INVESTIGATIONS OF NUCLEAR STRUCTURE AND
NUCLEAR REACTIONS
INDUCED BY COMPLEX PROJECTILES

Progress Report for the Period
September 1, 1989 – August 31, 1990
for
Department of Energy Grant DE-FG02-88ER-40406

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I. OVERVIEW

The research program of our group covers four areas of nuclear physics: (1) selected studies of the structure of nuclei at high angular momentum, (2) properties of nuclei at high excitations and angular momentum, (3) mechanisms of heavy-ion induced reactions from energies near or below the Coulomb barrier up to intermediate energies reaching ~ 100 MeV/nucleon, and (4) development and use of novel techniques and instrumentation addressing the needs of areas (1), (2) and (3) in unique ways.

Significant progress has been made in all the areas of our research program during the past year. The lists of publications and invited talks are given in Chapter V. In the past 3 years, 7 letters have been published and 1 submitted for publication, 15 full papers were published and 3 were submitted for publication, and 11 publications of invited talks appeared in conference proceedings.

In the following, we highlight our accomplishments and advances in the four main areas of our effort. In the first area, we concentrated on structure of nuclei in the mass 80 region with emphasis in searching for predicted superdeformed structures in the $Z = 38$, $N = 44$ region. We believe that we have indications from E_γ - E_γ correlations of a ridge that may be associated with the predicted superdeformation in ^{82}Sr . A search for the predicted discrete superdeformed band in ^{82}Sr is in progress. These studies were made possible by the channel selecting power of the Dwarf Ball and Wall system. The details of this work are given in sections IIA1 and IIA2 of this report.

In the second area we include a broad range of properties of hot, rapidly rotating nuclei. The question of nuclear shapes as a function of temperature and spin is one of the main topics of interest. Here, we understand that there are two probes that provide shape information. The first one uses the decay of the giant dipole resonance (GDR) built on excited states, and the second one uses the α -particle emission from excited compound nuclei as the probe.

Our group has concentrated on the development and understanding the α emission as a probe of deformation of excited nuclei. In particular, emission of subbarrier particles along the short or long axis of a deformed prolate nucleus is reflected in a decrease or increase of yield along these directions. We have made major progress in this effort and have completed a systematic study of the effect of deformation on the subbarrier portion of the α spectra. We studied a variety of systems from ^{110}Sn to ^{170}Yb . We have measured experimentally and interpreted theoretically spectra and angular distributions with respect to the spin direction using a statistical model formalism that incorporates deformation effects. We have concluded that for the heavier (rare earth) systems there are deformations that increase with spin. In contrast for the lighter ($Z = 50$) systems the data could be explained without invoking deformation. For the intermediate ^{138}Nd system, small deformations were required. Thus, the subbarrier α -emission is a good probe for nuclear deformation for hot nuclei in rare earth or heavier systems. It is important that the average α multiplicity be smaller than unity for the probe to be effective. This work is discussed in detail in sections IIA3 and IIA4 of the report.

On a related topic we searched for the possible influence of nuclear deformation on proton evaporation spectra in the hope that they might have an influence on the population of superdeformed bands. To our surprise, we found large shifts in the proton spectra when different rotational bands are populated by the (^{34}S , $2p2n$) reaction leading to ^{82}Sr . These shifts are too large to be due to deformation. We interpreted them to be associated with near yrast to near yrast proton emission that preferentially populates the yrast band at high spin. A detailed discussion is given in section IIA5. We have also demonstrated, based on statistical model calculations, that deformation effects are not easily observable in the subbarrier region of the channel selected proton spectra when nuclei in the $A = 82$ or $A = 133$ regions are populated (See section IIA6).

At somewhat higher temperatures (2-3 MeV) we have studied nuclear shapes by measuring the shape of the GDR. A dramatic narrowing of the GDR was observed with a distinct transition towards an oblate shape. Details are given in section IIA7.

We have utilized incomplete fusion reactions to produce nuclei with even higher temperatures (3-6 MeV). We have made careful analysis of light-charged particle energy spectra in order to determine the nuclear level density at high excitations. These studies are important because they reflect both the effect of the surface diffuseness and of the variation of the nucleon effective mass with temperature. Our findings are summarized in section IIC3.

In the third area of reaction mechanisms we have made substantial progress both on our studies of fusion reactions near the barrier and of incomplete fusion and fragmentation reactions in the 10-65 MeV/u region.

On the problem of subbarrier fusion we have measured cross sections and spin distributions in the fusion of $^{64}\text{Ni} + ^{100}\text{Mo}$ and $^{16}\text{O} + ^{148}\text{Sm}$. At the lowest bombarding energies, σ_ℓ extends to higher ℓ values than do predictions of barrier penetration models that include coupling of principal elastic channels (see section IIB1).

In fusion reactions near the barrier that involve symmetric and asymmetric entrance channels, we have observed dramatically different shapes of the GDR spectra between compound nuclei decaying via states with the same spin. The effect is present in $^{164}\text{Yb}^*$ compound nuclei but it is very strong in the decay of $^{160}\text{Er}^*$ nuclei both produced at the same excitation energy in ^{16}O and in ^{64}Ni bombardments. The shapes of the GDR from the asymmetric channel are well understood, but those from the symmetric channel have a large excess of high energy γ -rays and do not resemble the shapes expected for large prolate or oblate deformations. Further work is needed to explain these results (section IIB2).

In incomplete fusion reactions with asymmetric entrance channels, a portion of the projectile and its momentum are transferred to the target creating an evaporation residue with varying amounts of linear momentum and excitation energy. The remaining part of the projectile escapes with an unknown excitation and then decays before reaching the detectors. In another scenario, the projectile may fragment first, then one of the pieces is captured by the target and the remaining fragments reach the detectors. The detailed understanding of these mechanisms, as manifested by the linear momentum transfer, the

angular momentum transfer, and the excitation energy sharing between the primary reaction products, is the central theme of our studies of incomplete fusion reactions. We limited ourselves to asymmetric entrance channels, to mainly nonfissile targets and projectile energies in the range 10-25 MeV/u. We exploited two complementary powerful approaches, the first involves detection of the ER and the coincident emissions, while the second utilizes 4π detection of all the projectile-like or intermediate mass fragments and their coincident light particles.

For the reactions of 25 MeV/u $^{28}\text{Si} + ^{100}\text{Mo}$ we decomposed the incomplete fusion ER velocity distribution into 26 different highly fragmented channels and correlated their yield with the incomplete fusion and projectile fragmentation Coulomb corrected Q-values. Both correlations are equally good. We concluded that these two mechanisms cannot be distinguished from such correlations alone and that dynamical effects must be considered. We further made a complete reconstruction of the linear momentum and excitation energy imparted to the ER. The excitation energy increases monotonically with momentum transfer and this allows preparation and selection of hot nuclei for study with known excitation energy (sections IIC1, IIC2).

A major advance in our investigations of all reaction mechanisms came after the calibration of the light output of the Dwarf system [CsI(Tl) detectors for intermediate mass fragments up to $Z = 23$ and energies from 1-30 MeV/u] (see section IIB1). The analysis of many experiments involving intermediate mass fragment production really bloomed after this.

The complementary studies of incomplete fusion with the 4π detection of all emitted light ions and IMF's involved the reaction of 25 MeV/u $^{16}\text{O} + ^{159}\text{Tb}$, $^{28}\text{Si} + ^{100}\text{Mo}$, and 19 MeV/u $^{48}\text{Ti} + ^{93}\text{Nb}$. We have demonstrated that the relation between target excitation and linear momentum transfer can be determined as a function of the degree of fragmentation of the primary projectile-like fragment. From this, a detailed measurement of the excitation energy sharing will be obtained (section IIC5). Comparisons between the three different reactions are forthcoming.

At higher energies, we have studied the characteristics of heavy-ion collisions of 45 MeV/u reactions of ^{84}Kr with a variety of targets. Correlations between IMF and LCP multiplicities were obtained. We are currently examining the global event characteristics in terms of planarity and sphericity of the events in order to see whether we have evidence for complete disassembly of the composite system at these incident energies.

We have also been analyzing two experiments in which the hard photon production at high energies is studied as a function of the LCP and IMF multiplicities.

We have made substantial improvements both on the Dwarf Ball and Wall detectors and on the associated electronics. These improvements will permit a substantial increase in the possible counting rates of the Dwarf system and will permit the use of our present electronics in running the new highly segmented forward hodoscope presently under construction named the "MiniNose". The latter device will augment the capabilities of the MSU Miniball and will provide us with more reliable data on the production of IMF's at the highest MSU energies for the heaviest projectiles.

We have made considerable progress in the development, improvement and adoption of many theoretical codes, related to the modeling of the experimental results that we have. We also made improvements both in the hardware and software capabilities of our computer system.

II. SCIENTIFIC RESULTS

IIA. NUCLEAR STRUCTURE STUDIES

During the past year we have carried out a few selected spectroscopic investigations using discrete γ -ray spectrometry. Special emphasis was given to investigations relating to the properties of nuclei in extreme states of deformation, angular momentum and excitation energy. Superdeformed band structures have been found by many groups in a number of nuclei in the Ce, Dy and the Hg isotopes and significant progress has been made in understanding these structures. However, superdeformed bands have been predicted to exist in the mass 80 region and their observation is crucial in understanding the relative importance of the deformation driving forces.

In this case, the strong, short-range, attractive nuclear interaction maximizes the number of neighboring nucleons and leads to spherical nuclei. On the other hand, the electrostatic repulsion between the protons promotes nonspherical shapes and leads to fission for the heaviest systems. The existence of shell corrections creates a low density of single particle states with stronger binding which stabilizes large deformations. These shell effects were used by Strutinski to explain fission isomers and predict the existence of superdeformed structures at low spin 25 years ago. Finally, the centrifugal distortion arising from the large rotational frequencies at high spins increases the stability of the rapidly rotating deformed nuclei. In ^{152}Dy the centrifugal stabilization nearly compensates for the decrease in electrostatic energy relative to the actinides and leads to a superdeformed structure in ^{152}Dy .

For the lighter systems in the mass 80 region, the deformation-driving electrostatic repulsion is further substantially decreased and it is very important to establish whether the centrifugal distortion can stabilize the structure and lead to superdeformation.

In our experiments the Dwarf Ball + Wall system provides the much needed channel selection and helps overcome several technical difficulties associated with the observation of such structures in neutron deficient nuclei far from stability. We have used this device in two experiments to look for superdeformed structures in ^{82}Sr (see section IIA1 below).

In addition we have been interested in the use of emission of light charged particles as a probe of nuclear deformation at high spin and excitation. In particular we have explored the influences of deformation on the subbarrier portion of the α and proton evaporation spectra. It was hoped that this may provide a better understanding of the mechanism that leads to the population of superdeformed states.

IIA1. Search for Superdeformed Shapes in the Mass $A \simeq 80$ Region - D.W. Stracener, D.G. Sarantites, N.G. Nicolis, A. Chbihi, T.M. Semkow, V. Abenante [WU], C. Baktash, G. Garcia-Bermudez, I.Y. Lee, N.R. Johnson, F.K. McGowan, M.L. Halbert, D.C. Hensley [ORNL],

Cranked shell model calculations have for many years predicted that shell corrections can stabilize superdeformed shapes at high spins in some nuclei. Specifically, these calculations point to a number of nuclei around ^{146}Gd and ^{80}Sr as the best candidates for the observation of superdeformed structures.¹⁻³ Inspired by these predictions, several groups

have been studying nuclei in the $A \simeq 150$ region in search of evidence for the existence of these highly collective states. In these studies, the general line of approach is to look for the presence of a ridge-valley structure in the two-dimensional $E\gamma$ - $E\gamma$ correlation maps which signifies the existence of collective rotational bands. From the width of the valley, one infers the moment of inertia and thus, indirectly, the deformation associated with such a collective band. Indeed, two early experiments⁴ have revealed the presence of correlated γ -rays in ^{152}Dy . The deduced moment of inertia is very close to the theoretically predicted value. Pursuing their search, the Daresbury group has recently traced the origin of the observed ridge structure in ^{152}Dy to a discrete superdeformed band which extends up to spin $I \simeq 60$.⁵ Since then, many other superdeformed structures have been identified.^{6,7}

As mentioned above, superdeformed bands are predicted to exist also in the mass $A \simeq 80$ region. Figure IIA1.1 shows the single-particle levels in this region as a function of the quadrupole deformation β_2 . In an extensive set of calculations, Nazarewicz *et al.*³ conclude that many of these gaps survive at high rotational frequencies. The $N = 44$ gap, in particular, is predicted to give rise to strongly collective yrast states for spins $I \geq 30$. Good candidates for these bands are ^{84}Zr ($Z = 40$, $N = 44$), or ^{82}Sr with $Z = 38$, $N = 44$), which was selected in two experiments for investigation.

Figure IIA1.1 Single-particle levels in the mass $A \simeq 80$ region as a function of quadrupole deformation β_2 . Particle numbers giving rise to a large gap are indicated in circles. (From Ref. 3.)

One major difficulty in the spectroscopic study of the $A \simeq 80$ nuclei is the fractionation of their yield due to charged-particle emission. While yield fractionation is a minor difficulty in most routine spectroscopic studies, it becomes a major problem in this region when a weak ridge structure in one channel may be easily masked or washed out by contaminations from other channels. Unfortunately, no long-lived isomers are known or expected to exist in the nuclei of interest in the $A \simeq 80$ region that could be used for channel tagging. In the first experiment we have employed the reaction $^{52}\text{Cr}(^{34}\text{S}, 2p2n)$ at 130 MeV to populate the high-spin states in ^{82}Sr . In a second experiment we used the reaction $^{60}\text{Ni}(^{26}\text{Mg}, 2p2n)^{82}\text{Sr}$ at 110 MeV. The detection system consisted of the ORNL Compton-Suppression Spectrometer System (18 Ge detectors), the Spin Spectrometer, and the 4π CsI Dwarf Ball in the first experiment and both the Dwarf Ball and Dwarf Wall in the second one. The analysis of the first experiment has been completed and the second one is being analyzed by Dan Stracener as part of his Ph.D. thesis work.

