of magnitude. The vertical jitter we had always observed on the beam leaving the tandem was gone. And, even after extended operation at high voltage, there was no sign that charge was being dumped onto the column as it had over a period of many years. (A number of times in the past we thought we had fixed that problem, but it always reappeared.)

Operating at high voltage with the computer in the terminal driven by a computer outside the tank made control of the tandem susceptible to transients caused by tank sparks. It was necessary to do some minor beefing up of terminal components. It was also necessary to carefully shield all electrical leads leaving the tank and to surround each lead with ferrite cores to reduce the transients to an acceptable level. The system now runs reliably; it is not fazed by 9 MV sparks.

The new spiral inclined field beam tubes were to have been shipped in December 1993, but the manufacturer[6] ran into problems with the electrode material and has delayed shipment by four months. The problem has been solved and test reports for the two completed tube sections are satisfactory.

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[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 86.
[2]National Electrostatics Corp., Middleton WI.
[3]Nuclear Physics Laboratory Annual Report, University of Washington (1992) p. 74.
[4]J.W. Noé, *Symposium of North Eastern Accelerator Personnel,* Notre Dame University, 1986, (World Scientific, 1987) p. 168.
[5]G.W. Roth and W.G. Weitkamp, Nucl. Instrum. Methods **115**, 501 (1974).
[6]High Voltage Engineering Europa B.V., Amersfoort, the Netherlands.

In addition to the tandem upgrade, we have been improving other aspects of the control system of the tandem as described in Section 11.5 and have been designing an ion source to be installed in the terminal of the tandem, described in Section 11.6.

During the year from March 1, 1993 to February 28, 1994 the tandem operated 3,782 hours with a belt and 565 hours with a pelletron, for a total of 4347 hours. Additional statistics of accelerator operations are given in Table 11.1-1.

Table 11.1-1. Tandem Accelerator Operations
March 1, 1993 to February 28, 1994

	Activity	Days Scheduled	Percent
A.	Nuclear Physics Research, Ion Sources Alone	12	3
B.	Nuclear Physics Research, Tandem Alone		
	Light Ions	87	23
	Heavy Ions	9	3
	Accelerator Mass Spectrometry	9	3
	Subtotal	105	29
C.	Nuclear Physics Research, Booster and Tandem Coupled		
	Light Ions	8	2
	Heavy Ions	71	20
	Subtotal	79	22
D.	Outside Users		
	University of Washington Physics Department	3	1
	Ball Aerospace Systems Group	6	2
	Boeing Company, Tandem Alone	1	<1
	Boeing Company, Tandem and Booster Coupled	2	<1
	Subtotal	12	3
E.	Other Operations		
	Tandem Development	71	20
	Tandem Maintenance	49	13
	Unscheduled Time	37	10
	Subtotal	157	43
	Total	365	100

11.2 New resistors for the tandem accelerator

L.L. Geissel, C.E. Linder and W.G. Weitkamp

Beginning in 1992, when a need for a new resistor design became apparent, we ran a series of tests on five brands of metal oxide high voltage resistors, all of which were specified for a maximum continuous operating voltage of at least 30 kV and a continuous power of a least 12 watts. We purchased 20 or more of each type and installed test assemblies in our accelerator. The assemblies consisted either of our standard long PVC tubes or metal tube shields of the type described below. The criteria for our test were: 1) the resistors should not change resistance during high voltage operations, 2) the mechanical tolerances should be appropriate for use in precision shield structures, 3) the resistor substrates should be sufficiently rugged to withstand assembly, installation and normal use and 4) the resistors should be economical.

EBG resistors[1] were judged to be the best overall with respect to these criteria. This brand has not, to our knowledge, been used in this application previously. Besides performing well and having good mechanical uniformity, EBG resistors are among the least expensive and the factory will deliver in 6 weeks, not the 12 weeks quoted by the other supplier. It is important to note that our testing was not exhaustive because of limitations in time and the availability of resistors, i.e. we did not test all resistors in all configurations.

We based our design of the tube and spark gap to protect the resistor on the Florida State University[2], Notre Dame[3] and Oak Ridge[4] designs. There are two resistors to a column plane. Each resistor is mounted horizontally inside a 1 inch OD metal tube. At the free end of the resistor, a disk is attached to the resistor, forming a spark gap with the end of the tube.

