3.0 NUCLEUS-NUCLEUS REACTIONS

3.1 The giant-dipole resonance in hot Sn nuclei

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We have recently completed new measurements of ^{18}O + ^{100}Mo reactions, from E(^{18}O) = 125 to 217 MeV bombarding energy, in order to better determine the width evolution of the hot GDR versus excitation energy in near Sn compound nuclei. In making these measurements, we used our new setup with three large NaI spectrometers described in the 1997 Annual Report.[1] At these relatively high bombarding energies preequilibrium effects become increasingly important. To address this concern we first measured light charged particle emission and deduced the effect of preequilibrium energy and mass loss prior to compound nucleus decay. We find that approximately 20% of the full fusion excitation energy and several mass units are lost due to preequilibrium emission for bombarding energies as low as 11 MeV/nucleon.[2] The heavy residues resulting from fusionlike (complete + incomplete) events were also measured in order to help determine the initial compound nucleus formation cross section. This quantity is necessary to extract the giant-dipole strengths.

Using our array of three large NaI spectrometers along with a γ-ray multiplicity array, we have measured the γ-ray strength functions and angular distributions at five bombarding energies. The angular distributions permit a direct separation of the statistical GDR component from the bremsstrahlung due to the different rest frames for γ-ray emission. We therefore determine the bremsstrahlung yield underlying the GDR component without the uncertainty introduced by a bremsstrahlung extrapolation from higher energies. To analyze measured GDR data we perform a simultaneous fit of statistical emission summed with bremsstrahlung to both the measured γ-ray strength function and the $a_1(E_\gamma)$ coefficient determined from the angular distributions. In our analysis we account for the important dynamical effects of preequilibrium and bremsstrahlung in an effort to determine reliably the evolution of the GDR parameters and in particular the giant-dipole width versus E^*.

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[1] Nuclear Physics Laboratory Annual Report, University of Washington (1997) pp. 57-58.

[2] M.P. Kelly *et al*., Phys. Rev. C **56**, 3201 (1997).

3.2 Anomalous fission fragment anisotropies: quasifission or slow K-equilibration?

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There has been a persistent puzzle about the behavior of experimental fission fragment anisotropies in heavy ion induced reactions near the Coulomb barrier. As the bombarding energy decreases the anisotropy starts to rise rather than to continue to decrease with decreasing initial angular momentum as expected from a transition state statistical model. Recently it has been proposed that the origin of this discrepancy is the competition between quasifission and fusion-fission for collisions with the tips of prolate deformed nuclei.[3,4] A consequence of this suggestion is that nucleon emission leading to evaporation residues should be suppressed when quasifission is important.

To test this idea we have measured the yield of the 4n evaporation residue for the ^{12}C + ^{236}U reaction at near-barrier energies where the anisotropy changes from normal to anomalous. We have measured the evaporation residue yield of 20-minute ^{244}Cf by an activation technique. A thin Al foil is placed downstream to catch the recoiling residues. After a bombardment of about 40 minutes the catcher foil is rotated to a position in front of a surface barrier detector and the alpha activity is followed for several half-lives. The excitation function we have obtained is shown in Fig. 3.2-1. The full curve shows an excitation function calculated with the statistical model code PACE2,[5] with a normalization based on scaling of the liquid drop model fission barrier to approximately reproduce the evaporation residue yield at the higher energies where the quasifission contribution is expected to be small. It is seen that the experimental evaporation yield at lower energies, where the anisotropy becomes anomalous, is consistent with fusion fission. Also shown is a curve making the assumption that all collisions corresponding to an angle between the beam axis and the target nucleus symmetry axis of less than 30 degrees lead to quasifission. At low beam energies most of the collisions are with the tips due to the lower Coulomb barrier for such orientations. Hinde *et al.*[1,2] suggested that for the ^{16}O + ^{238}U reaction the critical angle was 35 degrees. This assumption is inconsistent with our observed evaporation residue yields at low energies. The observation of the expected amount of evaporation residues for fusion reactions is consistent with formation of a compound nucleus with most of its degrees of freedom equilibrated, but with a lifetime too short for full equilibration of the K (projection of angular momentum on the nuclear symmetry axis) degree of freedom.