Figure IIA1.2. Partial Level Scheme for ^{82}Sr .

In the off-line analysis of the first experiment, we generated a 3000×3000 -channel $\gamma - \gamma$ coincidence matrix subject to the requirements that: (1) the Dwarf Ball detects at least one proton; and (2) the total coincidence fold from the Spin Spectrometer should exceed a minimum value of $k = 7$. These conditions resulted in spectra that were dominated by γ -rays from ^{82}Sr . Figure IIA1.2 shows a partial level scheme for ^{82}Sr , which was constructed using the above data. In addition to establishing two new bands, we have extended four of the previously known⁸ bands to spins that range from 20 to $27\hbar$. Together, they represent the most extensive high-spin band structure obtained in a medium-heavy nucleus. The detailed interpretation of the band structures in ^{82}Sr in terms of the cranked shell model are discussed in the next section.

Figure IIA1.3. $E\gamma$ - $E\gamma$ two-dimensional map for ^{82}Sr from the proton-gated data. The energy dispersion is 8 keV/channel.

In searching for superdeformed states, we have closely examined the above two-dimensional $\gamma - \gamma$ coincidence matrix. Figure IIA1.3 shows this matrix following subtraction of the uncorrelated background of coincidence γ -rays. A weak ridge-valley structure is evident in this figure. The first ridges are separated by approximately 300 keV, which implies a dynamic moment of inertia of $2\mathfrak{I}^{(2)}/\hbar^2 \simeq 53 \text{ MeV}^{-1}$. This corresponds to a deformation of $\beta \simeq 0.5$ for a deformed rigid rotor. Lack of sufficient statistics has so far prevented us from establishing a SD discrete band that is associated with this ridge-valley structure. The second experiment has provided better statistics (3×10^8 events) and smaller Doppler broadening due to detector size since a more asymmetric reaction was used. The Doppler broadening arising from sidekick that the recoils receive, due to particle emission, will be corrected on an event-by-event basis to improve further the energy resolution.

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8. P.S. Haskins *et al.* *Phys. Rev.*, **C32**, 1897 (1985).

IIA2. Shape Coexistence and Disappearance of Pairing Correlations in ^{82}Sr . C. Baktash⁽¹⁾, G. Garcia-Bermudez^(1,2), D.G. Sarantites⁽³⁾, W. Nazarewicz⁽⁴⁾, V. Abenante⁽³⁾, J.R. Beene⁽¹⁾, H.C. Griffin⁽⁵⁾, M.L. Halbert⁽¹⁾, D.C. Hensley⁽¹⁾, N.R. Johnson⁽¹⁾, I.Y. Lee⁽¹⁾, F.K. McGowan⁽¹⁾, M.A. Riley^(1,2), D.W. Stracener⁽³⁾, T.M. Semkow⁽³⁾, and A. Virtanen^(1,2)
 (1) ORNL, (2) JHIR, (3) WU, (4) Warsaw, (5) UM

Below we give the abstract of a paper submitted to *Physics Letters* (Appendix A) summarizing the interpretation of the band structures observed in ^{82}Sr .

ABSTRACT: Extensive high-spin band structures in ^{82}Sr were established using proton- γ - γ coincidence selection techniques. On the basis of Woods-Saxon cranking calculations with pairing, four of these bands are interpreted to have prolate, triaxial, oblate, or triaxial shapes. Pairing correlations are predicted to be very weak at high spins in this nucleus, and calculations with no static pairing successfully reproduce the experimentally observed crossing frequencies and alignments despite the fact that none of the bands displays a rigid-rotor behavior. It is concluded that the observation of rigid-rotor behavior is neither necessary nor sufficient for the disappearance of static pairing in nuclei.

IIA3. Deformation Effects in the Compound Nucleus Decay Using the Spin Alignment Method. - N.G. Nicolis, D.G. Sarantites, L.A. Adler, F.A. Dilmanian, K. Honkanen*, Z. Majka, L.G. Sobotka, Z. Li, T.M. Semkow [WU], J.R. Beene, M.L. Halbert, D.C. Hensley [ORNL], J.B. Natowitz, R.P. Schmitt, D. Fabris, G. Nebbia and G. Mouchaty [TAMU]

During the past several years we have been exploring in some detail the usefulness of the emission of subbarrier α particles from compound nuclei as a probe of nuclear deformation of the hot highly rotating nuclei. Two aspects of the subbarrier emission have been examined: (1) the energy spectra of the emitted particles, and (2) the angular distributions of the α -particles with respect to the spin direction as a function of α -energy.

The detailed analysis and the results have been published in a comprehensive article (Appendix B) and have been presented in several invited talks (Appendix C: Invited talk at the *International Conference on the Spectroscopy of Heavy Nuclei*, Crete, June, 1989; Appendix D: Invited talk at the ACS Symposium on *The Spectroscopy of Exotic Nuclei*, Miami Beach, Sept. 1989; Appendix E: Invited talk at the *Nuclear Structure in the Nineties* conference, Oak Ridge, April, 1990; Appendix F: Invited talk at the Zakopane School of Physics, Zakopane, Poland, May 1990).

We have examined five different compound systems at the following indicated excitation energies and ℓ_{crit} values: ^{110}Sn (94 MeV, 70 $\hbar$), ^{114}Sn (79 MeV, 65 $\hbar$), ^{138}Nd (82 MeV, 79 $\hbar$),

^{164}Yb (67 MeV, $7\frac{1}{2}\hbar$) and ^{170}Yb (135 MeV, $77\hbar$). Our analysis of the data is based on detailed statistical model calculations using the code PACEX, which is an improved version with extensive modifications and revisions of the code PACE2S. These are described in section IIIB4. Our results can be briefly summarized as follows:

- (1) For the rare earth systems ^{164}Yb and ^{170}Yb , we find that subbarrier spectra and angular distributions support the presence of deformation effects. The deformation is increasing with spin and corresponds to $\beta = 0.15$ at spin $\simeq 35\hbar$ and $\beta = 0.35$ at spin $\simeq 64\hbar$. These deformations are consistent with the analysis of Aleshin¹ (See Fig. IIA3.2) who, using our angular distribution data, finds comparable deformations to those that we deduced from the analysis of the α spectra.

Figure IIA3.1. Angular correlation coefficients A_2^I as a function of α -particle energy ϵ for emission from ^{170}Yb (left frame) and ^{164}Yb (right frame) at $E^* = 135$ MeV, and $E^* = 72$ MeV, respectively for $I = 64\hbar$. The open circles are from our data (Appendix B). The bold lines are for a spherical calculation and the dashed line is for a deformed calculation with $\beta = 0.38$ assuming a multistep α emission. The thin solid line is for a single step emission with an unrealistically large deformation.

- (2) For the intermediate mass system ^{138}Nd smaller deformations are needed to interpret the subbarrier yield of the α spectra.
- (3) For the lighter systems $^{110,114}\text{Sn}$, we find no need to introduce deformation in order to explain the data.
- (4) The subbarrier α emission is a good probe for deformation for excited compound heavy systems (in the rare earth region). The emission of subbarrier α particles occurs, according to simulations, from lower excitations than those of the initial compound nucleus. For this reason it is important that the α -particle multiplicity be lower than unity. Thus competing channels involving different Z values are not present and this permits the subbarrier yield to be governed by the deformation in a few excited isotopes of the initial compound system that participate in the de-excitation process.
- (5) In our analyses we have introduced the deformation primarily into the penetrability term as described in Appendix B. However, the level densities employed in our analyses

include deformation effects to the extent that they are present in the experimental yrast lines used for the deformed nuclei present in the de-excitation sequence.

* Deceased.

1. V.P. Aleshin, J. Phys. G:Nucl. Phys., 16, 853 (1990).

IIA4. Utility of α Emission as a Probe of Nuclear Shape in Medium and Light Mass Systems. – N.G. Nicolis and D.G. Sarantites.

Recent analyses of α -particle spectra from the light compound $^{60}\text{Ni}^*$ system at moderately high excitation (formed in the reaction of 120 MeV ^{30}Si with ^{30}Si) have shown large discrepancies between the experimental and calculated spectra.¹ A good description was proposed¹ with the emission barrier significantly reduced and the entrance channel critical angular momentum decreased below the experimental value. Such modifications in the parameters of the statistical model calculations suggested emission from an oblate shape with an axis ratio $\approx 3:1$.¹ The analysis leading to such unrealistic deformations was criticized by Nicolis and Sarantites² (see Appendix G for a reprint) who showed that standard analysis with a realistic set of parameters for the evaporation code PACEX reproduced the data of Ref. 1 without the need to introduce deformation. The reason for the originally reported surprisingly large deformations has been traced in the use of simplistic models in the interpretation of the complex decay sequences in these light systems.³ Critical analyses³ of α spectra from systems with $A \leq 75$ did not show the need for introducing deformation, although for some of the systems, deformation effects were introduced by increasing the level density at high spins by lowering the yrast line and using the Fermi gas level density expression.³ It has also been pointed out³ that in the lighter systems where many charged particles are emitted the observed spectra are sums of spectra from a large number of decay sequences and this perhaps masks the effect of deformation on the observed spectra. For heavier systems and for moderate excitation energies where the α -particle multiplicity is of the order of 1 or less, these difficulties are avoided.

In conclusion, although α -emission below the evaporation barrier is a good probe for nuclear shapes of hot, rapidly rotating nuclei in the rare earth region, for lighter systems in the Sn region or other systems lighter than Sn, this probe is not sensitive to the deformation.

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IIA5. Nuclear Structure Effects in Proton Evaporation Spectra – D.W. Stracener, D.G. Sarantites, N.G. Nicolis, V. Abenante, Z. Majka, T.M. Semkow [WU], C. Baktash, G. Garcia-Bermudez, J.R. Beene, N.R. Johnson, M.J. Halbert, D.C. Hensley, F.K. McGown, I.Y. Lee, M.A. Riley, A. Virtanen [ORNL], H.C. Griffin [U. Mich].

The study of rotational motion of highly deformed nuclei is perhaps one of the best ways of studying collective motion in small quantal many-body systems. A striking example is the recent observation of superdeformed bands corresponding to a spheroidal shape

with axis ratio 2:1.¹ Theoretical calculations that explain these shapes predict structures with even larger deformations ('hyperdeformed' nuclei with axis ratio $\sim 3:1$) for rare earth nuclei at high spins that are near the stability limit against fission.² Since superdeformed nuclei are produced in very small yields in heavy-ion fusion reactions, it is important to understand the mechanisms for populating these local minima, if ways of producing hyperdeformed nuclei are to be found. The mechanism for their population may be determined by the influence of the potential energy minima on the particle-emission probabilities via enhanced level densities and penetrabilities. These influences will be more pronounced for charged-particle emission, because evaporation below the emission barrier is expected to be enhanced by deformation or structural effects.^{3,4} Therefore, charged particle emission may play an important role in the population of hyperdeformed nuclei. In particular, proton emission may be more important than α emission, since protons do not remove much angular momentum and can probe deformation with minimal perturbation of the emitting system.

We addressed experimentally the issue of structural influences on the shapes of the proton spectra. We have observed for the first time a strong dependence of the probability for subbarrier proton emission on the nature of the rotational bands populated in the final nucleus.

It has been known for some time that α -particle emission from excited nuclei, particularly below the evaporation Coulomb barrier, is sensitive to nuclear shapes.³⁻⁷ Our recent work (see ref. 8 and Appendix B) has demonstrated that a decrease in the evaporation barrier for α -particles due to deformation is capable of explaining $\alpha - \gamma$ angular distribution data and α -particle energy spectra.

This raises the issue of whether the subbarrier proton emission is sensitive to deformation effects and if so can differences in proton energy spectra be observed when rotational bands of different structure and deformation are populated.

We have addressed these issues in a recent study involving the reaction $^{52}\text{Cr}(^{34}\text{S}, 2n2p)^{82}\text{Sr}$ at 130 MeV. We have observed for the first time a strong dependence of the probability for subbarrier proton emission on the nature of the rotational band populated in the final nucleus.

The results to this study have been published in the Phys. Rev. Letters (see Appendix H for a reprint) and reported in several invited talks (See Appendices C, D, E, F and G). The reader is referred to the appendices for details (In particular, Appendix H and E).

Here we summarize the observations and conclusions and discuss recent calculations supporting our interpretation of the results:

- (1) As expected, the proton spectra from the ($^{34}\text{S}, 2p2n$) reaction coincident with the ground state $2^+ \rightarrow 0^+$ transition show a strong angular momentum dependence (see Fig. 2a in Appendix H) that can be understood in terms of phase space arguments from a statistical model calculation.
- (2) Furthermore, the proton spectra coincident with high spin states in a given rotational band have the same shape (see Fig. 3b in Appendix H).
- (3) Large shifts are observed when proton spectra associated with different rotational bands are compared. The spectra coincident with the yrast and the ground band shift

down and up in energy, respectively, when compared to the two other bands. These shifts are large, but smaller than those associated with the spin effects seen in γ -ray multiplicity gating.

- (4) The angular distributions of the subbarrier protons associated with the yrast band are enhanced relative to those from the $2^+ \rightarrow 0^+$ ground transitions which include the total channel yield.
- (5) The γ -ray multiplicity distribution associated with the population of the high spin states in the yrast and the ground band are the same. This indicates that the same entry regions are involved in the population of the various rotational bands.

These results are very surprising because the entry states are expected to lie at considerably higher excitation energies than the gating transitions and any correlation between the proton spectrum and the nature of the band being populated ought to be washed out by the statistical γ -ray emission.

We have carried out numerous detailed statistical model calculations in effort to reproduce the observed shifts in the proton spectra. In all the cases either the opposite trend was found or a spin fractionation for the entry states leading to the high spin yrast and ground band was required, contrary to result (5) above.