We have made three innovations in the design of the resistor mounting. First the resistors are connected together by #14 copper wire crimped into Mate-N-Lok pins. These pins have spring tabs which hold tightly in a small hole. The connector is easy to remove, cheap to make and reduces the number of screws which can fall into the column. The second innovation is to use a stainless steel spinning as half of the spark gap. This is lighter in weight than the disks used in other designs so it puts less stress on the resistor and is also cheaper to make. The third innovation is to use interior star lock washers to not only keep the parts from unscrewing but also to give a some adjustability to the alignment of the resistor.

Nearly all the parts for the required 800 resistor shields were made in our own shops; considerable effort was spent in devising jigs and tooling to make the construction of the parts as inexpensive but precise as possible. The resistors and shields were carefully assembled so as to maintain a spark gap of 0.100 ± 0.005 inch. Our calculations indicate that this gap gives protection comparable to the spark gaps on the column.

Half the resistors are mounted on the top of the column and half on the bottom. At the same time that we installed resistors, we polished the column end pieces (to which the resistor are attached) to minimize sharp points which could induce column sparks.

After one resistor connector failed because it was hit by a spark, we enclosed the connectors and connecting wire in a short piece of plastic tubing. No further failures have occurred.

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[1]EBG Inc., Camp Hill PA.

[2]K.R. Chapman, *Symposium of North Eastern Accelerator Personnel*, Kansas State University, 1990, (World Scientific, T.N. Tipping and R.D. Krause, eds., 1991) p.175.

[3]E. Berners, *Symposium of North Eastern Accelerator Personnel,* Chalk River, 1990, to be published.

[4]N. Jones and P.F. Pittner, Nucl. Instrum. Methods A **328,** 191 (1991).

11.3 Tandem terminal computer

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

The control scheme for the various tandem terminal functions has been changed from a set of lucite rods running the length of the column to a commercial microprocessor-based controller operating in the terminal. This has made it easier to accommodate the upgrade of our tandem to a pelletron charging system. The alternative to this would have been to move the lucite rods to some other location to make room for the pelletron, which would have involved drilling new holes in the tank and devising new linkages for the rods. We decided that this would be difficult to design, increase down time for the conversion, and leave us restricted to the limitations in flexibility inherent to the mechanical control rods.

The computer selected is the ControlNet*TM* device interface family system made by Group 3.[1] The hardware package consists of a small (13.9 cm by 7.6 cm by 12.8 cm) enclosure which accepts a processor board and three interface boards. Interface boards presently available from Group 3 include a single channel fast ADC/DAC with 16 bit resolution, a digital I/O board with 24 channels selectable as either input or output, an 8 channel ADC board, an 8 channel DAC board, and motor controller boards for either 4 DC motors or 4 stepping motors. Power for the computer and external devices is provided by a 28 VDC direct off-line switching power supply which will accept DC, 60 Hz AC or 400 Hz AC input power. This simplifies testing with the tank open because we can plug the computer into a 60 Hz source of power rather than start the chains to run the terminal alternators.

The processor board communicates with a loop controller board through a fiber optic link. The loop controller board fits into any IBM 386/486 or compatible computer. For the fiber optic link we used two strands of an inexpensive ($0.90 per foot),[2] unjacketed plastic fiber with optical properties matching those required by the controller. We chose unjacketed fibers because jacketed fibers exhibit tracking problems along the jacket-fiber interface where small voids can be left partially evacuated from tank pumping. We built a tank feed-through by epoxying two short strands of the fiber into a steel plug. The fibers and feed-through are connectored with Hewlett Packard HFBR series connectors to be compatible with the computer and loop controller.