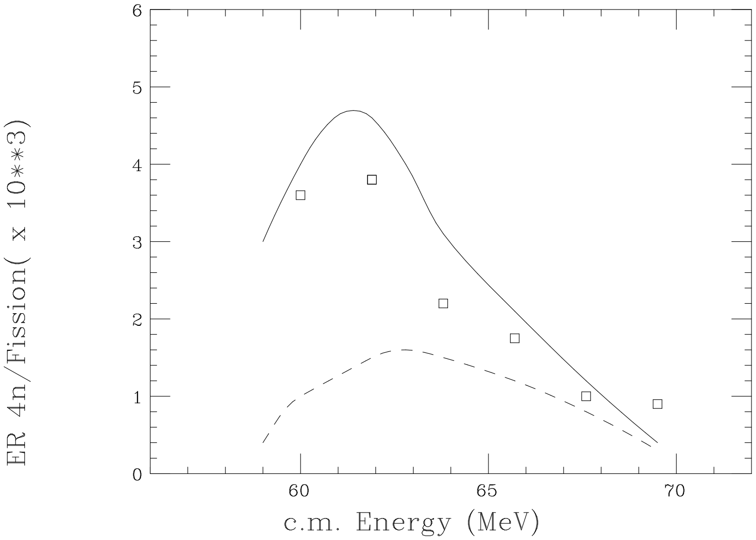

Fig. 3.2-1. The ratio of the 4n channel evaporation residue yield to the fission cross section as a function of bombarding energy in the center of mass. The circles represent the experimental data and the full curve represents a standard statistical model calculation. The dashed curve represents the result expected when interactions with the tips of the nucleus result in quasifission.

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[3] D.J. Hinde *et al.*, Phys. Rev. Lett. **74**, 1295 (1995).

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[5] A. Gavron, Phys. Rev. C **21**, 230 (1980).

3.3 Why the standard methods of calculating fission rates are flawed at high spin

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The methods presently used to calculate fission rates fail to correctly take into account the rotational degrees of freedom of compound nuclei rotating in 3 dimensions. The equations used by others do not describe the full fission decay width, but the fission decay width for a system with fixed spin, K, about the symmetry/fission axis. The fission barrier heights, B_f, and the potential curvatures, ω_{eq} and ω_{sp}, should all be considered functions of K, and the fact that K is not a constant of the motion of the system needs to be taken into account before a correct expression for the fission decay width can be determined. This problem is easily overcome by labeling states by their orientation in space in addition to their shape and collective momentum/kinetic energy. By assuming axially symmetric shapes, the sum over all possible orientations in space can be obtained by summing over all possible K from K =-J to J, where J is the total spin and K is the projection of J onto the symmetry axis of the system. The Bohr-Wheeler fission decay width then becomes

$$\Gamma_f^{BW} = \frac{\Sigma_K P(K)\Gamma_f^{BW}(K)}{\Sigma_K P(K)}, \tag{1}$$

where $\Gamma_f^{BW}(K)$ is the Bohr-Wheeler decay width as a function of K

$$\Gamma_f^{BW}(K) = \frac{\hbar\omega_{eq}}{2\pi}\exp\left(\frac{-B_f}{T}\right) \tag{2}$$

and P(K) is the probability that the system is in a given K state

$$P(K) = \frac{T}{\hbar\omega_{eq}}\exp\left(\frac{-V_{eq}}{T}\right). \tag{3}$$

V_{eq} is the sum of the Coulomb, nuclear and rotational energies at the equilibrium position as a function of K.

The latest version of the statistical model code, JOANNE4, calculates fission decay widths using Eq. (1). In Fig. 3.3-1 JOANNE4 calculations (solid lines) are compared to measured pre-scission neutron multiplicities, ν_{pre}. A parameter which controls the temperature dependence of the potential energy surfaces was adjusted such that the measured evaporation residue and fission cross sections are reproduced. The JOANNE4 model calculations give a reasonable reproduction of the ν_{pre} data for the three O-induced reactions considered here. The dashed lines show 'standard model' calculations,[6,7] which fail to reproduce the ν_{pre} data.

From the JOANNE4 calculations presented here it is concluded that in O-induced fusion-fission reactions, with initial excitation energies $\lesssim$80 MeV, the ν_{pre} data are consistent with the fission of fully equilibrated systems and that the collective motion in the fission degree of freedom is not necessarily strongly overdamped, in contradiction with the conclusions drawn by others.