A reasonable explanation of the observed large shifts is suggested by the steep experimental yrast line and consequently the entry line in ^{82}Sr , which is only a few MeV above the yrast line. These observations and the data suggest that the population of the rotational bands in ^{82}Sr , and in particular the yrast band, are populated by near yrast to near yrast proton emission, which significantly restricts the washing out by the statistical γ -rays of the correlation of the proton spectrum with the populated bands. This explanation is further supported by the stronger anisotropies observed (result 4 above) and by the statistical model calculations which suggest that 59% of the cascades involve a proton as the fourth emitted particle in the (^{34}S , $2n2p$) reaction. This is shown in Fig. IIA5.1(a) where the population of the the proton emitting states leading to ^{82}Sr is shown as a density plot. The four stages of emission are visible. We further realize that according to the statistical model calculations, the subbarrier protons are by and large associated with the fourth chance emission. This is clearly seen in Fig. IIA5.1(b) where a density map is shown of the proton energy as a function of the excitation energy of the proton emitting states.

It is worth noting that in the ^{82}Sr case, proton emission from near-yrast states may be associated with a predicted mechanism based on instability toward nucleon emission of large spins, connected with the population of $h_{11/2}$ resonance states in nuclei in this region.⁹ Those predicted yrast proton transitions were also expected to have enhanced anisotropies as observed in our work.

In order to understand the origin of the observed effects of the protons, statistical model calculations which incorporate nuclear structure effects must be done. The existing code PACEX, although improved and extended to handle deformation effects does not include specific nuclear structure effects. In order to incorporate structure effects into the population of levels in fusion reactions, we are examining the possibility of merging

Figure IIA5.1 (a) Density plot of the proton emitting states calculated with PACEX for the reaction $^{52}\text{Cr}(^{34}\text{S}, 2p2n)^{82}\text{Sr}$ at 130 MeV. A γ -ray multiplicity selection $M_\gamma > 10$ has been applied. (b) Density plot showing the energy of the emitted protons as a function of the excitation energy of the proton emitting states that lead to ^{82}Sr calculated with PACEX.

or cascading the codes PACEX and the code GAMBLE¹⁰. The code GAMBLE is ideally suited for our purpose because it allows the population of individual states in a final product to be calculated. Normally, the code accepts as input entry state population distributions and follows the decay of these states by γ decay. We are investigating the possibility of using GAMBLE in this mode or modifying it to allow population by the last particle to be included in the de-excitation process. Since detailed structural information (multipole character, strength functions, etc.) is input to the code it appears suitable for our purposes. The code in its standard form is already running in our computers.

Since the publication of these first results, we have been analyzing a follow up experiment in which ^{82}Sr was produced in the reaction $^{60}\text{Ni}(^{26}\text{Mg}, 2p2n)$ at 110 MeV. In this experiment several improvements were made:

- (a) The Dwarf Ball and Wall were employed, which yielded significantly more accurate angular distributions than our earlier experiment;
- (b) Both γ -ray multiplicity and total γ -ray energy information were recorded with the spin spectrometer, which allow for combined (M_γ, E_γ^*) gating in order to emphasize the observed effects;
- (c) Better energy resolution in the Ge spectra was obtained by reducing the Doppler broadening for the high spin transitions. This was done by using a reaction with smaller recoil velocity and by applying corrections for the sideward kick of the evaporation residues by the protons and neutrons event by event.

The analysis of this experiment has progressed considerably. The energy calibrations of all the detectors (Dwarf Ball + Wall, Ge, and NaI) have been made. The particle

identification completed. The recoil corrections remain to be done in order to allow for the final prescan. This work is part of the Ph.D. thesis of Dan Stracener.

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IIA6. Proton Emission as a Probe of Nuclear Deformation – N.G. Nicolis and D.G. Sarantites.

As was mentioned in the previous section, one of the motivations for studying the shapes of the proton spectra was to establish the extent to which they reflect effects of deformation. The observed shifts of the proton spectra from the $^{52}\text{Cr}(^{34}\text{S}, 2n2p)$ reaction associated with the population of different rotational bands appear to be too large to be due to differences in the deformation associated with each rotational band (See, for example the theoretically predicted deformations described in Appendix A). In order to estimate the magnitude of the effect of deformation on the proton evaporation spectra, we carried out a series of calculations for the $^{52}\text{Cr}(^{34}\text{S}, 2n2p)^{82}\text{Sr}$ reaction at 130 MeV using the code PACEX. As before (see Appendix B) the deformation was introduced in the penetrability term and only the nuclei with $Z = 40, 39$, and 38 were assumed to have a deformation given by $\beta = 0.3$.

Figure IIA6.1. Proton spectra calculated for the reaction of 130 MeV ^{34}S with ^{52}Cr . The thin and thick lines correspond to calculations with a spherical and deformed optical model potential. The curves (a), (b), and (c) are for all protons from ^{86}Zr , all protons leading to ^{82}Sr , and protons associated with $M_\gamma > 13$ leading to ^{82}Sr , respectively.

A number of observations can be made from these preliminary calculations:

- (1) The individual exit channel cross sections are different compared to a spherical calculation for the same system.
- (2) The percentage of the cascades involving a proton as a fourth particle decreases somewhat (from 59% for the spherical to 48% for the deformed one).
- (3) The yield of subbarrier protons for the sum of all channels from the $^{86}\text{Zr}^*$ compound nucleus increases relative to the spherical calculation, but this is small compared to what was found for the α spectra in the Yb systems (See Fig. IIA6.1). For all protons leading to ^{82}Sr and those associated with the $M_\gamma > 13$ also leading to ^{82}Sr , the proton spectra from the calculation with deformation show a decrease in the subbarrier yield compared to the spherical case. This is a trend in the opposite direction than expected (Fig. IIA6.1b and IIA6.1c). A likely explanation is that many channels involving low energy proton emission compete and remove the yield from the 2p2n channel. We are at present exploring this possibility further.
- (4) The above results suggest that because of the mentioned uncertainties in the calculated spectra, the channel selected proton spectra may not be useful as a probe of nuclear deformation.

Recently, the Chalk River group^{1,2} has reported that the proton spectra from the $^{105}\text{Pd}(^{32}\text{S}, 2\text{p}2\text{n})^{133}\text{Nd}$ at 155 MeV leading to the normal deformation and the superdeformed bands in ^{133}Nd are identical in shape. The subbarrier protons leading to the superdeformed band, however, have a stronger anisotropy with respect to the spin direction relative to the normal deformation band.

In order to understand this behavior, we have carried out two preliminary calculations for that system. For the deformed case, we used $\beta = 0.4$ for the $Z = 62, 61$ and 60 nuclei. The calculated proton spectra leading to ^{133}Nd were found to be identical for the spherical and the deformed case. We are pursuing the analysis of that system further in consultation with the Chalk River group.²

In summary, it appears from the present preliminary calculations that the subbarrier part of the proton evaporation spectra does not reflect deformation effects.

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IIA7. Giant-Dipole Resonance Studies in Hot Nuclei - J.R. Beene, M. Thoennessen, F.E. Bertrand, C. Baktash, R.L. Auble, M.L. Halbert, R.L. Varner [ORNL], H.P. Morsch, W. Spang [Jülich], D.G. Sarantites and D.W. Stracener [WU]

Many measurements have been carried out using the giant dipole resonance (GDR) in excited nuclei to determine the shape of the nucleus as a function of angular momentum and temperature.^{1,2} Such studies are of particular interest for very hot nuclei ($T \geq 2$ MeV) because shape changes as a function of temperature have been theoretically predicted.³ Unfortunately, such investigations are generally hampered by the fact that the width of the GDR increases with increasing excitation energy,² giving rise to large uncertainties in the extraction of shape parameters. In the Sn⁴ and rare earth⁵ nuclei it has been found

that the width of the GDR at a temperature of 2 MeV is twice that at zero temperature. While the increase of the giant resonance width with temperature can be interpreted⁶ by thermal shape fluctuations, motional narrowing has been predicted⁷ to cause a reduction of the giant resonance width at high temperatures.

In this work we have measured evaporation-residue- γ -ray coincidences in the reaction $^{16}\text{O} + ^{159}\text{Tb}$ at beam energies of 300 and 400 MeV. The heavy recoils were detected by two (6×9 cm) avalanche counters, 37 cm downstream from the target and triggered the Spin Spectrometer which detected the coincident γ -rays.

In the γ -ray spectra corresponding to excitation energies above 140 MeV a split giant resonance was observed. A dramatic narrowing of the GDR was seen at temperatures in the $T = 2\text{--}3$ MeV range with widths comparable to those of the $T = 0$ GDR. This new phenomenon makes it possible to extract accurate strength ratios S_1/S_2 for the two frequencies and to infer the evolution of the mean nuclear shape with temperature. A distinct transition towards an oblate shape at high temperature was observed, in agreement with expectations. However, this transition occurs at higher temperatures than predicted.

This work was summarized in a paper published in *Phys. Rev. Letters*. A preprint is included as Appendix I.

In order to bridge the gap between these results and lower energy work, we carried out another experiment in which we measured an excitation function for the excitation of GDR with the reaction $^{16}\text{O} + ^{159}\text{Tb}$ at bombardment energies of 140 and 220 MeV. The results are being analyzed by W. Spang (Jülich) as part of his Ph.D. thesis.

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IIB. FUSION REACTIONS NEAR AND BELOW THE BARRIER

IIB1. Angular Momentum Effects in Subbarrier Fusion – M.L. Halbert, J.R. Beene, D.C. Hensley [ORNL], K. Honkanen* T.M. Semkow, V. Abenante, D.G. Sarantites and Z. Li [WU]

In the past several years, we have been interested in the population and decay of the entry states from fusion reactions. The availability of the Spin Spectrometer opened the possibility of detailed studies of spin distributions in individual nuclides formed as evaporation residues.¹ Such measurements are particularly useful near and below the barrier in the entrance channel.

The cross sections for fusion of heavy ions near and below the Coulomb barrier are known to be far larger than the predictions of traditional models that are quite successful above the barrier.² Considerable success in reducing the discrepancy by several orders of magnitude has been achieved by taking into account coupling to quasidelectric channels in several different ways.³⁻⁵ Knowledge of the angular-momentum dependence of subbarrier fusion would allow a deeper examination of the various models, but with few exceptions,⁶⁻⁸ previous experiments did not provide such data. In the present work, information on angular momenta was obtained by measurement of γ -ray multiplicities with the Spin Spectrometer.⁹ The experimental method identified the evaporation residues and hence provided ℓ distributions for each exit channel. The present measurements also bear fairly directly on the role of unusual configurations of the fusing system and their possible evolution to superdeformed shapes.⁷

In our work we have produced the compound nucleus $^{164}\text{Yb}^*$ by means of two reactions $^{64}\text{Ni} + ^{100}\text{Mo}$ and $^{16}\text{O} + ^{148}\text{Sm}$ in a series of bombardment energies.

A detailed comparison of the cross sections and the deduced σ_ℓ distributions with various fusion models, including channel coupling has been made in a paper published in the *The Physical Review*. A preprint is included as Appendix J. The abstract is given below.

ABSTRACT: Angular-momentum distributions σ_ℓ for the compound nucleus ^{164}Yb were deduced from measurements of γ -ray multiplicity for all significant evaporation residues from fusion of ^{64}Ni and ^{100}Mo . At the lowest bombarding energies the σ_ℓ extend to higher ℓ values than do predictions of barrier-penetration models that include coupling of the principal inelastic channels, even if the coupling strengths are increased to match the experimental excitation function. Likewise, σ_ℓ from a real potential with an energy-dependent shape fitted to the excitation function fails to reproduce the experimental σ_ℓ distribution. Better success is achieved with models in which fusion occurs at large distances.

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IIB2. Entrance Channel Effects in Fusion Reactions Near the Barrier - M. Thoennessen, J.R. Beene, M.L. Halbert, D.C. Hensley, D. Horen, F. Bertrand [ORNL], D.G. Sarantites, D. Stracener, K. Honkanen*, T.M. Semkow, and V. Abenante [WU]

Recently Ruckelshausen *et al.*¹ reported the existence of entrance channel effects for the ^{156}Er compound system formed at the same excitation energy in the reactions $^{64}\text{Ni} + ^{92}\text{Zr}$ and $^{12}\text{C} + ^{144}\text{Sm}$. From the measured M_γ distributions, the σ_ℓ distributions that lead to the various exit channels were obtained. Fig. IIB2.1 shows the ratio of σ_{2n}/σ_{3n} from Ref. 1. A strong dependence on entrance channel is observed.

Figure IIB2.1. Ratio of 2n/3n yields for $^{64}\text{Ni} + ^{92}\text{Zr}$ and $^{12}\text{C} + ^{144}\text{Sm}$ reactions as a function of compound-nucleus spin. The results are compared with a statistical-model calculation which predicts identical ratios for both entrance channels.

The above result is in contrast with our findings for similar systems $^{64}\text{Ni} + ^{100}\text{Mo}$ and $^{16}\text{O} + ^{148}\text{Sm}$ forming the same nearby compound nucleus $^{164}\text{Yb}^*$. In Fig. IIB2.2, we show the ratios of σ_{3n}/σ_{4n} and σ_{2n}/σ_{3n} as functions of M_γ (simply related to spin) from the decay of $^{164}\text{Yb}^*$ compound nuclei formed at $E^* = 49.4$ and 40.4 MeV, respectively, by two entrance channels, $^{64}\text{Ni} + ^{100}\text{Mo}$ and $^{16}\text{O} + ^{148}\text{Sm}$ in each case. It appears that in

Figure IIB2.2. Ratios of 2n/3n (a) and 3n/4n (b) yields for the $^{64}\text{Ni} + ^{100}\text{Mo}$ and $^{16}\text{O} + ^{148}\text{Sm}$ as a function of measured γ -ray multiplicity. It is seen that the ratios are very similar and this does not support the existence of entrance channel effects for this system.

our system, ^{164}Yb , entrance channel effects are completely absent, since the cross section ratios for the two entrance channels are very similar.

These observations indicate that this effect may be due to structural differences which influence the decay path of the compound nucleus instead of dynamical effects in the entrance channel. Further work along these lines must be done in order to understand the origin of this unexpected behavior.

