INVESTIGATIONS OF NUCLEAR STRUCTURE AND NUCLEAR REACTIONS INDUCED BY COMPLEX PROJECTILES

Progress Report for the Period
September 1, 1990 – August 31, 1991
for
Department of Energy Grant DE-FG02-88ER-40406

D.G. Sarantites - Principal Investigator

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MASTER

CONTENTS

I. OVERVIEW	1
II. SCIENTIFIC RESULTS	5
A. NUCLEAR STRUCTURE STUDIES AT HIGH SPIN	5
1. Search for Superdeformation in the $A \simeq 80$ Region.	5
2. Shape Coexistence and Disappearance of Pairing Correlations in ^{82}Sr .	8
3. Search for Multiple Superdeformed Bands in ^{136}Pm .	8
4. Alignment Processes and Shape Variations in ^{184}Pt .	9
5. Nuclear Structure Effects in Proton Evaporation Spectra.	9
B. STUDIES AT THE INTERFACE OF STRUCTURE AND REACTIONS	13
1. Population of Entry States in Heavy-Ion Fusion Reactions.	13
2. Entrance Channel Effects in Fusion near the Barrier.	15
3. Lifetimes of Subbarrier α -particles and Protons by the Atomic Clock Method.	19
4. Very Large Deformation Observed at High Excitation Energies via GDR Studies.	22
C. PRODUCTION AND STUDY OF HOT NUCLEI	24
1. Production of Hot Nuclei -- The Nuclear Level Density at High Excitations.	24
2. Statistical Deuteron and Triton Emission from Highly Excited Compound Nuclei.	27
D. INCOMPLETE FUSION AND FRAGMENTATION REACTIONS	32
1. Linear Momentum and Excitation Energy Reconstruction in Incomplete Fusion Reactions	32
2. The Mechanisms for Dissassembly of Excited ^{16}O Projectiles into Four α Particles.	32
3. A 4π Approach to the Energy Division in the Reactions of 19.1 MeV/nucleon $^{48}\text{Ti} + ^{93}\text{Nb}$.	33
4. Dissipative Collisions of 28.2 MeV/nucleon ^{136}Xe with ^{207}Bi -- Particle Multiplicity Correlations	36
5. A Study of the Particle Multiplicity Dependence of the High Energy Photon Production in a Heavy-Ion Reaction.	38

III. INSTRUMENTATION AND ANALYSIS	39
A. ADVANCES IN INSTRUMENTATION	39
1. The Dwarf Ball and Wall System.	39
2. The Miniwall	42
B. COMPUTER FACILITY	44
1. The Nuclear Chemistry Computer Facility	44
IV. SCIENTIFIC AND TECHNICAL PERSONNEL	45
A. WASHINGTON UNIVERSITY PERSONNEL	45
B. COLLABORATIONS	45
V. PUBLICATIONS	46
A. PAPERS PUBLISHED OR SUBMITTED (1988–1991)	46
B. PAPERS PRESENTED IN MEETINGS (1988–1991)	50
VI. APPENDICES	53
A. Shape Coexistence and Disappearance of Pairing Correlations in ^{82}Sr .	53
B. Alignment Processes and Shape Variations in ^{184}Pt .	60
C. Alpha-particle and Proton Probes of Nuclear Shapes in the Rare Earth and Mass 80 Regions (Crete).	62
D. Alpha-particles as Probes of Nuclear Shape in the Rare Earths and Structure Effects on Proton Emission in the Mass-80 Region (Miami).	64
E. Alpha-particle Emission as a Probe of Nuclear Shapes and Structure Effects in Proton Evaporation Spectra (ORNL).	66
F. Alpha-particles as Probes of Nuclear Shape and Structure Effects in Proton Evaporation Spectra (Zakopane).	83
G. Observation of Entrance Channel Effects in Compound Nucleus Formation with high energy γ -rays.	85
H. Very Large Deformation Observed at High Excitation Energies.	94
I. Yield Decomposition and Excitation Energy Reconstruction in an Incomplete Fusion Reaction.	96
J. Determination of the Nuclear Level Density at High Excitation Energy.	112
K. EVAP: A Monte Carlo Statistical Model Evaporation Code for High Energy Compound Nucleus Reactions.	125
L. Statistical Emission of Deuterons and Tritons from Highly Excited Compound Nuclei.	173

M. The Mechanism for the Disassembly of Excited ^{16}O Projectiles into Four Alpha Particles.	200
N. A Study of the Particle Multiplicity Dependence of the High Energy Photon Production in a Heavy-Ion Reaction.	239

I. OVERVIEW

The research program of our group touches five areas of nuclear physics: (1) Nuclear structure studies at high spin; (2) Studies at the interface between structure and reactions; (3) Production and study of hot nuclei; (4) Incomplete fusion and fragmentation reactions; and (5) Development and use of novel techniques and instrumentation in the above areas of research.