Many previously deduced properties of the viscosity of nuclear matter should be viewed with caution. The large volume of heavy-ion induced fission data measured over the past decade, with the aim of deducing the properties of nuclear viscosity, needs to be reanalyzed using the concepts discussed here.

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[6] D.J. Hinde *et al.*, Nucl. Phys. A **452**, 550 (1986).

[7] D.J. Hofman *et al.*, Phys. Rev. C **51**, 2597 (1995).

[3] H. Rossner *et al.*, Phys. Rev. C **45**, 719 (1992).

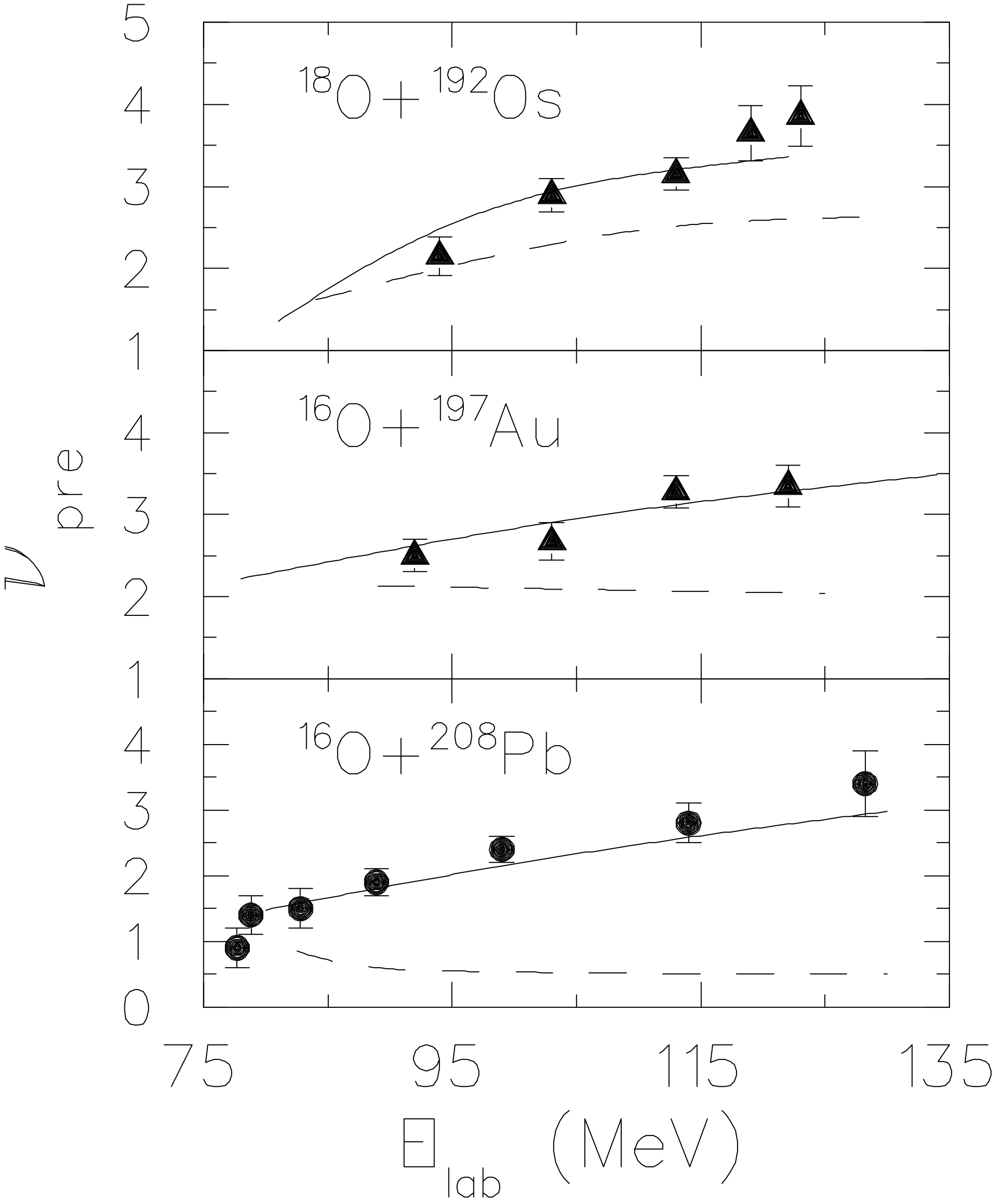

Fig. 3.3-1. Pre-scission neutron multiplicities, ν_{pre}, as a function of the projectile energy for three O-induced reactions. The triangles and circles show the data of Ref. 1 and Ref. 3, respectively. The dashed lines show 'standard model' calculations.[1,2] The solid lines show calculations of ν_{pre} obtained using Joanne4 with no dynamical fission delay time.