If the entrance channel effects are indeed present they should be reflected in the yield of hard photons that accompany nuclear collisions. The emission of hard photons of energies in the vicinity of the GDR is expected to be emitted in the early stages of the reaction at times comparable to the emission of the first neutron. Therefore, they provide a sensitive probe and can sense the presence of entrance channel effects in the decay of the composite system.

In order to test this possibility we carried out recently an experiment in which high energy γ -rays were detected with the ORNL BaF_2 array (a set of four 19-detector BaF_2 packs) in coincidence with the Spin Spectrometer NaI detectors. The trigger was a sum energy in excess of 6 MeV in one of the BaF_2 packs or in a cluster of NaI detectors in

the backward half of the spin spectrometer. The systems studied were 233.5 MeV ^{64}Ni + ^{100}Mo , ^{64}Ni + ^{90}Zr , and 82.8 MeV ^{16}O + ^{148}Sm , and 86.3 MeV ^{16}O + ^{144}Nd , which produced the $^{164}\text{Yb}^*$ and $^{160}\text{Er}^*$ compound systems at the same excitation energy.

A pair of Compton suppressed Ge detectors were also used in parallel in order to identify the channels involved and determine the spin distributions that are involved in these reactions.

Further experimental details are given in Appendix K, where a preprint of a paper presented at the Notre Dame meeting (May 1990) is included.

The results are briefly summarized here:

- (1) The γ -ray spectra from the ^{16}O -induced reactions show a typical GDR bump that can be explained by statistical model calculations.
- (2) The ^{64}Ni induced reactions show γ -ray spectra with a dramatically different shape (Fig. IIB2.1)

Figure IIB2.1. Gamma spectra for ^{160}Er (a) and ^{164}Yb (b). The ^{64}Ni (upper) and ^{16}O (lower) spectra are normalized to each other with Ge detector yields. The solid curves result from CASCADE calculations assuming a superdeformed shape for the compound nuclei.

- (3) When the spectra are normalized to the evaporation residue cross section the symmetric channel yield of high energy γ -rays is significantly higher than from the asymmetric channels.
- (4) The symmetric-channel γ -spectral shapes cannot be explained using parameters corresponding to superdeformed shapes. (Solid lines in Fig. IIB2.1).
- (5) These results explain the low neutron multiplicities found for the symmetric case in ^{160}Er .^{2,3}

Some speculations are offered in Appendix K for the possible origin of these remarkable differences in the γ -ray spectra. These entrance channel effects need further investigation and experiments for this purpose will be initiated by our group.

* Deceased

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Figure IIB3.1. Entry-state distributions for the xn products from the $^{50}\text{Ti} + ^{130}\text{Te}$ reaction. (a) Experimental contour maps in (E^* , M_γ) space for the three strongest channels. (b) Calculated (E^* , M_γ) maps from the statistical model. The contour lines are for a linear scale increasing inward with the step indicated for the lowest intensity line in $\mu\text{b/MeV}$.

IIB3. Population of Entry States in Heavy-Ion Fusion Reactions. – N.G. Nicolis, K. Honkanen*, D.G. Sarantites, T.M. Semkow, M. Rajagopalan, M. Jääskeläinen, R. Woodward, F.A. Dilmanian [WU], J.R. Beene, D.C. Hensley, J.H. Barker, M.L. Halbert, S.P. Sorensen and W.T. Milner [ORNL].

The transfer of orbital angular momentum into intrinsic spin of the reaction products plays an important role in reaction mechanisms. For fusion reactions spin distributions and associated excitation energy distributions in the evaporation residues can be deduced from measurements of the population of the entry states, which is accomplished with the Spin Spectrometer.

A few years ago we completed a set of measurements addressing the careful measurement of the population of the entry states in several systems including 136 MeV $^{20}\text{Ne} + ^{146}\text{Nd}$ and 224 MeV $^{50}\text{Ti} + ^{130}\text{Te}$. The cross section and the entry state population for the major exit (HI, xn) and (HI, α xn) channels have been measured. Statistical model calculations including finite range corrected fission barrier reproduce the main features of the data. For both reactions the cross sections, the average γ -ray multiplicities and their widths for all the exit channels are well reproduced by the calculations. The two dimensional (E^* , M_γ) distributions from theory are narrower along the E^* direction (at constant M_γ) than experiment. This is shown in Fig. IIB3.1.

The differences in the upper edge of the entry state populations reflect the effect of fission to neutron emission competition when the fission cross section is large as in the $^{50}\text{Ti} + ^{130}\text{Te}$ case. From the $^{20}\text{Ne} + ^{146}\text{Nd}$ system where the fission cross section is small, the differences in the shape of the upper edge in the total entry state distribution reflects the competition between fusion and peripheral collisions. A manuscript for publication of this work is under preparation.

* Deceased.

IIC. INCOMPLETE FUSION AND FRAGMENTATION REACTIONS

The reactions of two colliding heavy-ions can be classified as (1) those that lead to complete fusion when the composite system carries the full incident momentum, excitation energy and angular momentum, and (2) those that lead to partial momentum transfer with emission of one or more intermediate mass fragments. For low incident energies of ≤ 8 MeV/u one distinguishes binary reactions as those involving emission of a projectile-like fragment (PLF) and a target-like fragment (TLF). As the bombardment energy is increased above ~ 10 MeV/u a continuous evolution of decay processes of the composite system come into play ranging from the simpler binary decay into a PLF and a TLF that can be distinguished experimentally for asymmetric entrance channels, to the more complex processes involving projectile and/or target fragmentation resulting in the emission of several intermediate mass and/or heavier fragments, and finally to the complete nuclear disassembly into many fragments where no TLF remains.

The complexity of these reactions necessitates as complete an experimental characterization of the experimental variables as possible. In particular, the question of the total energy reconstruction in complete, incomplete fusion and multifragment producing reactions must be addressed. Coupled to this is the transfer of linear momentum, angular momentum and excitation energy to the major reaction products.

In order to characterize in detail these reactions we have constructed a highly segmented 4π charged particle array (the Dwarf Ball and Wall, see section III) that can be operated independently or inserted in the Spin Spectrometer at ORNL. This multilayered detection system provides intermediate mass fragment (IMF) identification ($Z = 3 - 24$) and energy measurement, light-charged particle identification (p, d, t, ^3He , ^4He) and energy measurement, and when operated inside the Spin Spectrometer, the γ -ray multiplicity, the neutron multiplicity, and the total γ -ray energy in an event-by-event mode.

Equipped with these tools, we have proceeded in the past few years to address the above issues on several fronts.

In the first series of experiments in the energy range 12-25 MeV/u we have selected as projectiles ^{16}O , ^{28}Si and ^{48}Ti , which are progressively less prone to fragmentation at these energies, and non-fissile targets. Our objectives for these experiments were (1) to study the relative importance of incomplete fusion and projectile fragmentation as a function of the mass of the projectile; (2) to establish the connection between momentum transfer and excitation energy imparted to the target-like fragment (TLF); and (3) to study the partition of excitation energy between the binary reaction partners which at these energies account for most of the cross section.

In order to accomplish these goals, in some of the experiments we measured directly the evaporation-like residue velocities and the associated light particles and fragments with the Dwarf system, and in complementary measurements, we triggered on the Dwarf system to

TABLE IIC2.1. Reaction Systems Studied.

System	E_{beam} (MeV)	Trigger	PPAC present	E_{full}^* (MeV)	$\sqrt{(E - V)/A}$ (cm/ns)	$\Theta_{gr,lab}$
1) $^{16}\text{O} + ^{159}\text{Tb}$	400	Wall+Ball	Yes	342	6.4	10.0°
2) $^{28}\text{Si} + ^{181}\text{Ta}$	333	Si	No	222	3.9	25.5°
3) $^{28}\text{Si} + ^{100}\text{Mo}$	701	Wall+Ball	No	525	6.6	6.5°
4) $^{28}\text{Si} + ^{100}\text{Mo}$	701	PPAC	-	525	6.6	6.5°
5) $^{48}\text{Ti} + ^{93}\text{Nb}$	677	Wall+Ball	No	381	3.4	10.5°
6) $^{48}\text{Ti} + ^{93}\text{Nb}$	915	Wall+Ball	No	538	4.1	7.5°
7) $^{48}\text{Ti} + ^{100}\text{Mo}$	677	PPAC	-	399	4.8	10.6°
8) $^{48}\text{Ti} + ^{100}\text{Mo}$	915	PPAC	-	560	5.7	7.6°

provide an unbiased trigger. The systems studied are summarized in Table IIC2.1. Further details are given in sections IIC1 to IIC3.

In this section we also report on a program aimed at shedding some light on the mechanism of intermediate mass fragment production in more energetic heavy ion collisions in the energy range of 35-100 MeV/u. The first experiment in the latter series had as objective to establish the connection between charged particle multiplicities and linear momentum transfer in a fissile system, using the folding angle technique and to study the correlation between fission fragments and light ions.¹

In a separate experiment we have aimed at establishing the characteristics of heavy-ion collisions at 45 MeV/u by studying the intermediate and light mass fragment production in the reactions of ^{84}Kr with a variety of targets from ^{12}C to ^{181}Ta . In a third experiment, our objective was to supplement this work with an excitation function with ^{40}Ar projectiles for energies between 25 - 70 MeV/u, and to extend this work to the heavier ^{128}Xe projectile. In the latter two experiments the Dwarf system was employed in a self-triggered mode.

1. M.B. Tsang *et al.* *Phys. Lett.*, **B220**, 492 (1989).

IIC1. Decomposition of Incomplete Fusion into Highly Fragmented Channels

- A. Chbihi, L.G. Sobotka, Z. Majka, D.G. Sarantites, D.W. Stracener, V. Abenante, T.M. Semkow, N.G. Nicolis [WU], D.C. Hensley, J.R. Beene and M.L. Halbert [ORNL].

The purpose of this work was to provide a comprehensive study of an incomplete fusion reaction by classifying the various exit channels associated with this process in terms of the momentum transferred to the target-like residue. We have chosen to study incomplete fusion in the reaction $^{28}\text{Si} + ^{100}\text{Mo}$ at 25 MeV/u. The measurements involved coincidences between evaporation residues (ER) and light charged particles (LCP), intermediate mass fragments (IMF), neutrons and γ -rays. The results of this work were submitted for publication and a preprint is attached as Appendix L. The most important results were:

- (1) The incomplete fusion ER velocity distribution was decomposed into those for 26 different highly fragmented exit channels. Each exit channel involved several forward emitted LCP (this is illustrated in Fig. 2 of Appendix L).
- (2) The relative yield of every exit channel was determined from the ER velocity distribution for that channel.
- (3) The channel yields appeared to correlate better with the Q-value of projectile fragmentation and not with the Q-value for incomplete fusion or the transferred fraction of the projectile. However, when a Coulomb correction was applied then the correlation for the incomplete fusion was much improved. In fact, the correlations with the Coulomb corrected projectile fragmentation or incomplete fusion are very similar (See Fig. 3 in Appendix L) suggesting that one cannot distinguish between the two mechanisms from such correlations alone and that the detailed dynamics must be considered.
- (4) The excitation energy imparted to the ER increases monotonically with momentum transfer. This is deduced from the LCP and neutron multiplicities measured at large angles ($> 35^\circ$). (See Fig. 4a in Appendix L).
- (5) The angular momentum transfer at a given linear momentum transfer depends on the degree of fragmentation of the unfused portion of the projectile.

The results (1), (2), and (5) are new. The result (3) is corroborated by work from Möhring.¹ The fourth result is not unexpected, but it provides a nice proof that the large angle multiplicities are a measure of the violence of the reaction (See also our work in Ref. 2). The forward light charged particle multiplicities cannot be used to select the violence of the reaction. In fact, the anticorrelation of the IMF multiplicity with momentum transfer shows the expected trend, that if several IMF's are observed in the forward direction, then the TLF remains cold (see also section IIC5).

1. K. Möhring, *et al.*, *Phys. Lett.*, **B203**, 210 (1988); private communication, (1989).

2. M.B. Tsang, *et al.*, *Phys. Lett.*, **B220**, 492 (1989).

IIC2. Linear Momentum and Excitation Energy Reconstruction in Incomplete Fusion Reactions – A. Chbihi, L.G. Sobotka, Z. Majka, D.G. Sarantites, D.W. Stracener, V. Abenante, T.M. Semkow, N.G. Nicolis [WU], D.C. Hensley, J.R. Beene, and M.L. Halbert [ORNL].

The main objective of this work was to examine in detail the methods available for reconstructing the energy balance in incomplete fusion reactions in the light of our 4π measurements of LCP and neutrons associated with ER's at various linear momentum transfers. This work is part of a paper submitted for publication and a preprint of this is included as Appendix L.

The main results of this work are:

- (1) The partition of linear momentum between various sources is deduced using the measured residue velocity, multicomponent fits to LCP's, and mean neutron multiplicities.
- (2) The reconstruction of the linear momentum indicates that a substantial fraction of the momentum is not detected by our apparatus when slow ER's are produced. With

reasonable assumptions, this missing momentum can be calculated and the initial excitation energy of the compound-like system can be obtained as a function of the residue velocity (See Figs. 11 and 12 in Appendix L).

- (3) The excitation energy of the compound-like system can also be calculated from the multiplicities of the TLF emissions. This excitation energy agrees to 10% with the result from (2) above and shows the consistency and validity of the assumptions involved. A monotonic relationship between V_{ER} and the excitation energy was established.
- (4) The methods outlined in (2) and (3) indicate that incomplete fusion reactions can be used to produce hot nuclei with known excitation in the temperature range between 3.0-6.0 MeV.

The results (1) and (2) are not new, but we have introduced several improvements to the work of Wada *et al.*¹ The result (3) is new. It should be noted, however, that the extraction of the excitation energy depends on the assumptions in (2) and on the measured velocity of the ER.

1. R. Wada *et al.*, *Phys. Rev. C* **39**, 497 (1989).

IIC3. Determination of the Nuclear Level Density at High Excitation Energy – A. Chbihi, N.G. Nicolis, L.G. Sobotka, D.G. Sarantites, D.W. Stracener, Z. Majka, [WU], D.C. Hensley, and J.R. Beene [ORNL].