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 we published 6 letters, 2 rapid communications and 9 full papers. We also submitted for publication 3 full papers. In addition, 8 publications of invited talks appeared in conference proceedings.

In the following, we highlight our accomplishments and advances in the five areas of our effort. In the first area, we continued our search for superdeformation in the mass 80 region. From new experiments we have indications of a ridge in the E_γ - E_γ matrix in ^{82}Sr , which may correspond to the predicted superdeformation. An improved decay scheme for the high spin states in ^{82}Sr has been obtained and a long paper outlining the shape coexistence and disappearance of pairing correlations in ^{82}Sr is under preparation. We have carried out a search for multiple superdeformed bands in ^{136}Pm and neighboring nuclei, using the Dwarf Ball as a channel selector. We have further confirmed in new experiments the existence of large shifts in the proton evaporation spectra when different rotational bands are populated by the (^{34}S , 2p2n) reaction leading to ^{82}Sr . A long paper is under preparation summarizing our results in detail.

In the second area we include studies covering the strong interplay between use of reactions and structure. We have continued the analysis of earlier data leading to population of entry states in rare earth systems at energies well above the barrier.

At lower excitation energies, corresponding to fusion near the Coulomb barrier we have observed in reanalysis of earlier data strong entrance channel effects in the spin dependence of cross sections for various $\sigma(\text{HI}, \text{xn})$ channels depending on whether the compound nuclei $^{164}\text{Yb}^*$ and $^{160}\text{Er}^*$ were formed in symmetric ($^{64}\text{Ni} + ^{100}\text{Mo}$, $^{64}\text{Ni} + ^{96}\text{Zr}$) or asymmetric ($^{16}\text{O} + ^{148}\text{Sm}$, $^{16}\text{O} + ^{144}\text{Nd}$) bombardments at matched excitation energies. Furthermore, dramatic differences in the shape and strength of the GDR spectra were observed depending whether the compound nuclei were produced by symmetric or asymmetric entrance channel reactions. Our current understanding of these effects can be summarized by the presence of dissipation phenomena on the way to fusion. The shape and energy equilibration are much slower for the symmetric case with significant emission of giant dipole γ -rays and particles prior to full equilibration. A coherent picture for the explanation of these effects will have to account for the large differences in cross sections in the channels that involve α -particle emission. To shed further light in this problem we have carried out two experiments and have measured spectra of charged particles in the above reactions. We hope to see

differences in the subbarrier region and the angular distributions of the α -particle spectra when the entrance channels are symmetric or asymmetric.

On a different problem, we know for sometime now that in statistical model calculations a substantial fraction of the subbarrier α -particles are emitted from low excitations near the yrast line. If this is true, then a fraction of the emitted α 's may have a significantly long lifetime to be measurable by the x-ray atomic clock method. We have measured α -particles in coincidence with K x-rays in the reaction $^{60}\text{Ni} + ^{100}\text{Mo} \rightarrow ^{160}\text{Yb}^*$ at 250 MeV. The majority of the x-rays originate from the daughter Er nuclei following fast α nxn emission and then γ -decay which produces K vacancies by internal conversion. Observation of the compound nucleus Yb x-rays in coincidence with the subbarrier α 's indicates that the α emission follows the x-ray emission. Since the latter has a mean life of $4 \times 10^{-18}\text{s}$, this provides a clock which shows that part of the α -emission is to be slower than that time scale. We have indeed found a small Yb x-ray peak in coincidence with the low energy α 's and have thus clocked α emission. Further analysis of this experiment is in progress.