The double shielding for the controller is our own design and consists of two welded aluminum enclosures electrically isolated from each other except for a single contact point. We chose the contact point to be a copper conduit which penetrates both boxes. The conduit has a length to diameter ratio greater than 10 and acts as a wave guide below cutoff. This greatly reduces any RF energy entering the boxes. This conduit is also used to route the fiber optics into the shielded enclosure. The inner enclosure was designed to be large enough to accommodate two Group 3 device interface modules. Electrical penetrations of the enclosures are through π-type feed-through filters. Additional filtering between the enclosures is by board mounted T-type filters which have a very high insertion loss. Transient suppressors are used to shunt transients to case ground at the outside of both enclosures. All of the filters and suppressors are commercially available and inexpensive. We have designed and manufactured small, modular printed circuit boards to house the filtering and suppression components and used the feed-through filters as a base for connectoring these boards. This produces an assembly which is modular, easily disassembled, and easily serviced.

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[1]Group 3, Auckland, New Zealand, and distributed by GMW Associates in Redwood City, CA.
[2]Edmund Scientific Company.

11.4 Tandem terminal controls

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

A microcomputer based controller was installed in the terminal of the tandem this year as a part of the tandem upgrade. This has provided the lab with a means to control and monitor terminal parameters that is both flexible and easy to expand. The controller is described in Section 11.3. The interface boards that we are using at this time are a 24 channel digital I/O board configured with 12 inputs and 12 outputs, an 8 channel analog input board, and a 4 channel DC motor controller board.

The computer presently controls the terminal vertical and horizontal steerers, the stripper foil mechanism, the gas stripper canal position, and the stripper canal gas delivery system. The terminal steering systems each consist of two high voltage power supply modules wired in opposition with AC inputs taken from the wiper of a variac. Rotation of each variac is controlled by a DC motor driven by the DC motor control board. The AC output of each variac is coupled through an isolation transformer, rectified, filtered and attenuated by a resistor divider to produce DC voltage inputs for the analog input board. This provides us with an indication of the relative steering settings.

The foil stripper mechanism is driven by a DC motor whose direction is controlled by a relay energized by the digital I/O board. The foil mechanism is started by a momentary signal from the digital I/O board and stopped after each revolution by the action of a microswitch dropping into a detent. The Gordo control computer (see Section 11.5) monitors the requested direction and the microswitch closure to keep a running foil count. We are presently ironing out a bug which occasionally causes an unrequested foil increment during the power up or power down sequence of the terminal computer.

The gas stripper canal is driven into and out of the beam with an existing 10 turn mechanical device. This is also turned with a DC motor. The in and out positions are indicated by microswitches connected to the digital I/O board. The travel is limited in both directions by another set of microswitches operated in parallel. The gas delivery system has a cutoff solenoid valve which is actuated by a 28 VDC line from the switching supply that powers the computer. The 28 VDC is switched by a relay driven by the digital I/O board. The motor controller board runs a DC motor which turns a precision needle leak valve. The motor also drives a 10 turn pot which, when connected to the precision 5 VDC supply from the motor control board, provides a readback of the valve position through one of the analog inputs.

To date, the computer has run with the terminal at 9.0 MV for eight hours of conditioning during which over 50 tank sparks were logged, after which we stopped counting. In addition, we have had experimental runs of over 250 hours duration with a terminal voltage of 8.5 MV to 9.0 MV during which many unlogged tank sparks were produced with no interruption of service. Each spark produces a momentary discontinuity in the terminal computer data stream, but a test performed using a photo flash gun near the unjacketed fiber optics gave a strong indication that this discontinuity is caused by the intense light disturbance produced by the spark rather than an electrical disturbance. The system logs an error in the data stream and then resumes operation with no apparent change in any of the terminal parameters.

11.5 Expansion of the tandem controller

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

Last year the 20 year old Texas Instrument 5TI-1000 Sequencer was replaced with a 80386 class PC running a control program written in C++. This controller (Gordo)[1] has the job of controlling the tandem vacuum system, the low energy buncher interlocks, the Faraday cup interlocks, some of the radiation safety system and this year was expanded to include the tandem terminal vertical and horizontal steereres, the gas stripper system and the foil stripper motor. Control is based on ladder diagrams that can be changed without stopping the controller. See Fig. 11.5-1 for a typical display screen.

Until this year the Gordo's I/O was strictly binary. With the addition of the tandem terminal microprocessor (see Section 11.3) the need arose to be able to process analog signals as well. Meters, bar graphs, digital displays, charts, motor controls, and DACS were added to the types of devices which can be displayed by Gordo. All analog display devices have upper and lower limits that can be used in interlock logic or alarms. The charts can sample either binary or analog information at user defined sampling rates. All device information is also forwarded to the Linac control system for display and interaction in the control room.