We have demonstrated in our studies described in the preceeding two sections that we can use incomplete fusion reactions to produce hot nuclei with known excitations up to 402 MeV for nuclei with mass ≈ 110 . Having done this we turned our attention to the study of one of the important properties of highly excited nuclei, namely the nuclear level density.

At moderate excitations, the Fermi gas model¹ provides an equation of state $U = aT^2$, where the level density parameters $a = \pi^2 A/4\epsilon_f \simeq A/15$ and T is the temperature. Experimentally, the values of a are larger than this estimate, being typically $a \simeq A/8$. There are two reasons for this. The first is the influence of the diffuse surface of real nuclei,² which would give $a = A/[14.61(1 + 4A^{-1/3})]$. The second one is the increase in effective mass of the nucleon^{3,4} for the nuclei at $T = 0$. As the temperature is increased, the effective mass decreases and this should reflect a decrease in the level density parameter.

In this work we have carefully examined and employed two different techniques for extracting the level density constant, a , from evaporative spectra emitted from nuclei at different excitations. These methods are utilizing analysis of spectra from the whole cascade and of difference spectra from two different excitations.

In the analysis of the whole cascade spectra, the slopes of the evaporation spectra must be multiplied by a correction factor⁵ f_{IV} in order to permit one to relate these corrected slopes to the statistical temperatures (which are connected to the first chance emission). These correction factors were determined by detailed statistical model simulations which are described at length in Appendix M and are shown in Fig. 2 of Appendix M.

Figure IIC3.1. Experimental (points) and calculated (histograms) light particle multiplicities emitted from evaporation residues for the six V_{ER} bins corresponding to the excitation energies indicated in the abscissa. The left, middle and right values in each histogram are calculated for the $k = A/a$ values of 6.0, 8.5 and 11.0 MeV, respectively.

The correction factors f_W were found to be independent of the value of a , but depend critically on the angular momentum distributions of the hot nuclei and consequently they depend on the type of emitted particle.

In the analysis of the difference spectra, following a procedure employed by Gonin *et al.*⁶, the evaporative spectra from two nearby excitations are subtracted and the difference spectrum is assumed to originate from the region of excitation between the two initial excitations. Again, correction factors must be employed to permit the association of the slopes of the difference spectra with the statistical temperatures. These correction factors f_D were extracted also from detailed statistical model calculations and are shown in Fig. 4 of Appendix M. They are in general smaller than those from the whole spectra and they are found to depend also on the angular momentum distributions involved.

Figure IIC3.2. Values of the Fermi gas inverse level density constant $k = A/a$ as a function of the temperature. The triangles are from our work. The dashed and solid lines are calculated in Ref. 4 (see text).

In these analyses the evaporation code PACEX was employed for the simulations (see section IIIB4 and Appendix M.) The correction factors f_W and f_D extracted from these simulations were employed to correct the slopes of the whole evaporation and difference spectra obtained from our incomplete fusion study. The difference spectra were derived by subtraction of spectra from two different ER velocity bins which correspond to different excitations. In these analyses we employed primarily spectra of protons and deuterons which had correction factors that are least sensitive to angular momentum. It is, however, imperative that the statistical model calculations reproduce reasonably well both the slopes and the particle multiplicities. Our calculations of the particle multiplicities are summarized in Fig. IIC3-1. The neutron, proton, and α -particle multiplicities are reproduced to better than 30% with $a = A/8.5$ or $A/11$ for all excitations. The deuteron and triton multiplicities, however, are overestimated by a factor of $\simeq 2.5$. This difficulty is associated with either a failure of the optical model penetrabilities for these particles

or other effects such as clustering at the surface not included in the standard statistical models.

In summary, the level density constants $k = A/a$ extracted from our data are shown in Fig. IIC3-2, where they are plotted as a function of the temperature T . The open full triangles are from this work, the open circles are from Ref. 7 and the full circle from Ref. 6. The dashed curve is for a constant diffuseness $d = 0.7$ fm and the solid curve was obtained⁴ with $d = 0.7(1 + 0.01T^2)$ fm. Part of the difference between the value of Gonin *et al.*⁶ and our values may be due to differences in the diffuse surface between the $A = 160$ and $\simeq 110$ nuclei employed, respectively.

1. A. Bohr and B.R. Mottelson, "Nuclear Structure", Vol. 1. W.A. Benjamin, Inc. (1969).
2. J. Toke and W.J. Swiatecki, *Nucl. Phys.* **A372**, 141 (1981).
3. P.F. Bortignon and C.H. Dasso, *Phys. Lett.* **B189**, 381 (1987).
4. S. Shlomo and J.B. Natowitz, Texas A&M, preprint # 90-08 (1990).
5. D. Hilscher *et al.* *Phys. Rev.* **C36**, 208 (1987).
6. M. Gonin *et al.* *Phys. Lett.* **B217**, 406 (1989).
7. K. Hagel *et al.* *Nucl. Phys.* **A486**, 429 (1988).

IIC4. Target Excitation and Angular Momentum Transfer in Reactions of $E/\text{nucleon} = 11.9$ MeV $^{28}\text{Si} + ^{181}\text{Ta}$ - Z. Majka, V. Abenante, Z. Li, N.G. Nicolis, D.G. Sarantites, T.M. Semkow, L.G. Sobotka, D.W. Stracener [WU], D.C. Hensley, J.R. Beene [ORNL], and H.C. Griffin [U. Mich.]

In the first experiment with the plastic Dwarf Ball¹ we have studied the energy deposition and angular momentum transfer in the target-like fragments in the reaction 11.9 MeV/u $^{28}\text{Si} + ^{181}\text{Ta}$. This work has been published in *The Physical Review* (included as Appendix N).

Briefly, the detection of charged particles, neutrons and γ -rays in coincidence with projectile-like fragments has provided some insight into both the excitation energy and spin of the TLF as a function of the PLF parameters. The main results were:

- (1) The TLF excitation energy increases monotonically with the decreasing PLF energy for low energy losses and saturates for the region corresponding to completely damped collisions (see Figs. 8 and 10 in Appendix N). This saturation was shown to be correlated with non-binary processes, including non-equilibrium light particle emission and projectile break-up. While we were unable to quantitatively determine the relative magnitudes of non-equilibrium light particle and sequential light particle decay, both forward light particle and forward Li production increase with decreasing projectile energy and charge. (The former are indicators of non-equilibrium and/or projectile decay while the latter indicates massive projectile break-up.) These mechanisms provide the explanation for the saturation of the target excitation energy.
- (2) To place the magnitude of target excitation into perspective we have assumed that the available energy for excitation is obtained from binary kinematics. We then find that for the fully damped region, the TLF excitation is as much as 40% lower than the value expected in the equal temperature limit (Table I and Fig. 14 in Appendix N). If a significant fraction of the forward non-TLF light particles is assumed to be

emitted with the beam velocity, then the fraction of the excitation transferred to the TLF increases, however, the equal temperature limit is still not reached.

- (3) The angular momentum transfer to the TLF's showed that after the deeply inelastic (DI) collisions the TLF spin is lowest for the lightest PLF's. The situation is reversed for the quasi-elastic (QE) processes. Moreover, we have found that in the DI energy region the TLF spin is independent of the PLF energy. In the QE energy region the TLF spin increases with the decreasing energy of the PLF and reaches a constant value in the DI energy region. Model calculations which apply the critical angular momentum condition to the exit channel reproduce the dependence of the angular momentum transfer on PLF charge for the DI processes.

More detailed measurements, capable of completely identifying the various projectile fragmentation channels and other non-binary processes are needed to further characterize the energy balance in these reaction channels. Such experiments are described in the following sections of the report.

1. D.G. Sarantites, *et al.*, *Nucl. Instr. and Meth.*, **A264**, 319 (1988).

IIC5. A 4π Approach to Linear Momentum Transfer and Excitation Energy Division in Incomplete Fusion and Projectile Fragmentation Reactions – A. Chbihi, V. Abenante, D.W. Stracener, D.G. Sarantites, Z. Majka, L.G. Sobotka, and N.G. Nicolis [WU], D.C. Hensley, J.R. Beene, and M.L. Halbert [ORNL].

In this work, we concentrate on the study of the linear momentum transfer and of the energy sharing in binary and projectile fragmentation reactions taking advantage of 4π detection. We will restrict ourselves to the reaction systems (1), (3), and (6) described in Table IIC2-1.

In our previous analyses (sections IIC1 and IIC2) we took advantage of the characterization of the events by the measured velocity of ER's, from which the momentum transferred to the TLF was derived. Here, we take the complementary approach and deduce the linear momentum transferred to the TLF from the forward momenta of all the fragments detected in the Dwarf Wall and part of the Ball. In fact, we can separate the events in terms of the IMF multiplicity detected forward.

For the ^{28}Si and the ^{48}Ti induced reactions, we selected the events that include detected IMF's. We find that these events have $\approx 90\%$ of the yield in 1 IMF, $\approx 9\%$ in two IMF's, and $\approx 1\%$ of the yield in 3 or more IMF's. In Fig. IIC5.1(a) we show the distribution of the sum of the charges (ΣZ_i) detected in the Wall from the $^{28}\text{Si} + ^{100}\text{Mo}$ reaction when 1, 2 or ≥ 3 IMF's are present. It is seen that the charge for ≥ 3 IMF's exceeds significantly the projectile charge. In Fig. IIC5.1(b) we show the distributions of the fraction of the detected forward momentum along the beam direction when 1, 2, or ≥ 3 IMF's are present in the Wall. The shift toward higher forward momentum when more IMF's are detected is apparent.

There is a strong positive correlation between the forward momentum and detected total charge for all IMF multiplicities. For the ≥ 3 IMF's and the largest momenta, the total detected charge exceeds considerably that of the projectile. This indicates that when

the projectile picks up mass, it fragments considerably. We will be correlating this with the target excitation determined by the backward multiplicities in order to unambiguously prove this mechanism.

Figure IIC5.1. (a) Sum of the forward ($\leq 35^\circ$) detected charge distributions for 1, 2, and 3 or more IMF's observed in the Wall from the 25 MeV/u $^{28}\text{Si} + ^{100}\text{Mo}$ reaction. (b) Distribution of the percent of the total momentum along the beam direction when 1, 2, and 3 or more fragments are detected in the Wall.

It is easy to decompose the momentum distributions of Fig. IIC5.1b into the components associated with each ΣZ_i value detected in the forward direction. This is shown nicely in Fig. IIC5.2(a) for the case where only 1 IMF is detected, and in Fig. IIC5.2(b) when 2 IMF's are detected. It is seen from Fig. IIC5.2(a) that for $\Sigma Z_i = 17$, the detected fraction of the projectile momentum reaches values of $\approx 85\%$. This is a striking result because such processes involve highly fragmented forward emission with very low target excitations.

We can easily probe in more detail and decompose the distributions shown in Fig IIC5.2 into channels involving specific detected Z_{IMF} values. When this is done, we find that for any value of ΣZ_i the momentum distributions along the beam direction are very similar and nearly independent of the partition. We illustrate this in Fig. IIC5.3, where the left panel shows the momentum distributions when only one Carbon and the right panel when only one Neon IMF are detected for the indicated values of ΣZ_i . The distributions for

Figure IIC5.2. Percent momentum distributions along the beam direction from the $^{28}\text{Si} + ^{100}\text{Mo}$ reaction at 25 MeV/u for various values of the total detected charge in the Wall ($\theta_{lab} < 35^\circ$) when only one IMF is detected (a) or when two IMF's are detected (b).

Figure IIC5.3. Channel decomposition of the forward momentum distributions from the 25 MeV/u $^{28}\text{Si} + ^{100}\text{Mo}$ reaction for the indicated values of ΣZ_i when only one ($Z = 6$) IMF is detected (left panel) or when only one Ne ($Z = 10$) IMF is detected (right panel). The average values of the distributions are nearly the same for any ΣZ_i .

$\Sigma Z_i = 6$ in the C case and $\Sigma Z_i = 10$ for the Ne case show the contributions from relaxed and quasielastic components. As ΣZ_i increases the momentum distributions become progressively more similar. The average $\Sigma P_i/P_{beam}$ values, however, are very similar for the two cases shown as well as for other partitions. The distributions shown in Figs. IIC5.1 - IIC5.6 were corrected for the evaporative part present at forward angles by removing from the distributions all light charged particles with energies below the evaporative peak.

Figure IIC5.4. Backward charged particle multiplicities as a function of the forward detected fractional momentum along the beam direction from the 25 MeV/u $^{28}\text{Si} + ^{100}\text{Mo}$ reaction. The forward multiplicities are from all forward detected partitions. The anticorrelation is apparent.

The anti-correlation of the LCP multiplicities from the TLF with the forward momentum is shown in Fig. IIC5.4 for all detected channels. A detailed analysis for all partial partitions is in progress.

The results presented so far were for the $^{28}\text{Si} + ^{100}\text{Mo}$ system. A similar analysis of the $^{48}\text{Ti} + ^{93}\text{Nb}$ experiment gives very similar results, but with substantially larger dynamic range of detected ΣZ_i values. In Fig. IIC5.5 we show the correlation between the average fractional momentum and ΣZ_i for the detected forward particles for various single PLF's detected in the Wall (ranging from $Z = 3$ to 15). This confirms the results from the $^{28}\text{Si} + ^{100}\text{Mo}$ reaction (see Fig. IIC5.3) indicating that the detected momentum is essentially independent of the partition.

In these reactions we find considerable sequential forward emission from the PLF. An example of this is shown in Fig. IIC5.6 as an energy correlation between the IMF (Z

= 14) detected in any 8.4° Wall detector and the α -particles detected in any one of its neighboring Wall detectors. The two kinematic solutions are clearly seen. Note the rather high detection threshold for the IMF (8.5 MeV/u) and the α 's (3.5 MeV/u) due to the relatively thick ($\approx 80 \mu\text{m}$) plastic scintillators in the Wall detectors.

Further analysis is in progress to correlate the forward momentum for each position with the TLF excitation. In Addition, the PLF excitation in the rest frame of the forward emissions will be correlated with the target excitation. We expect to obtain a clear picture of the energy and momentum balance in these reactions. This work is the main part of the Ph.D. thesis of Vincent Abenante.