3.4 Light-charged particles from fusion-evaporation in the $^{19}F + ^{180}Ta$ system

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Lately, our investigations of large-scale nuclear shape changes have focused on the $^{19}F + ^{181}Ta \rightarrow ^{200}Pb$ system. In this past year we have conducted a systematic exploration of both the fusion-fission and the fusion-evaporation channels. Light-charged particles (p's, d's and α particles) in coincidence with evaporation residues were measured at E_{lab}=121, 154 and 195 MeV with the aim of determining the Fermi-gas level density parameter. As described in an earlier report,[8] we are investigating the conclusion made by Fabris *et al.*[9] (based on α particle results from the same system) that the level density parameter decreases dramatically from A/8.3 (MeV^{-1}) at a thermal excitation energy of U=20 MeV to A/12 (MeV^{-1}) at U=100 MeV.

In our current experiment light-charged particles (LCP) were detected at θ_{lab}=120° and 160°. Although the analysis is still in progress, the resulting proton and α particle center-of-mass spectra appear identical to those that we have measured previously.[1] More extensive simulations, to account for the efficiency of the deflector plate setup, will be necessary to determine the LCP multiplicities. The LCP angular distribution information will be used as an additional check of the statistical model simulations and as an aid in the evaluation of any pre-equilibrium particle emission contribution to the data.

The greatly improved statistics of our current results enable detailed comparisons with various statistical model predictions. Preliminary calculations with JOANNE[10] reproduce, with slight reductions in the optical model emission barrier heights, the α particle spectra at E_{lab}=154 and 195 MeV using constant level density parameters of A/11 (MeV^{-1}) and A/12 (MeV^{-1}), respectively. As suggested by recent theoretical discussions,[11,12] an equally good description of such particle emission spectra can be made using a level density parameter that varies smoothly with excitation energy from ~A/8(MeV^{-1}) at U=0 MeV to some minimum value, a_{min}~A/(9-15???) (MeV^{-1}), at the highest compound nucleus excitation energy. In such calculations, the range over which the continuously varying level density parameter needs to vary is much less than when fixed excitation energy independent values are used at each bombarding energy. In fact, our previous results at E_{lab}=150 and 190 MeV, while reproduced with constant level density parameters similar to those needed at E_{lab}=154 and 195 MeV, were consistent also with calculations using a level density parameter with a modest dependence on excitation energy. Specifically, a linear decrease from A/8.1 (MeV^{-1}) at U=0 MeV to A/9.2 (MeV^{-1}) at U=100 MeV was sufficient to describe the observed spectra. In any case, the need for the strong excitation energy dependence of the Fermi-gas level density parameter as proposed by Fabris *et al.* is not indicated by any of our results.

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[*] Present address: Los Alamos National Laboratory, Los Alamos, NM.

[8] Nuclear Physics Laboratory Annual Report, University of Washington (1996) p. 30.

[9] D. Fabris *et al.*, Phys. Rev. C **50**, R1261 (1994).

[10] J. P. Lestone, Nucl. Phys. A **559**, 277 (1993).

[11] S. Shlomo and J.B. Natowitz, Phys. Rev. C **44**, 2878 (1991).

[12] J.P. Lestone, Phys. Rev. C **52**, 1118 (1995).

3.5 ^{19}F + ^{181}Ta: Fission fragment and evaporation residue measurements

A.L. Caraley and J.P. Lestone[*]

Angular distributions of evaporation residues and of fission fragments, along with fission fragment folding angle distributions, have been measured at E_{lab}=121, 135, 150, 164, 180, 188 and 195 MeV. As well as extending earlier such measurements by Hinde *et al.*,[13] the fission and residue results provide supplementary information for the statistical model calculations used in the level density investigation.