In the near future, the Gordo will be expanded to be able to access 16 more ADC channels. These channels will be used to provide interlocks for the tandem vacuum system and to echo the tandem vacuum information to the Linac control system.

Fig. 11.5-1. A typical Gordo display page.

[1]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 89.

11.6 Tandem terminal ion source

L. De Braeckeleer, G.C. Harper, D.W. Storm, K.B. Swartz and W.G. Weitkamp

Part of the mass-8 beta-decay experiment requires a high intensity beam of 3-Mev ^{3}He. The machine time that would be necessary for this part of the experiment using the existing alpha source is estimated to be several months. In order to reduce this time, a study was initiated last year to examine the possibility of installing an ion source capable of producing high intensity beams of $^3He^+$ and $^4He^+$ in the terminal of the Van de Graaff. An RF discharge source has been purchased from NEC and testing of the source began this year.

In the configuration anticipated for the experiment, the foil changer in the Van de Graaff terminal would be removed from its port, which is 60° off the beam axis, and in its place the RF discharge source would be installed. The beam from the ion source is to be deflected through 60° back onto the Van de Graaff beam axis by a permanent magnet assembly. Extraction and optical matching to the beam tube is to be provided by an einzel lens and extractor assembly designed and built last year.

Ion sources of this variety with a 2 mm diameter aluminum canal are specified to deliver 400 μamps $^1H^+$ and 200 μamps of $^4He^+$ with expected output current inversely proportional to $\sqrt{m}$ where m is the mass of the ion in AMU. The gas load produced is of the order of 1 to 2 mTorr-l/sec. We expect to use an extraction voltage of 18 kV.

We have purchased a source with a 1 mm diameter canal. In an RF discharge source with canal diameter, D, the gas flow is expected to be proportional to D^3 and the output current proportional to D^2. We expect a source with a 1 mm canal to deliver about 60 μamps of $^3He^+$ with a gas load of about 0.2 mTorr-l/sec. Initial tests have shown that the source with extractor assembly produces only 3 μamps of analyzed beam with a gas load of 1.8 mTorr-l/sec when optimized. An unanalyzed beam of about 40 μamps has been measured at the output of the extractor assembly while using ^{3}He gas, but only 30 μamps were observed while using hydrogen. The source was run with an unusually low probe voltage to maximize the beam. Maximum beam occurred for a probe setting of 1 kV where 6 kV was expected.

We have contacted the manufacturer and discussed this discrepancy. We provided them with a sketch of our extractor and einzel lens design and they recommended modifying the extraction electrode in a way that would increase the downstream aperture and eliminate a possible constriction in the beam. We were also advised to polish the surface of this electrode. These modifications have been carried out and further tests of the source will be performed this year.

11.7 Booster operations

J.F. Amsbaugh, D.T. Corcoran, G.C. Harper, M.A. Howe, D.W. Storm, D.I. Will and J.A. Wootress

During the period March 1, 1993 to February 28, 1994, the booster was operated for 81 days, as compared to 48 days in the same period a year earlier and to 71 days in the same period two years earlier. This increase is in spite of the shutdown of the tandem for installation of the new charging system and the associated terminal controls.

Beams ranged in mass from ^{1}H to ^{58}Ni, and included He, ^{12}C, $^{16,18}O$, ^{32}S, ^{40}Ca, and ^{58}Ni. This year there were more runs with ^{40}Ca than any other beam.

In March we opened cryostat #1 to replace a coupler and to replace the ion gauge filament. We warmed and vented cryostat #5 to replace the ion gauge filament, but as no other repairs were necessary it was not opened. For most of the year we were able to operate all but one of the 39 resonators. That one had a coupler stuck at strong coupling. As of February, however, two more couplers are stuck at strong coupling. These will be repaired during the next few months. We continue to operate the low beta resonators at an average field of 3.0 MV/m and the high beta ones at average of 2.4 MV/m. Most of these resonators were plated when the linac was being assembled over five years ago. Approximately four of them were replaced with replated ones three or four years ago.