Figure IIC5.5. Average forward fractional linear momentum along the beam direction as a function of the detected ΣZ_i for forward partitions involving only 1 Li, C, F, Mg, and P (squares, circles, triangles, diamonds and crosses, respectively) from the reaction $19.1 \text{ MeV/u } ^{48}\text{Ti} + ^{93}\text{Nb}$. The tight correlation indicates that the forward momentum along the beam direction is nearly independent of the partition into forward fragments.

Figure IIC5.6. Energy correlation between a Si IMF and α particles from the 19.1 MeV/u $^{48}\text{Ti} + ^{93}\text{Nb}$ reaction. The IMF was detected at $\theta_{lab} = 8.4^\circ$ and the α particles in any of the nearby Wall detection (average $\Delta\theta \simeq 7.5^\circ$). The energies are in MeV/u. The two kinematic solutions are clearly seen and correspond to the sequential emission of α particles from the primary PLF. For lighter IMF's the two solutions come closer in E_α .

IIC6. Characteristics of Heavy-Ion Collisions at 45 MeV Nucleon. Reactions of ^{84}Kr with ^{12}C , ^{27}Al , ^{45}Sc , ^{93}Nb , ^{159}Tb and ^{181}Ta - L.G. Sobotka, Z. Majka, R.J. Charity, D.W. Stracener, D.G. Sarantites [WU], G. Auger, E. Plagnol, Y. Schutz [GANIL], R. Dayras, J.P. Wieleczko [SACLAY], J. Barreto [ORSAY] and E. Norbeck [U. of I.]

One of the most stimulating and challenging aspects of the intermediate-energy heavy ion collision studies is the observed growth of intermediate mass fragment (IMF) production with beam energy. A variety of models have been proposed for the complex-fragment formation mechanisms ranging from the binary decay mechanism¹ to a large group of multifragmentation mechanisms.² On the other hand, very little experimental data are available (those that are mostly single fragment inclusive measurements) and an unambiguous verification of the models has not been feasible up to the present time. An event-by-event coincidence measurement of all reaction products with a large solid angle acceptance is required in order to understand the fragment formation mechanism. Only recently, the LBL/GSI Plastic-Ball-Wall detector system was used to study light charge particles (LCP) and IMF emission over a large solid angle in 200 MeV/nucleon heavy ion collisions at Bevalac.³ Emulsion data at energies between 55 and 110 MeV/nucleon give direct evidence for events with a complete explosion of the system.⁴ These data provided the impetus for us to generate a data set on which statistical analyses can be performed with the aim of determining the mechanism for these explosion events.

Here we report the observation of the complete disintegration of colliding nuclei in 45 MeV/Nucleon ^{84}Kr induced reactions. Using a 4π type detection system we selected a

subset of events for which the total undetected charge in each event is smaller than one-third of the target nucleus charge. The characteristics of these events suggest that they originate from a different process than those accompanied by a heavy remnant.

The experiment was performed at the GANIL facility. A 45 MeV/nucleon ^{84}Kr beam was used to bombard several targets (^{12}C , ^{27}Al , ^{45}Sc , ^{93}Nb , ^{159}Tb and ^{181}Ta) placed in the Cyrano scattering chamber. Here we focus on the results from the $^{84}\text{Kr} + ^{159}\text{Tb}$ reaction. The IMF's and LCP's were detected with the 103 element Dwarf system.⁵ Each phoswich detector consisted of a thin fast plastic scintillator foil followed by a thick CsI(Tl) scintillator. The thickness of the fast plastic scintillators varies from 200 μm to 10 μm for the detectors between 8° and 156° . The thicknesses of the CsI(Tl) detectors also vary with angle, being 20 mm for angles between 8° and 35° , 8 mm between 35° and 56° and 4 mm for angles greater than 56° . In order to suppress secondary electrons and X-rays the detectors located at $\theta > 60^\circ$ and the detectors located at $12^\circ < \theta < 60^\circ$ were covered by Au foils of 1.7 mg/cm² thick and Ta foils of 7.4 mg/cm², respectively. The most forward detectors at $\theta < 12^\circ$ were shielded by Ta of 10 g/cm². These absorbers lowered the efficiency for the detection of the IMF's, but still allowed for the detection of LCP's. Two opposite detectors have been replaced by two small entrance and exit beam tubes which act as cleanup collimators. Two additional elements were removed for insertion of the target and viewing a scintillator in the target position, which was used for beam focusing. The detection array provided an angular coverage corresponding to approximately 93% of 4π .

The system was employed in a self-triggering mode. Isotopic identification for the LCP's ($Z \leq 2$) and elemental identification of the IMF's up to $Z = 24$ was obtained by integrating the photomultiplier anode current during three different time intervals. This information was also used to obtain the energy of the LCP's. The detection thresholds vary from 3.8 MeV to 1.0 MeV for protons and from 15.0 MeV to 3.6 MeV and for alpha particles from the most forward to the most backward angles. All heavier fragments which passed through the absorber were included in the multiplicity determination even when they stopped in the plastic scintillator foils. The resulting detection thresholds varied from 1.8 MeV/nucleon to 0.4 MeV/nucleon for the forward and the backward angles, respectively.

In Figure IIC7.1 we have plotted the distribution of total charge (thick solid line) detected by Dwarf-Ball-Wall system for the reaction $\text{Kr} + \text{Tb}$. One can see that in this measurement a significant number of events were recorded for which more than 75% of total charge of the projectile and target nuclei ($Z_{\text{tot}} = Z_p + Z_t = 101$) was detected (shaded area in Figure IIC7.1). Distributions of the detected charge in the LCP's (dashed line) and in the IMF's (thin solid line) for this subset of events are also shown in Figure IIC7.1. Here, we observe that as much as one-third of the total detected charge is in the form of the LCP's.

The LCP multiplicity, M_{LCP} , as a function of the multiplicity of the IMF's, M_{IMF} , is shown in Figure IIC7.2(a). One can see that the M_{LCP} distributions have two components [see Fig. IIC7.2(a)]. When only a few IMF's are detected the M_{LCP} distributions peak at rather low value ($M_{\text{LCP}} < 8$). As the number of detected IMF's is increased the M_{LCP} distributions become broader, almost flat-topped, and extend to considerably higher

Figure IIC7.1. Total detected charge distribution (thick solid line). Distributions of detected charge in the LCP's and the IMF's for the shaded area of the total detected charge are given by dashed and thin solid lines, respectively.

Figure IIC7.2. (a) The LCP multiplicities (thick solid lines) and correlation between the multiplicity of the IMF and the LCP multiplicities (thin solid lines) for the $^{84}\text{Kr} + ^{159}\text{Tb}$ system. (b) The same as (a) but for $Z_{det} > 75$. (c) The same as (a) but for $20 < Z_{det} < 45$.

values. For still larger M_{IMF} values, the M_{LCP} distributions regain a peaked form but with substantially greater mean value than for the distribution for the low M_{IMF} values. In Figs. IIC7.2(b) and (c) we again plot the correlation between the IMF multiplicity and the LCP multiplicity, however, with the requirement that the total detected charge (Z_{det}) is greater than 75% of Z_{Tot} [Fig. IIC7.2(b)] and that $20 < Z_{det} < 45$ [Fig. IIC7.2(c)]. Here we observe one component distributions of the M_{LCP} which peak at high/low values for

a large/small value of the total detected charge, respectively. The same features are seen for all heavy targets, see Fig. IIC7.3.

Figure IIC7.3. The top panels show the heavy fragment (thin lines), LCP (dashed lines) and total charged particle multiplicity distributions (thick lines) from the 45 MeV/u ^{84}Kr bombardment of the indicated targets. The bottom panels show the LCP multiplicities observed in coincidence with the indicated number of intermediate mass fragments ($A > 4$).

Since the detection system is efficient for the detection of light ions but becomes more inefficient as the charge increases and the ion velocity decreases (due to absorbers), the events with low values of total detected charge must be associated with one or a few undetected massive heavy ions. This suggests that the component of the M_{LCP} distribution in coincidence with only a few IMF's which also tends to have a large deficit in the total detected charge, results from deep inelastic like or fusion events in which a massive residue survives but escapes detection. On the other hand, the component of the M_{LCP} distribution in coincidence with several IMF's is associated with well characterized ($Z_{det} > 75$) nuclear explosion with no surviving massive remnant.

One of the important questions in intermediate energy heavy-ion reactions is whether the complex exit channel configurations which are observed, are the result of new decay modes of highly excited nuclear configurations or the result of multiple sequential decays of the sort familiar in low energy studies. The possibility of a prompt-one step nuclear

disassembly has been raised by several theorists. Unfortunately, the difference in the observables generated by multistep sequential and prompt one step are rather subtle. However, López and Randrup⁶ have shown that there is a difference in the global event shapes.

We are presently working on a comparison of experimental event shapes vs those generated by the sequential emission code GEMINI. Our logic is quite different than other intermediate energy global event shape analyses, in that we are trying to develop an event selection rather than a particle selection. The standard method is to use all events but only those which satisfy a midrapidity gate. This means that large multiplicity central events are mixed with small portions (but many of them) of more peripheral events. We have not as yet determined what the most reasonable method of event selection is but we anticipate some combination of large background multiplicity and the absence of excessive forward momentum.

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L. Csernai and J. Kapusta, *Phys. Rep.* **131**, No. 6 (1986).
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6. J.A. López and J. Randrup, in *Nuclear Dynamics and Nuclear Disassembly*, Ed. J.B. Natowitz, (World Scientific, 1989), p.400.

IIC7. Origin of Hard Photons in Heavy-ion Collisions - A. Chbihi, L. Gallamore, N.G. Nicolis, D.G. Sarantites, L.G. Sobotka, D.W. Stracener [WU], J.R. Beene, F.E. Bertrand, M. Thoennessen [ORNL], R. DeSousa, N. Carlin, C.K. Gelbke, Y.D. Kim, W.G. Lynch, R. Ronningen and M.B. Tsang [MSU]

The study of high energy photons emitted in HI reactions has recently received much attention because photon emission from any stage of the reaction will not be altered by final state interactions.

It has been argued by several groups that incoherent nucleon-nucleon scattering can account for the inclusive hard photon production in intermediate energy collisions (see a review by V. Metag in Ref. 1). In this case the leading nucleon-nucleon interactions would dominate the hard photon production, which would be essentially independent of the dynamics that govern the evolution of the reaction. Others have claimed that compound nucleus decay with inclusion of the quasi-deuteron resonance can explain the inclusive data.² From the reaction mechanism standpoint, however, the most appealing idea is that of a collective or cooperative action of many nucleons to produce the hard photons. This was first proposed by Shyam and Knoll³ as an explanation of the subbarrier π production. This will go in hand with IMF production. Similarly, a positive correlation between IMF and hard photon production is expected from models that include coalescence heating.⁴⁻⁶ Thus, in Friedman's calculations⁶ the production of Li occurs at a later stage after the expansion and cooling of the system by nucleon emission. At this point, when the system has low pressure then the coalescence of several nucleons becomes energetically favored.

High energy nucleon-nucleon interactions will also be favored by the coalescence energy and this will enhance hard photon production.

This latter explanation can be checked experimentally by measuring the correlation between the production of IMF's and hard photons. Apart from the trivial anti-correlation imposed by energy conservation one must find a synergic effect in order to support the coalescence picture.

We have carried out two experiments in order to study the origin of hard photons. The first one was done at ORNL employing the reactions 25 MeV/u $p + {}^{159}\text{Tb}$ and ${}^{16}\text{O} + {}^{159}\text{Tb}$. Four 19-detector packs of BaF_2 were used in coincidence with the Dwarf Ball and Wall. The data are being analyzed by D. Stracener, D.G. Sarantites, and the ORNL group.

The second experiment was done at the MSU superconducting cyclotron facility in collaboration with the ORNL group of Beene and the MSU group of Gelbke and Lynch. We used the reactions 30, 45 and 65 MeV/u ${}^{40}\text{Ar} + {}^{159}\text{Tb}$, and 31 and 41 MeV/u ${}^{128}\text{Xe} + {}^{159}\text{Tb}$. Two of the ORNL packs of 19 BaF_2 detectors were employed in coincidence with the Dwarf system. The analysis of this experiment is mainly the responsibility of L. Sobotka. At the same time in this run at MSU we have obtained some excitation function data for the production of intermediate mass fragments.

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2. N. Herrmann *et al.*, *Phys. Rev. Lett.* **60**, 1630 (1988).
3. R. Shyam and J. Knoll, *Nucl. Phys.* **A426**, 606 (1984).
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6. W.A. Friedman, *Phys. Rev. Lett.* **60**, 2125 (1988).

IIC8. Azimuthal Distributions of Fission Fragments and α Particles Emitted in the Reactions ${}^{36}\text{Ar} + {}^{238}\text{U}$ at $E/A = 20$ and 35 MeV and ${}^{14}\text{N} + {}^{238}\text{U}$ at $E/A = 50$ MeV - M.B. Tsang, Y.D. Kim, N. Carlin, Z. Chen, C.K. Gelbke, W.G. Gong, W.G. Lynch, T. Murakami, T. Nayak, R.M. Ronningen, H.M. Xu, and F. Zhu [MSU], L.G. Sobotka, D.W. Stracener, D.G. Sarantites, Z. Majka, and V. Abenante [WU].

Intermediate energy nucleus-nucleus collisions exhibit a subtle interplay between mean-field and nucleon-nucleon collision dynamics. At low incident energies, the mean field is largely attractive. As a consequence, light particles are predominantly emitted to negative deflection angles in the entrance channel reaction plane.¹⁻⁶ With increasing energy, individual nucleon-nucleon collisions are less hindered by the Pauli exclusion principle and the azimuthal distribution of the emitted particles should become more isotropic. A number of measurements¹⁻⁶ are in qualitative agreement with such expectations. To be more quantitative, however, one must locate the entrance channel reaction plane experimentally and know how accurately it has been determined. Well calibrated techniques for determination of the orientation of the reaction plane are also essential for measurements of triple differential cross sections⁷ $\sigma(E, \theta, \phi)$ and for transverse flow analyses.⁸

In order to explore the distribution of particles in and out of the reaction plane and to explore techniques for reaction plane determination, we have investigated correlations between coincident fission fragments and a particles emitted in the reactions $^{36}\text{Ar} + ^{238}\text{U}$ at $E/A = 20$ and 35 MeV and $^{14}\text{N} + ^{238}\text{U}$ at $E/A = 50$ MeV. The experiment was performed with beams from the K500 cyclotron of Michigan State University.