In another experiment we have measured the giant dipole resonance (GDR) in coincidence with fission fragments and with evaporation residues in order to study nuclear shapes at high excitation. We have found evidence for very large deformation from GDR observed in coincidence with fission fragments from the reaction $^{16}\text{O} + ^{159}\text{Tb}$ forming ^{175}Ta at 123.4 MeV of excitation. The deformation corresponds to $\beta = 0.55$ for $T = 1.5$ MeV and it is interpreted to be due to emission from the compound nucleus on the way to fission with possible structural influences that enhance the observed deformation.

In the third area we addressed the issue of producing hot nuclei in order to study their properties. In a series of two papers we employed an incomplete fusion reaction to fully characterize the excitation energy of hot nuclei. From the energy spectra and light charged particle multiplicities we were able to infer that the level density parameter, a , in a Fermi gas description decreases as the excitation energy of the nucleus increases. Whereas the proton and α spectra and multiplicities were both consistent with a reduced level density parameter at high excitation ($T \sim 3.5$ MeV), the deuteron and triton multiplicities were overpredicted in the simulations employed for extracting the level density parameter. This signified a serious deficiency in our ability to calculate evaporatively deuterons and tritons from highly excited nuclei. We have shown in a new paper that a description of the deuteron and triton data is possible, provided that the corresponding inverse cross sections are reduced over the optical model predictions. For deuterons the required reduction is consistent with experimental deuteron fusion cross sections. This breakdown of the traditional approach is attributed to the large percentage of non-fusion components contained in the optical model absorption cross section.

In the fourth area a number of diverse projects have been carried out. A new method for investigating the mechanism and time scale for the disassembly of excited projectiles has been developed. It relies on the determination of the relative angle distributions of the remnants of the projectile breakup as detected and characterized in a 4π detection.

We have thus studied the breakup of ^{16}O into four α -particles and of ^{28}Si into a variety of exit channels such as $^{12}\text{C} + 4\alpha$, or $^{16}\text{O} + 3\alpha$, etc. From detailed simulations of these decay mechanisms we found that the $^{16}\text{O} \rightarrow 4\alpha$ decay is exclusively sequential, while $^{28}\text{Si} \rightarrow ^{12}\text{C} + 4\alpha$ is a mixture of sequential decay and fission. Information about the time scales has also been obtained.

We have studied the excitation energy division in reaction of $^{49}\text{Ti} + ^{93}\text{Nb}$ at 19 MeV/nucleon. We have utilized the 4π nature of the Dwarf Ball and Wall in order to separate the binary ($\sim 90\%$) events from those where more than one intermediate fragments are produced. We have reconstructed the primary projectile like fragments and were able to deduce the total kinetic energy loss (TKEL). As a function of the latter we obtain the target excitation from the light charge particle and neutron emission at large angles. We find that the excitation energy imparted to the target increases with the transferred mass from the projectile to the target.

We have studied dissipative collisions of ^{124}Xe with ^{207}Bi at 29 MeV/nucleon, by combining the Dwarf Ball and Wall with the U. of Rochester 4π neutron multiplicity meter. We found that there is a strong correlation between the neutron and charged particle multiplicities. There is, however, an important delay in the charge particle multiplicity, indicating that a low excitations neutron emission dominates, whereas for high excitation both particles and neutrons are emitted in a correlated way.

Finally we have studied the charged particle multiplicity dependence of the high energy photon (bremsstrahlung) production in the 65 MeV/nucleon reaction of $^{40}\text{Ar} + ^{165}\text{Tb}$. We find a strong dependence of the bremsstrahlung production with particle multiplicities. Unlike expectations, the inverse slope parameter is found to be independent of the particle multiplicity. The bremsstrahlung yields are consistent with the main features of a VUU calculation that incorporates the general scaling of the geometric model of Nifenecker and Bondorf. In contrast, the yields are not well correlated with the impact parameter derived by integrating the particle multiplicities by a simple one-to-one mapping.

In the last area of instrumentation and analysis we have made substantial progress. We have improved the Dwarf Ball detector system by building 18 2-mm thick CsI(Tl) detectors that can be used in front of Ge detectors to minimize absorption. We have now designed, constructed and used a set of new discriminators (112 channels) capable of discriminating in width and amplitude. This allows us to eliminate essentially all the electron pulses from the target and thus lower the thresholds significantly.

A new set of multihit TDC have been ordered to be used with the DBW and the new Miniwall. The latter is a 110 detector hodoscope compatible with the MSU Miniball which was designed and constructed at Washington University by L. Sobotka. The new discriminators and the multihit Lecroy TDC's were our contribution to this project.