Some of the Leybold-Hereaus turbomolecular pumps with greased steel bearings had exhibited mediocre lifetime and, when repaired, the lifetimes were often less than one thousand hours. The older of these pumps had run for 40 to 50 thousand hours, and were beginning to fail. Consequently we decided two years ago to replace all the pumps which used greased steel bearings. Some of those which operate with the rotation axis vertical and the bearings down have been replaced with units using oiled bearings. The remainder have been replaced with pumps using greased ceramic bearings. Either of these options has given good service, with no failures to date.

We had one compressor failure this year. At 56k hours the motor shorted. Our oldest compressor now has 63k hours.

11.8 Improvements to the linac control system

M.A. Howe

The Linac Control Computer had two hardware failures last year. Last summer the main code development hard drive began showing large numbers of errors and was replaced with a 250 MByte SCSI drive. In January, a fan in the expansion crate failed and caused the failure of the DHV11 serial interface board. That board is the interface to most of the satellite controllers and was replaced.

The Linac control system (CSX) was granted access to more tandem parameters with the addition of the Group 3 microcomputer in the terminal and the modifications to the Gordo controller (see Sections 11.4 and 11.5). A display page was added to provide an interface to the terminal vertical and horizontal steerers, the stripper foil mechanism, the gas stripper canal positioning motor, and the gas stripper cannel gas delivery system.

A vacuum recovery page was added to streamline the restart of the Linac vacuum system pumping stations. This page is an interface to a series of finite state machines that run three times per second and make state transitions based on the current state of each pumping station. Any or all stations can be selected on the touch screen for start up.

CSX can now make a postscript hard copy of most display pages in black and white or color. Pages that can not be hard copied are those that rely on 'tricks' such as off screen bitmaps that are used to speed up some of the complex display operations.

In the near future, the Cave 1 Gordo will be operational and will make available to CSX a large number of parameters from the cave vacuum systems and the radiation safety system.

11.9 Cryogenic operations

M.A. Howe, D.I. Will and J.A. Wootress

The booster linac is cooled by liquid helium which is thermally shielded by liquid nitrogen.[1] A Koch Process Systems, Inc, 2830S Helium Refrigerator[2] continuously reliquifies helium purchased as bulk gas. Helium usage of 223,100 SCF in 1993 increased 102% from that in earlier years.[3] Extensive sniffing with a helium leak detector revealed three major helium loss sites. Two were on RS Screw Compressor[2] skid 2 (subsequent to failure and replacement of the pump core), and these were readily resealed. The third and largest loss site has been traced to the warm nitrogen gas exhaust from the refrigerator's liquid nitrogen precool system. This precool system consists of the following items listed in order from inlet to outlet: an inlet solenoid valve controlled by a liquid level sensor in a liquid nitrogen phase-separator pot (E-12), a two-passage aluminum plate-fin heat exchanger (HX-1B, in parallel with E-12) which dumps heat from warm supply-pressure helium to boiling liquid nitrogen, a safety relief line and valve, a three-passage aluminum plate-fin heat exchanger (HX-1) transferring heat from warm supply-pressure helium gas to cold return-pressure helium gas and/or nitrogen vapor, and an exhaust check valve. The leakage of 4 scfm helium must occur in one or both heat exchangers (HX-1 and/or HX-1B). With warm nitrogen gas introduced into the pressure relief line between HX-1 and HX-1B and with both inlet and exhaust open to atmosphere, all the leaking helium appeared at the inlet port (on the upstream arm including only HX-1B). The exhaust stream (from the downstream arm including HX-1) showed a helium concentration essentially the same as that in the prepure nitrogen gas flowing into the pressure relief line. Helium flows passively through HX-1B whenever the refrigerator is in use, but only initial precool of the refrigerator during startup (a twice yearly occurence here) requires active heat transfer from HX-1B.[4] The temporary (and perhaps semi-permanent) solution to this helium leakage has been to seal off the liquid nitrogen precool system at its inlet and outlet (when the precool is not in use). Thus sealed the system pressurizes with helium to the supply pressure of ≈ 250.[5] On the inlet line a 300 psig working pressure globe-pattern pneumatic inlet valve followed by a check valve replaces the original low pressure inlet solenoid valve. On the relief line a 300 psig safety relief replaces the original low pressure relief. On the exhaust line a larger flow capacity 300 psig safety relief valve and a ball valve with a microswitch sensing the fully open position have been added upstream of the existing exhaust check valve. The pneumatic inlet valve power is enabled only when the outlet ball valve microswitch indicates fully open.