The data were analyzed by Betty Tsang and a paper was published in Rapid Communications in *The Physical Review*. A reprint is included as Appendix O and the abstract below summarizes our results:

ABSTRACT: Azimuthal correlations between coincident fission fragments and α particles were measured for the reactions $^{36}\text{Ar} + ^{238}\text{U}$ at $E/A = 20$ and 35 MeV and $^{14}\text{N} + ^{238}\text{U}$ at $E/A = 50$ MeV. At all energies, coplanar emission is enhanced. The azimuthal distributions for fission fragments and α particles are decoupled using a simple parameterization. Both azimuthal distributions are highly anisotropic at lower incident energies; these anisotropies decrease with energy. At the highest incident energies, energetic α particles emitted at large transverse momenta appear to be more suited than fission fragments to tag the orientation of the entrance channel reaction plane.

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4. M.B. Tsang *et al.*, *Phys. Lett.* **148B**, 265 (1984); C.B. Chitwood *et al.*, *Phys. Rev.* **C34**, 858 (1986).
5. D. Ardouin *et al.*, *Nucl. Phys.* **A447**, 585c (1985).
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III. INSTRUMENTATION AND ANALYSIS

IIIA. NEW INSTRUMENTATION

IIIA1. Improvements in the Dwarf Ball and Wall – D.G. Sarantites, L.G. Sobotka, L. Gallamore, D.W. Stracener, J. Elson, and J.T. Hood.

The performance and characteristics of the Dwarf Ball and Wall system have been described in detail in a paper accepted for publication in *Nucl. Instr. and Methods* (a preprint is included as Appendix P).

In the process of testing the performance of Dwarf System detectors and comparing the performance of our detectors with those of the MSU Miniball¹ we observed that there may be some possibilities for improving the performances of the Dwarf detectors. One factor is the use of UV transparent light guides that might enhance the amount of light from the fast plastic (420 μm shifting to 380 μm for thinner scintillators) that reaches the photocathode. A second factor was the uniformity of the light output across the face of the detector.

We have tested the transmission of the light from the scintillators through UV light guides and normal lucite ones and find no statistically meaningful difference between them.

Next, we acquired new CsI(Tl) scintillators from Quartz and Silice, Inc. and tested the light output uniformity with a precisely collimated α -source. We found that practically all scintillators had typical non-uniformity $\pm 0.6\%$ (from the center to the outer radius). We cut the scintillators to the geometry of the Dwarf Ball detectors and assembled several elements. The new detectors showed non-uniformities as large as 4% from the center to the edge. Similar non-uniformities were found in the already assembled detectors in the Ball. We are now trying methods of surface treatment to make the light collection more uniform. If this works, we will apply this method to the present detectors and if need be we will replace the crystals.

We are also in the process of assembling replacement (spare) detectors for about 25% of the Ball and Wall detection to replace those elements with the poorest particle identification resolution.

1. R.T. DeSouza *et al.* Preprint MSUCL-720 (NIM in press).

IIIA2. The MiniNose – L.G. Sobotka, D.G. Sarantites, J. Elson, and J.T. Hood.

Last year we proposed to construct a highly-segmented forward array of CsI(Tl) + fast-plastic scintillators to complement the MSU Miniball at forward angles (a detailed working design is given in the accompanying proposed program).

We have acquired samples of CsI(Tl) scintillators (2.5 x 2.5 x 5.0 cm) from several manufacturers and tested their uniformity. The detectors await testing with beam to establish the performance for interdeterminate mass fragment resolution with the longer crystals. These tests awaited the construction of a new prototype splitter module necessary for the integration of the signals from 16 detectors with the single gate to the ADC. The details of this module are discussed in the next section. The beam test will be scheduled

for October and then we will proceed with the completion of the design and construction of the hodoscope.

IIIA3. New Electronics of the Dwarf Ball, Wall, and MiniNose - J. Elson, D.G. Sarantites, L.G. Sobotka, and D.W. Stracener.

As a result of the extensive tests on the performance of the Dwarf Ball and Wall system in preparation of a NIM manuscript for the Dwarf system (see Appendix P for a preprint), and in view of the special needs for the proposed hodoscope (the MiniNose) we have discovered a number of deficiencies in our electronics modules for the Dwarf system. In the following we summarize the problems and then the steps taken to correct them.

- (1) With respect to the counting rate stability of the CsI(Tl) detectors, we discovered that the AC coupling constants in our slow splitter were too long. This resulted in a decrease in gain for the slow and long components at high counting rates due to a base line shift (see fig. 19 in Appendix P). This is in the opposite direction to the pile-up.
- (2) The present homemade discriminators produce a logical pulse width which is equal to the width of the linear pulse above the discrimination level. This effect, although useful for rejecting narrow pulses from target electrons, caused a loss of triggers when the Dwarf system was run at high counting rates. This caused loss of multiplicity information under conditions of counting rates in excess of ≈ 2 KHz (for example, at 7 KHz a loss of triggering efficiency of $\approx 20\%$ was observed).
- (3) For high gain applications the present photomultiplier tubes show a significant number of dark current pulses which have rise and decay times of ≈ 2 ns, and amplitudes equivalent to 1-2 MeV α 's. These unwanted pulses trigger our leading edge discriminators. Similarly, fast pulses of large amplitude can arise from electron production in the target, particularly when heavy beams are used. Depending on the beam intensity, these pulses can pileup and reach amplitudes as high as 20 MeV. Their intensity can be quite high in applications where high beam currents are needed when low efficiency external devices are used to trigger the Dwarf system. The amplitude of these pulses can be reduced to some extent by use of undesirably thick absorbers (here use of deflecting magnets or applying high voltage to the target are out of the question).
- (4) The concept of using a common FERA ADC gate, produced by the earliest trigger in a bank of 16 detectors, works well for the Dwarf Ball and Wall. A difference of only 1.2 ns exists between pulses from 2 and 25 MeV/u particles in the Ball (because of its small size giving a flight path of 38 mm). For the Wall the difference increases to 4.8 ns (flight path of 13 cm), and for the MiniNose to 29 ns (flight path of 80 cm). This indicates that in the MiniNose, the pulses from the fast plastic associated with the low energy particles will walk out of the fast gate, causing loss of resolution and efficiency.
- (5) The warmup of the Dwarf system with its operation in vacuum raises the operating temperature 26°C to 34°C . This causes a 7% and 20% reduction in gain of the slow and the long component light output of the CsI(Tl), respectively (see Fig. 21 in Appendix P). This occurs in a period of ≈ 6 hours after which the gains remain constant.

The following steps were taken to correct the above problems:

- (a) Problem (1) was corrected in the present splitters by shortening the AC coupling constants significantly.
- (b) Problem (2) was corrected by introducing a high frequency pass filter before the discriminator. This produces a fast negative going pulse preserving the fast rise time of the input signal and having a crossover at ≈ 400 ns with a positive overshoot that returns to the base line in about $1 \mu\text{s}$. Thus, all the discriminator pulses now have width close to 400 ns which varies very little with the threshold level.
- (c) The difficulty with the bank gating, discussed in (3) above, can be removed in a clever and economical way. Normally, the solution would have been to introduce linear gates for every detector (particularly for the MiniNose hodoscope). This is both expensive and incompatible with the compact electronics for the Dwarf system. Instead, we have taken advantage of the insensitivity of the FERA ADC's to the positive part the linear pulse and designed a new *three-way splitter*, which solves the walk problem and can allow improved the performance up to high counting rates of 20 KHz per detector. The fast branch of the new *three-way splitter* passes only the fast pulses from the plastic scintillator. An example of this is shown in Fig. 7 of Appendix P, where oscilloscope traces of the raw and shaped pulses are shown using an α source and a CsI(Tl)-plastic phoswich with a $30 \mu\text{m}$ fast scintillator. The digitized gain was shown to be independent of the linear delay in a stretched gate for the fast ADC. The improved stability to counting rate is also shown in Fig. 20 of Appendix P. The shaped slow and long CsI(Tl) components have crossover times at 2 and $4 \mu\text{s}$ and their overshoots return to base in 5 and $15 \mu\text{s}$, respectively. Tests with beam of a 16-channel prototype have been scheduled early this fall. Then, we will proceed with the construction of 8 modules for the complete Dwarf system.
- (d) Problem (4) can be solved by designing a *two-dimensional discriminator* that is capable of rejecting both triggering pulses below a certain amplitude and width. Such a discriminators will fulfil our objective because all the usefull pulses have widths larger than 5 ns due to the CsI(Tl). Even when low energy particles stop in the fast plastic, they always have a low amplitude slow component (large width above the discriminator level) that can be accepted in the trigger. A single channel for the new *two-dimensional discriminator* has been assembled and tested. It performs quite satisfactorily. The layout for the complete module has been designed and a single prototype module is under construction. The new discriminator incorporates the input shaper described in (b) above.
- (e) The solution to problem (5) is obvious. A warm-up period of 6 hours is necessary prior to data taking. However, once the Dwarf system has reached a steady operating temperature, it is possible to open up for a short repair or target change with minimal delay, since the slow cooling rates observed allow data taking to resume after pumpdown.

IIIA4. Large Area Neutron Time of Flight Detectors – D.G. Sarantites, J.T. Hood, and L.G. Sobotka.

Last year we proposed to construct a number of large area neutron detectors. We have acquired on loan ten RCA 4522 5" photomultiplier tubes from ORNL. These tubes were originally in the Spin Spectrometer and have been replaced by new ones due to some loss of gain and energy resolution when operated with the NaI(Tl) detectors. For timing purposes using NE-213 scintillators, they are quite adequate for neutron detectors.

The detectors currently under construction, are cylindrical 25 cm in diameter and 7 cm thick. The PMT tubes view the scintillators through air of a conical, light reflecting, coupling container. We have employed such a detector design some 15 years ago with Pilot 102 scintillators. With the NE-213 scintillator in this geometry we were able to achieve acceptable separation between neutron and γ -ray pulses by pulse-shape discrimination.

IIIB. METHODS OF ANALYSIS

IIB1. Z and E Dependence of the CsI(Tl) Light Output and Energy Calibration of the Dwarf System – D.W. Stracener, A. Chbihi, V. Abenante, and D.G. Sarantites.

The energy calibration of the detectors of the Dwarf Ball and Wall is essential in the analysis of the data from this detection system. Six experiments addressing reaction mechanism questions have been done by our group that needed energy calibrations for intermediate mass fragments. The problem is by no means trivial in terms of effort. This is because there is a strong non-linear dependence of the light output of the CsI(Tl) scintillators as a function of Z and energy of the detected ion.

For this purpose we developed a simple and rapid method for measuring the light output of the CsI(Tl) for many Z values and for a broad range in incident energies. A set of four 40 μ m thick Si surface barrier transmission detectors were employed as ΔE detectors in (ΔE , E) telescope arrangements with each CsI(Tl) element of the Dwarf system as the E detector. The Si detectors were accurately gauged for thickness with the 8.78 MeV α particles from ^{212}Po . We employed the reaction 19.0 MeV/A ^{48}Ti on ^{100}Mo to produce intermediate fragments and light ions. A set of 24 Ball and 12 Wall detectors were calibrated by positioning them 4 at a time behind the 4 Si detectors. The plastic scintillators were removed and the CsI(Tl) detectors were individually wrapped with aluminized mylar (170 $\mu\text{g}/\text{cm}^2$). Event data were recorded with a low and a high gain for both the Si and the CsI(Tl) signals. The elements up to Z=24 were fully resolved and some isotopic resolution for Li and Be was observed. This is shown in Fig. 12 of Appendix P, where maps of the Si ΔE vs. the CsI(Tl) slow are displayed for two Si ΔE gains are displayed as density plots. The Si ΔE detectors were calibrated with α particle sources and the linearity was checked with pulsers. The relative light output was determined from lines drawn on the ridges of each ion species. From the energy of each ion deposited in the Si ΔE detector, the energy of the ion entering the CsI(Tl) detector was calculated using the code STOPX based on the Ziegler¹ parametrization of the stopping power equations. In order to find a common reference for the light output we calibrated the CsI(Tl) detectors with protons using the elastically and inelastically scattered protons from the reaction $^{12}\text{C}(p,p')$ at 14.0 and 22.0

MeV. The pulse height of the slow component corresponding to 20 MeV protons was used as the reference.

The results are discussed in detail in section 4.2 of Appendix P. A summary of the nonlinearities can be seen in Fig. 18 of Appendix P. Here, we note that significant variations were found between the light output of different detectors. If the average light output from 36 detectors is used for energy calibration, uncertainties in the energy were estimated to be $\pm 3.5\%$, $\pm 5.0\%$ and $\pm 6.5\%$ at 2.0, 8.0, and 15.0 MeV/u, respectively. The observed differences in light output between detectors is probably due to non-uniform Tl doping of the CsI(Tl) crystals.

A convenient empirical equation for energy calibration purposes is given by eq. (8) of Appendix P, namely,

$$\epsilon = a \cdot \ell + b \cdot \ln(1 + c \cdot \ell) \quad (1)$$

where ϵ is in MeV/u, ℓ is the light output relative to that for 20 MeV protons, and the coefficients a , b , and c are adjustable parameters obtained by a least-squares fit of the above equation to the data (they are given in Table 4 in Appendix P and are plotted in Fig. IIB1.1 as full symbols).

Figure IIB1.1. Suggested values of the coefficients a , b , and c of eq. (1) for extrapolating the energy calibration to higher energies for the CsI(Tl) detectors for the higher $Z_{AMF} = 18 - 23$.