We have made improvements in our computer system. We have acquired a new DEC 3100 model 76 work station. We have also obtained the necessary hardware and converted our computer system to a local area cluster, independent of the department of chemistry

network. We have developed new data analysis graphics software for DEC windows. We have also acquired a PC-486 computer in order to run commercial graphics packages that allow us to prepare better quality and faster graphics.

II. SCIENTIFIC RESULTS

IIA. NUCLEAR STRUCTURE STUDIES

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],

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 regions and some 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 a superdeformed structure in ^{82}Sr .

In the first experiment we have employed the reaction $^{52}\text{Cr}(^{34}\text{S}, 2\text{p}2\text{n})$ at 130 MeV to populate the high-spin states in ^{82}Sr . In a second experiment we used the reaction $^{60}\text{Ni}(^{26}\text{Mg}, 2\text{p}2\text{n})^{82}\text{Sr}$ 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.

In the off-line analysis of both experiments, 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 $k_{\gamma} = 7$. These conditions resulted in spectra that were dominated by γ -rays from ^{82}Sr . Figure IIA1.1 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 IIA1.1. Partial Level Scheme for ^{82}Sr . Band labels are denoted by numbers in parentheses on top.

Figure IIA1.2. $E\gamma$ - $E\gamma$ two-dimensional map for ^{82}Sr from the proton-gated data. The energy dispersion is 8 keV/channel.

In searching for superdeformed states, we are closely examining the above two-dimensional $\gamma - \gamma$ coincidence matrix. Figure IIA1.2 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 $2\mathcal{J}^{(2)}/\hbar^2 \simeq 53\text{MeV}^7$. This corresponds to a deformation of $\beta \simeq 0.5$ for a deformed rigid rotor. In an effort to identify a discrete SD band, we are currently employing several algorithms that permit detailed searches with multiple gates based on assumed bands with constant or slightly varying moments of inertia.

1. C.G. Anderson *et al.*, *Phys. Scripta* **24**, 266 (1981).
2. J. Dudek and W. Nazarewicz, *Phys. Rev.*, **C31**, 298 (1985).
3. W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson and I. Ragnarsson, *Nucl. Phys.*, **A435**, 397 (1985).
4. Y. Schutz *et al.*, *Phys. Rev. Lett.*, **48**, 1535 (1982).
5. B.M. Nyako *et al.*, *Phys. Rev. Lett.*, **52**, 811 (1986).
6. P.J. Nolan and P.J. Twin, *Ann. Rev. Nucl. Part. Sci.*, **38**, 533 (1988).
7. F.S. Stephens *et al.*, *Phys. Rev. Lett.*, **64**, 2623 (1990).
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) UMich.

Below we give the abstract of a paper published in *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.

Further detailed analysis has led to an improved decay scheme where the top few transitions in several of the bands are changed.

A full experimental and theoretical paper is presently under preparation.

IIA.3 Highly Deformed Bands in ^{136}Pm .— M.A. Riley, T. Petters, J. Shick, [FSU], R.J. Charity, D.G. Sarantites, L.L. Wittmer [WU], C. Baktash, W. Gao, J.D. Garrett, M.L. Halbert, D.C. Hensley, I.Y. Lee [ORNL], and J. Simpson [Daresbury].

Following the initial discovery of discrete superdeformed bands in ^{132}Ce and ^{152}Dy ¹ this area of γ -ray spectroscopy has seen a great deal of activity by many groups worldwide. In the last few years however, almost all the superdeformed (SD) spectroscopy groups have concentrated on the A=150 and new A=190 regions. The excitement in these latter regions has been intense, particularly since non-yrast SD bands were observed in individual nuclei, which has led to the remarkable discovery of "identical" SD bands in neighboring nuclei.²

The A=130 SD or highly deformed region on the other hand has been largely overlooked during this period. A very key question is, do excited SD bands exist in this region? (which they should do!) and if so, do they show the remarkable degeneracies as seen in the other regions.