At all beam energies, the fission fragment angular distributions and the folding angle distributions are compatible with fission following complete fusion. At 121 MeV the fission cross section is in agreement with that measured previously by Hinde *et al*. In addition, the cross sections at the higher beam energies are consistent with expectations that the fission channel should comprise the majority of the fusion cross section in this energy regime for this system. The measured evaporation residue angular distributions are well reproduced by statistical-model-based simulations. The shapes of the distributions are dominated by target effects and are not particularly sensitive to the choice of level density parameter used in the simulations. A nominal value of A/11 (MeV^{-1}) reproduces the measured residue angular distributions at all seven beam energies.

The evaporation residue cross section measured at 121 MeV is also in agreement with that measured by Hinde *et al.* However, standard statistical model calculations (i.e., JOANNE,[14] CASCADE[15]) fail to reproduce the yields at the higher beam energies. The measured cross sections remain at ~400mb from 121 to 195 MeV, while the calculated values drop by approximately a factor of 2 over the same energy range. However, the overall shapes of the residue velocity distributions are consistent with statistical model predictions made assuming complete fusion. Even at E_{lab}=195 MeV, the amount of any incomplete fusion contamination is estimated to be less than 5%. Thus, incomplete fusion is not considered to be responsible for the observed “excess” residue cross sections at any of the beam energies.

Excess residue cross sections have been observed in only a few other systems: ^{16}O + ^{208}Pb, ^{32}S + ^{184}W, and ^{58}Ni + ^{112}Sn.[16,17,18] Interpretations of these results have focused primarily on the role of nuclear viscosity in the decay of the compound nuclei formed in these reactions and have led to estimates of the magnitude of the nuclear viscosity coefficient, γ.[19,20] However, the K-state model presented by Lestone [see Sec. 3.3] reproduces successfully the measured residue cross sections, as well as the pre-scission neutron multiplicities, for the ^{16}O + ^{208}Pb system without the need for any viscosity. A preliminary calculation, using this K-state model, for the ^{19}F + ^{181}Ta system is also successful in reproducing the observed residue cross sections. In the future, it would be interesting to conduct a systematic measurement of residue cross sections formed by many different reactions to explore further the role of K-states in the competition between residue formation and fission.

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[*] Present address: Los Alamos National Laboratory, Los Alamos, NM.

[13] D. J. Hinde *et al.*, Nucl. Phys. A **385**, 109 (1982).

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[15] F. Pühlhofer, Nucl. Phys. A **280**, 267 (1977).

[16] K.-T. Brinkmann *et al*., Phys. Rev. C **50**, 309 (1994).

[17] B. B. Back *et al*., “Studies of Fission Hindrance in Hot Nuclei,” *International Workshop on Physics with Recoil Separators and Detector Arrays*, New Delhi, India, Jan. 1995.

[18] A. L. Caraley, SUNY Stony Brook Ph.D. thesis, unpublished (1997).

[19] D. J. Hofman *et al.*, Phys. Rev. C **51**, 2597 (1995).

[20] A. L. Caraley *et al.*, in preparation.

3.6 Angular distributions of fission fragments from ^{40}Ca + ^{192}Os, ^{nat}Ir, ^{194}Pt and ^{197}Au

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We have measured the angular distributions of fission fragments from the ^{40}Ca + ^{192}Os, ^{nat}Ir, ^{194}Pt and ^{197}Au reactions. A considerable change in the nuclear shape occurs in these reactions when the projectile plus target system changes into two nearly equally sized fission fragments. The details of this shape change might affect these four reactions and influence the angular distribution of fission fragments. The aim of the experiment was to look for a dependence of the fission fragment anisotropy on the shape of the ground state target nucleus. ^{192}Os is prolate with β_2=0.165; ^{194}Pt and ^{197}Au are oblate with β_2's of –0.143 and –0.10, respectively. The shape of Ir nuclei is unclear but they are expected to have an absolute deformation significantly less than the other three target nuclei involved in the study.

The measured fission fragment anisotropies from three reactions, ^{40}Ca +Ir, Pt and Au, are in agreement with each other when compared at the same center-of-mass energy relative to the fusion barrier. However, the ^{40}Ca + (prolate) ^{192}Os reaction has a significantly higher fission fragment anisotropy, relative to the other three reactions, at sub-barrier energies. Further work needs to be done to confirm this interesting possible dependence of fission fragment anisotropies on the shape of the target nuclei. All four reactions mentioned need to be restudied with longer (higher statistics) experimental runs. In addition, reactions involving more highly deformed prolate targets like W (β_2~0.23) and Hf (β_2~0.28) need to be explored.

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