We have recently realized that the coefficients for α particles can be refitted with a constraint that at large E_α they give the correct asymptotic values of the light output. The corrected values are given in Table 7 of Appendix P. We also point out that the coefficients for $Z = 18-23$ are only useful for the energy range 1-16 MeV/u where experimental data were taken. If extrapolation to higher energies is needed the extrapolated values shown in Fig. IIB1.1 by the open symbols may be more appropriate.

1. Code STOPX by T. Awes, using the parameterization of U. Littmark and J.F. Ziegler, "Handbook of Range Distributions for Energetic Ions in all Elements," Pergamon (1980). Vol. 6, p. 4.

IIIB2. Simulation of the Response of the Dwarf System Lisa L. Wittmer, Z. Majka, and D.G. Sarantites.

A quantitative knowledge of the response of the Dwarf System to a known input of charged particles of given multiplicities and energies is important for the diverse experiments that we have undertaken. There are two somewhat different instances where the response of the Dwarf system is needed. The first involves calculation of cross sections for specific channels often needed in fusion reactions, and the second when distributions of measured or derived quantities are considered. In the latter case, it is preferable to filter the results of model calculations through the detector response and then compare with experiment.

In any case, we make use of a computer code which incorporates the exact geometry of the Dwarf system and produces a matrix which maps the spherical polar angles θ and ϕ into the appropriate detector number. This matrix is then used in other codes which include energy thresholds, holes made by removing detectors, etc. in order to simulate the effect of the system response.

We have simulated the response of the Dwarf system for the reaction $^{28}\text{Si} + ^{58}\text{Ni} \rightarrow ^{86}\text{Mo}^*$ at 110 MeV. We used realistic thresholds and event data in the laboratory system produced by the code PACEX and calculated the response of the device for the major exit channels. The results are summarized in Table IIIB2.1. The various columns in the table show the percent distribution of the events into the possible gates indicated in the first column. Typically, the detection efficiency for a particle is 0.86 (includes the effect of holes, gaps, and thresholds in one of our experiments). Thus, the efficiency for detecting all 4 protons from the 4p channel is 54.5% ($\approx 0.86^4$), while the probability for detecting only 2 out the 4 protons is 9.1%. From the example of Table IIIB2.1 it is quite clear that the high multiplicity events contribute significantly to the lower multiplicity gates. For cross section measurements where Ge detectors are used to select a channel this is not a problem, because all that is needed is a good estimate of the Dwarf system efficiency. Also, spectra gated with Ge detectors are also unaffected by the channel mixing. Thus, the Dwarf System can be used in conjunction with the Ge detector to gate and separate channels.

The problem of channel mixing discussed above does not distort significantly channel identification for the reaction studies at energies below 25 MeV/u that we have been studying. This is because the charged particle multiplicities involved in those systems were small. For higher energy reactions and for reactions induced by very heavy projectiles the LCP charged particle multiplicities reach values of ≈ 20 and IMF multiplicities of ≈ 5 are common. In those cases channel selection becomes unimportant and global event quantities are more meaningful. In such cases the detector response must be entered in the model calculation and then compared with the data.

Table IIB2.1. Calculated (%) detection efficiencies for the reaction $^{28}\text{Si} + ^{58}\text{Ni}$ at 160 MeV.

Channel→ Yield	4p (22%)	α 2p (14%)	3pn (13%)	α 3p (9%)	2 α p (8%)	3p (7%)	2 α 2p (5%)
Gate	0	0.3	0.1	-	0.3	0.4	0.1
1p	1.1	3.6	5.8	0.9	2.3	5.3	0.5
2p	9.1	11.6	31.1	4.1		32.1	1.5
3p	35.3		63.0	10.3		62.3	
4p	54.5						
α		1.6		0.2	3.9		0.4
2 α					11.0		1.4
α p		20.4		4.9	23.1		6.9
2 α p		62.6			59.5		17.7
α 2p				26.7			19.7
α 3p				52.8			
2 α 2p							51.6

IIIB3. Statistical Model Calculations in Highly Excited Compound Nuclei with PACEX - N.G. Nicolis, D.G. Sarantites [WU], and J.R. Beene [ORNL].

The interpretation of the deexcitation properties of highly excited compound nuclei heavily relies on the comparison of the relevant quantities with the predictions of a statistical model calculation. Recent experimental efforts are focused on the study of the emission properties of highly excited and rapidly rotating compound nuclei. Topics of special interest are, for example, the investigation of the shapes of the deexciting nuclei through their charged particle decay properties and the behavior of the nuclear level density parameter at high excitations.^{1,2} Excitation energies of ≥ 200 MeV in the compound nucleus are typical in most of these studies.

It can easily be realized that the currently available statistical model codes have certain limitations for the interpretation of such experiments. Their main limitations arise from the excitation energy range of their validity and the type of the decay modes considered. Indeed, only n, p, α , and sometimes deuteron emissions were included in the past at compound nucleus excitation energies of up to ~ 200 MeV.

The need for statistical model calculations in highly excited compound nuclear systems has prompted the development of the high excitation energy Monte-Carlo evaporation code PACEX. The Monte-Carlo nature of the code makes it particularly useful in experimental studies with the Spin Spectrometer, where complicated gating conditions have to be simulated.

PACEX came after extensive modifications and revisions of the code PACE2S.³ The main features of PACEX are described briefly below:

- (1) The excitation energy range of the validity of the code was extended. Large (E^*, J) arrays have been employed, an E^* bin width which increases with increasing E^* and extra code to insure that level density arrays do not suffer exponential overflows at high E^* .
- (2) The number of the allowed particle decay modes was extended to n, p, α , d, t, ^3He and ^6Li emission. The user is able to decide about the number of modes to be included in a particular calculation (in the above order). In the present status, it is straightforward to include two additional decay modes, if necessary.
- (3) An improved treatment of the transmission coefficients for charged particle emission was included. Transmission coefficients for charged particle emission are usually derived from an optical model calculation. To reduce the computational time, PACE2S employed only a single optical model calculation for n, p and α emission from the compound nucleus. Transmission coefficients needed in the subsequent steps of the statistical model calculation were obtained from this one after Z, N and energy extrapolation. Although this method may be adequate if the number of emitted charged particles is small, it introduces uncertainties in the subbarrier yields of charged particles. Medium to light compound systems, neutron deficient systems and almost all of the very high energy systems were expected to involve uncertainties in their calculated low energy properties.

The above problem is now solved at two levels: (a) Exact transmission coefficients are created for each type of emitted particle in a specified range of energies. The results for each Z of the emitting system that is relevant in the calculation are stored in a file to be used by PACEX. In this option, the corresponding N is calculated internally, assuming a certain neutron excess. In the code, a scaling procedure takes into account the size differences of the different isotopes. (b) Exact transmission coefficients are created for each type of emitted particle in a specified grid in (Z, N) and a given range of energies. These files are then used in the statistical model calculation. This option is completely free of calculational uncertainties in the transmission coefficients.

- (4) The code provides the ability of simulating deformation effects in the penetrabilities for charged particle decay. The daughter nucleus is assumed to have an axially symmetric prolate (or oblate) shape, which is parametrized in terms of the quadrupole deformation parameter β_2 as

$$R(\theta) = R_0[1 + X(\beta_2) + \sqrt{5/4\pi}\beta_2P_2(\cos\theta)]. \quad (1)$$

Here, θ is the angle with respect to the symmetry axis and $X(\beta_2)$ is the volume conservation term. Optical model transmission coefficients for charged particle emission are calculated for all of the nuclei in the cascade [in a specified (Z, N) grid] at 9 different angles of emission from the nuclear surface from 5° to 85° in steps of 10° . At each angle, the optical model radii are scaled according to Eq. 1. The diffuseness of the Woods-Saxon nuclear potential of the spheroid is also modified, so that the normal derivative at each point on an equipotential surface is unaffected by the deformation¹. The above transmission coefficient sets are stored in computer files to be read by PACEX. In the execution of the program, charged particle emission from a particular point of the emitter nucleus surface is selected with a random number weighted by the corresponding surface element of the spheroid:

$2\pi R^2(\theta)\sin\theta\Delta\theta/S$. Here, S is the nuclear surface including the first order correction term due to deformation: $S = 4\pi R_0^2(1 + a_2^2/5)$, with $a_2 = \sqrt{5/4\pi}\beta_2$.

(5) An new option for the calculation of the nuclear level densities was included. This option makes use of the Lang formula⁴ with level density parameters and backshifts from the compilation of Dilg *et al.*⁵ Excitation energy limits have been introduced to study the effect of a changing level density parameter on the charged particle spectra.

(6) The code contains a "weighted" Monte-Carlo feature designed to study high energy gamma events. The weighing feature is turned on by setting a proper input flag. This feature is implemented by introducing games of Russian Roulette to kill off uninteresting cascades before computer time is wasted following them. At each step of a cascade which *has not yet produced a gamma*, a game of roulette is played, with a survival probability, p (constant for a run in the range 0 to 1). A weight is kept for each cascade. Cascades which are killed off in a game of roulette have their weight set to zero, and are not processed further. A cascade which survives a game has its weight multiplied by $1/p$. In addition an excitation energy limit is included, below which cascades are not followed.

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IIIC. COMPUTER FACILITY

IIIC1. Present Status of Our Computer Facility – New Hardware – D.G. Sarantites, L.G. Sobotka, and J. Elson.

As proposed, this year we upgraded our computer system both in CPU power and peripherals. There were two objectives that governed our choices in the upgrade. The first, as always, was get the most overall computing power for a given expenditure and the second one, to reduce substantially the yearly maintenance costs.

In order to achieve these goals, we decoupled, to a large extent, our computer system from that of the Chemistry Department. The system is now managed by J. Elson and our computer system is connected to the Chemistry computer facility (and to other computer systems on campus) only through the DEC ethernet for the purposes of having access to BITNET and a few expensive commercial software libraries such as IMSL and DISPLA. The new configuration of our system includes 3 VAX workstations of the 3000 series operated in a local area cluster mode.

A block diagram of the present system is shown in Fig. IIIC1.1. The new hardware acquisitions are the VAX station 3100 with the high resolution graphics and graphics accelerator (SPX), one new Exabyte tape cartridge drive and a new streamer CYPHER tape drive. The VAX station 3100 (NCHEM) is now the cluster server and has the four WREN V disks (586 Mb each) connected directly on the SCSI port. The VAX station 3100 (ALPHA) has now the new tape drive CYPHER, two Exabyte drives and a local WREN V disk all connected to the SCSI port. The VAX station 3500 (BETA) is a Q-bus machine

Figure IIIC1.1. Block diagram of our computer facility.

and has a tape drive (STC 1953) and two Exabyte drives on it but it is diskless. Thus, there are two work stations equipped for tape scanning and one for calculations only. All three workstations have high resolution color graphics.

The savings on maintenance comes from dropping the maintenance for the disks, the exabytes and the tape drives. We maintain these by using one of each of these peripherals as the spare and obtain factory repairs when needed. The CYPHER tape drive will replace the expensive-to-maintain STC 1953 drive, which will be retired when it fails. Another reduction of the maintenance cost is in the CPU's which have low cost maintenance as workstations compared to full μ VAX-3 units. Finally, the campus wide DEC software library provides us with inexpensive system software maintenance and upgrades.

IIIC2. New DEC Windows Graphics Software – K. Myers and D.G. Sarantites.

The current display system adopted by DEC is based on DEC-Windows, which is industry compatible with the X-window architecture. In order to fully convert to this system we needed to adapt our 1- and 2-dimensional histogram display and analysis packages to the DEC-Windows environment.

This was accomplished this year by developing a program called SNAP written in the language C, so that it can be exported to other operating systems like UNIX, ULTRIX, etc. Many new features were incorporated in SNAP including pulldown menu window, multiple display windows for a 1- and 2- dimensional color displays, delimiting XY lines and mask drawing interactive capabilities, etc.

The program was completed last February and has been in full use by the group. In many respects it is more convenient and faster than our previous display program.

IV. SCIENTIFIC AND TECHNICAL PERSONNEL

IVA. WASHINGTON UNIVERSITY PERSONNEL

The following table summarizes the manpower effort by our group for the periods indicated.

Person	Position	Effort During Last Year (months)	Effort During Last 3 Years (months)
D.G. Sarantites	P.I.	9	27
A. Chbihi	Research Associate	12	26
N. Nicolis	Research Associate	12	36
H.C. Griffin	Visiting Professor	-	4
Z. Majka	Visiting Professor	-	13
V. Abenante	Graduate Student	12	36
D. Stracener	Graduate Student	12	36
L. Gallamore	Graduate Student	1	1
L. Wittmer	Undergraduate	3	3
O. El-Ghazzawy	Software Specialist	-	9
K. Myers	Software Specialist	3	3
J. Elson	Electronics	6	18
J.T. Hood	Design Engineer	3	9
Total (person months)		73	207
Total (person years)		6.1	17.3

Dan Stracener and Vincent Abenante are in their last year of graduate work and will be graduating in approximately one year.

A. Chbihi has accepted a 5-year position at GANIL and will be leaving the group by the end of this year.

Larry Gallamore and George Munoz are new nuclear chemistry graduate students who should be selecting a thesis advisor by the end of next year.

Lisa Wittmer was a summer student from the University of Detroit who has been accepted at Washington University for graduate work in nuclear chemistry next year.

We have also enjoyed an extensive collaboration with Lee G. Sobotka and his group.

IVB. COLLABORATIONS

Our group has continued to enjoy fruitful collaboration with numerous members of the Oak Ridge National Laboratory, including J.R. Beene, F. Bertrand, M.L. Halbert, D.C. Hensley, C. Baktash, I.Y. Lee, and N.R. Johnson.

We have continued our collaboration with C.K. Gelbke, W. Lynch and M.B. Tsang of MSU.

At GANIL we worked with the in-house scientists G. Auger, E. Plagnol, Y. Schutz and J. Barreto, R. Dayras and J.P. Wieleczko from Saclay.

V. PUBLICATIONS

VA. PAPERS PUBLISHED OR SUBMITTED (1987-1990)

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VB. PRESENTATIONS IN MEETINGS (1987-1990)

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