In July/August an experiment was performed at the Holifield Heavy Ion Research Facility at Oak Ridge to search for multiple SD bands in the odd-odd nucleus ^{135}Pm . The reaction used was $^{34}\text{S} + ^{106}\text{Pd}$ at a bombarding energy of 165 MeV. Because charged particle emission competes on an equal footing with neutron emission in this mass region, the Dwarf Ball was used to select between the pxn, 2pxn, axn, paxn, etc., channels. High resolution γ -ray information was obtained using 18 Compton suppressed Ge detectors and fold and total energy information obtained from the Spin Spectrometer. A total of

$280 \times 10^6 \gamma - \gamma$ charged particle coincidences were recorded. These data are presently being analyzed.

1. P.J. Nolan and P.J. Twin, *Ann Rev. Nucl. and Part. Sci.* **38**,533 (1987).
2. T. Bryski *et al.*, *Phys. Rev. Lett.* **64**, 1650 (1990).

IIA4. Alignment Processes and Shape Variations in ^{184}Pt – M.P. Carpenter, *et al.*

This work is a complete study of the structure of ^{184}Pt which was recently published in *Nucl. Phys.* (See Appendix B). Bellow is the abstract from this work.

Abstract: High-spin states in the transitional nucleus ^{184}Pt were populated via the reactions $^{154}\text{Sm}(^{34}\text{S}, 4n)^{184}\text{Pt}$ and $^{172}\text{Yb}(^{16}\text{O}, 4n)^{184}\text{Pt}$. The yrast band was excited up to $I = 28\hbar$ and six new side bands built on both neutron and proton quasiparticle configurations were observed. Shell correction-type calculations indicate variations of the nuclear shape in different bands, especially as a result of band crossings due to the process of angular momentum alignment. Comparison of the band characteristics are made between ^{184}Pt and eight adjacent nuclei. The pattern of band crossings in these nine nuclei is considered from the viewpoint of blocking comparisons and of theoretical calculations. The competition between low-frequency $\nu i_{13/2}$ and $\pi h_{9/2}$ band crossings is discussed.

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.L. Halbert, D.C. Hensley, F.K. McGowan, I.Y. Lee, M.A. Riley, A. Virtanen [ORNL], and 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.

Related to this is the issue of structural influences on the shapes of the proton evaporation spectra. We have observed a strong dependence of the probability for subbarrier proton emission on the nature of the rotational bands populated in the final nucleus.

The results to this study have been published in the Phys. Rev. Letters⁵.

Here we summarize the observations and conclusions and discuss recent measurement and calculations supporting our observations and their interpretation.

- (1) As expected, the proton spectra from the (^{34}S , $2p2n$) reaction coincident with the ground state $2^+ \rightarrow 0^+$ transition show a strong angular momentum dependence (see Fig. 2a in Ref. 5) 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 Ref. 5).
- (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 an 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 50% 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.

Figure IIA5.1 (a) Density plot of the proton emitting states calculated with EVAP 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 EVAP.

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.

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.

The analysis of this second experiment is essentially complete. We have made efforts to ensure that the observed effect is indeed real. With improved statistics we have examined the Ge Spectra coincident with the gates used to produce the proton spectra for impurities from other channels. The gates on the yrast band were found to contain only transitions from levels within the same band (no extra peaks were found). For the ground band a small admixture from the (HI, 2pn) channel was found and this accounts for part of the observed upward shift in the proton spectra coincident with this band.

We note that the (HI, 2p3n) channel is not present in these gates, nor is it populated significantly in these reactions. Any other contamination will produce a shift in the opposite direction (upward shift) to the protons associated with the yrast band. We have also found that the proton energy shift occurs only for gates on transitions originating from levels with spins higher than 10^+ .

We have examined the dependence of the shift on the combined total energy (H) and multiplicity gating (k_γ). Whereas the multiplicity dependence is very strong, only minor shifts were observed for constant k_γ for different H_γ values. We are presently examining the shapes of the γ -ray continuum spectra associated with the gates that create the proton shift, with additional selection on proton energies.

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IIB. STUDIES AT THE INTERFACE BETWEEN STRUCTURE AND REACTIONS

IIB1. 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 were measured.

Figure IIB1.1. Comparison of calculated (histograms) and experimental (points) channel cross sections for the reaction 136 MeV $^{20}\text{Ne} + ^{146}\text{Nd}$.