A second[6] RS Screw Compressor failed during 1993 when its motor windings shorted phase-to-phase. A replacement pump core was installed successfully and is now running designated as RS-2a. This table shows screw compressor history here as of 1994 March 14:

Item	Total	1993	Status	Maintenance
RS-1	62,933 hours	8339 hours	running	replaced charcoal, oil
RS-2	55,958 hours	5117 hours	phases shorted	core removed 1993
RS-2a	3682 hours	2444 hours	installed 1993, running	new charcoal, oil
RS-3	22,752 hours	0 hours	shorted to ground	core removed 1990
RS-3a	32,008 hours	8387 hours	running since 1990	replaced charcoal, oil

[1]In 1993, shielding consumed 226,100 gallons of liquid nitrogen, an amount similar to previous years.
[2]A trademark of Process Systems International, Inc.
[3]Nuclear Physics Laboratory Annual Report, University of Washington (1993) p. 88; (1992) p. 84.
[4]Cooling capacity of 500 watts at 4 K *without* liquid nitrogen exceeds quiescent heat influx of ~100 watts plus maximum rf power input of ~350 watts.
[5]The working pressure of the liquid nitrogen precool system, 300 psig, is adequate for this purpose.
[6]Nuclear Physics Laboratory Annual Report, University of Washington (1991) p. 78.

12. NUCLEAR PHYSICS LABORATORY PERSONNEL

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[7]No longer associated with NPL.

13. DEGREE GRANTED, ACADEMIC YEAR, 1993-1994:

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"The astrophysical p wave S-factor of $^{12}C(\alpha,\gamma)^{16}O$ from the beta-delayed alpha-particle emission of ^{16}N," Z. Zhao, R.H. France III, M. Gai, E.L. Wilds, submitted to Phys. Rev. C.

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"^{14}C AMS dating of pollen from lake sediment and peat samples for paleoclimatic studies," T.A. Brown, G.W. Farwell and P.M. Grootes, 6th Internat. Conf. on Accelerator Mass Spectrometry. Sept 27-Oct. 1, 1993, Australian National University, Canberra, Australia and University of Sydney, Sydney, Australia.

"The extraction and ^{14}C AMS dating of pollen from lake sediment and peat samples for paleoclimatic studies," T.A. Brown, G.W. Farwell and P.M. Grootes, presented at the First Annual PALE (Paleoclimate from Arctic lakes and Estuaries) Research Meeting, Feb. 3-4, 1994, Boulder, Colorado, published internally by PALE for NSF.

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Invited Lectures on Fusion and Fission, Japan Winter School Nuclear Physics, 1993, R. Vandenbosch.

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"Measurement of weak induced currents in mass 8 nuclei," L. De Braeckeleer, invited paper APS spring Meeting, 1994.

"Spin induced shape transitions in Cu compound nuclei," Z. Drebi, K.A. Snover, A.W. Charlop, M.S. Kaplan, D.P. Wells and D. Ye, talk APS Spring Meeting at Crystal City, VA, 1994.

"Measurement of $\beta - \alpha$ angular correlation in ^{8}Li," E.G. Adelberger, J.F. Amsbaugh, L. De Braeckeleer, P. Magnus,D. Markoff, D. Storm, H.E. Swanson, K. Swartz,, D. Wright and Z Zhao, talk APS Spring Meeting at Crystal City, VA, 1994.

"D-D fusion induced by oxygen atoms and clusters impacting D_2O ice targets," F. Liang and R. Vandenbosch, talk APS Spring Meeting at Crystal City, VA, 1994.

"The astrophysical S-factor of $^{12}C(\alpha,\gamma)^{16}O$ reaction from the beta-delayed alpha-particle emission of ^{16}N," Z. Zhao, invited talk APS Spring Meeting at Crystal City, VA, 1994.

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