For the statistical model description of these data, we employ the evaporation code EVAP, described elsewhere in this report. Since EVAP differs in accuracy and features from the earlier used versions of PACE, we started a re-examination of these evaporation residue cross section and entry state data. Results from a preliminary calculation for the reaction 136 MeV $^{20}\text{Ne} + ^{146}\text{Nd}$ are given in Figs. IIB1.1 and IIB1.2. In this calculation we employed a simple input parameter set involving rotating liquid drop with finite range corrections yrast lines and fission barriers.

Figure IIB1.2. Comparison of the experimental (solid lines) and the calculated γ -ray multiplicity and total γ -ray energy distributions with the calculated ones (dashed lines) for the reaction $136 \text{ MeV } ^{20}\text{Ne} + ^{146}\text{Nd}$ (See text).

The symbols in Fig. IIB1.1 show the cross sections of various evaporation residue channels in the above reaction. The result of the calculation, indicated by the histograms, is in a good agreement with the data.

A partially good agreement is obtained in the description of the projected entry state distributions of these channels. The solid and dashed lines of Fig. IIB1.2 show, respectively, the experimental and calculated entry state distributions as a function of the total γ -ray energy (E^*) and gamma-ray multiplicity (M_γ). The total γ -ray energy (E^*) projections are reproduced relatively well in the peak position and absolute magnitude. The gamma-multiplicity projections agree well in shape, but they are overpredicted in absolute magnitude by two units. The dashed line M_γ -projections shown in Fig. 2IIB1.2 were shifted down in M_γ by two units, in order to obtain agreement with the data.

Different input parameter sets are currently tested in order to explain the deviations in the prediction of the M_γ -projections. A possible reason for these deviations may be

related to the fact that the experimental yrast lines of the above nuclei are steeper than the ones predicted in a liquid drop calculation.

Similar calculations are in progress for the 224 MeV $^{50}\text{Ti} + ^{130}\text{Te}$ reaction, for which fission competes strongly with neutron emission.

* Deceased.

IIB2. Entrance Channel Effects in Fusion Near the Barrier – D.G. Sarantites, J. Barreto, R.J. Charity, L. Gallamore, N.G. Nicolis, D.W. Stracener, L.G. Sobotka, L. Wittmer, [WU], J.R. Beene, C. Baktash, M.L. Halbert, D.C. Hensley [ORNL], and M. Thoennessen [MSU].

Heavy-ion fusion reactions near the Coulomb barrier have in recent years revealed a number of interesting effects. One of the most unexpected findings is the observation that the mode of decay of excited compound nuclei appears to depend on their mode of formation.¹⁻⁸ However, a satisfactory understanding of these effects is still lacking.

Large differences were originally found in the measurements of the σ_{2n}/σ_{3n} channel cross sections ratios as a function of the compound nucleus spin in the decay of $^{156}\text{Er}^*$ produced at an excitation energy of 47 MeV by the $^{12}\text{C} + ^{144}\text{Sm}$ and $^{64}\text{Ni} + ^{92}\text{Zr}$ reactions. We have confirmed these effects⁶ in the decay of $^{164}\text{Yb}^*$ formed at 49 MeV of excitation by the $^{16}\text{O} + ^{148}\text{Sm}$ and $^{64}\text{Ni} + ^{100}\text{Mo}$ reactions.

Figure IIB2.1. Channel cross section fractions for the 2n, 3n and 4n exit channels from the decay of ^{164}Yb at E^* of 49 MeV from ^{64}Ni (closed symbols) and ^{16}O (open symbols) reactions as a function of the k_{eff} (corrected for band head spin differences of the gating transitions). Strong deviations are seen above $k_{eff} \sim 15$.

This is shown in Fig. IIB2.1 where the cross section fractions for the 2n, 3n and 4n channels are plotted as a function of the γ -ray coincidence fold k_γ . It is seen that up to $k_\gamma \sim 15$ the cross section fractions for the 2n, 3n and 4n channels are identical. Above that, significant differences are observed. Interestingly, no difference for the 2n and 3n channels were observed for all spin populated (for k_γ between 5 and 20) in ^{164}Yb at 40 MeV of excitation as seen in Fig. IIB2.2. This is an astonishing excitation energy dependence.

Figure IIB2.2. Same as in Fig. IIB2.1, but for the 2n and 3n exit channels from the decay of ^{164}Yb at E^* of 40 MeV. Good agreement is observed for all k_{eff} values up to 20. Above that the ^{16}O channel is not significantly populated.

Further puzzling evidence on entrance channel effects is observed in the (HI, αn) and (HI, $\alpha 2n$) exit channels. These two exit channels appear to have also unexpected but different behaviors for near symmetric and asymmetric compound nucleus formation. Whereas for the $^{156}\text{Er}^*$ system, the αn channel appears to be dramatically shifted in spin¹ (Fig. IIB2.3), the $\alpha 2n$ channel for the $^{164}\text{Yb}^*$ system shows a large (nearly a factor of 2) difference in cross section at low k_γ and similar dependence at the higher k_γ values involved (see Fig. IIB2.4). Due to low cross sections involved in the αxn channels, spin distributions were not at that time available for the lower excitation energies.

It has been argued^{1,3} that during the dynamical evolution of the fusion process, the nuclei formed in the symmetric entrance channel become trapped in a superdeformed minimum, whereas for the ^{16}O induced reaction large deformations are not reached. The large deformations involved in this mechanism would favor enhanced α emission for the symmetric entrance system, a prediction not substantiated by the results shown in Fig. IIB2.4. An alternate explanation for the $\alpha 2n$ results may be that in the $^{148}\text{Sm}(^{16}\text{O}, \alpha 2n)$ reaction some incomplete fusion contribution is responsible for an excess cross section for this asymmetric entrance channel. This may be unexpected for such low energies, since statistical

Figure IIB2.3. Spin distributions for αn and $\alpha 2n$ exit channels from the decay of $^{156}\text{Er}^*$ at 47 MeV produced in the reactions indicated. Note the large displacements, particularly for the αn channel (Ref. 1).

model calculations account quantitatively for the cross sections for the asymmetric case and they overpredict the cross sections for the symmetric case. This argues against the latter explanation.

In further experiments with the $^{156}\text{Er}^*$ system large differences were found in fission cross sections,⁴ and neutron multiplicities^{2,5} from the decay of $^{156}\text{Er}^*$ for entrance channels having different mass asymmetry.

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 occur 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.

Interestingly, we have observed large differences for the γ -decay in the region of the GDR for both the $^{160}\text{Er}^*$ and $^{164}\text{Yb}^*$ compound nuclei formed by symmetric (^{64}Ni) and asymmetric (^{16}O) bombardments. (See Appendix G and Ref. 5).

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.
- (3) When the spectra are normalized to the evaporation residue cross section, the symmetric channel yield of high energy γ -rays is significantly higher in yield than from the asymmetric channel.

Figure IIB2.4. Channel cross section fractions for the $\alpha 2n$ exit channel from the decay of $^{164}\text{Yb}^*$ at E^* of 49 MeV from ^{64}Ni (open symbols) and ^{16}O (closed symbols) as a function of the k_{eff} . A strong difference is seen below $k_{eff} \sim 13$

- (4) The symmetric-channel γ -spectral shapes cannot be explained using parameters corresponding to superdeformed shapes.
- (5) These results explain the low neutron multiplicities found for the symmetric case in $^{160}\text{Er}^{2,4}$

The difficulties associated with the α emitting channels suggest that simple dynamical effects by themselves may not be responsible and points toward nuclear structure influences as the explanation. It is conceivable⁹ that unusually large E2 strengths stemming from the proximity of superdeformed minima may play a role in the de-excitation process in these systems and this may cause the emission of γ rays to precede particle emission. This will explain the elevated entry lines for the $1n$ exit channel³ and may have some relevance in the large γ -ray yields observed in the GDR experiments. This will be prominent for the symmetric entrance channels where higher spins are populated.

The full understanding of the origin of these entrance channel effects clearly needs more work. In a recent experiment performed last February we have successfully obtained α and proton spectra and angular distributions associated with individual exit channels from the decay of the $^{160}\text{Er}^*$ and $^{164}\text{Yb}^*$ compound systems formed at $E^*=52$ MeV in ^{16}O and ^{64}Ni bombardments. We expect that the shapes of the spectra and their angular distributions will be a sensitive probe for the entrance channel effects, and will help shed some light in distinguishing between the two mechanisms discussed above for the $\alpha 2n$ channel cross sections. The experimental analysis has progressed to the point where "physics tapes" have been obtained and we will be looking at the particle spectra shortly.

The strong excitation energy dependence observed for the (HI, xn) exit channels indicates that a similar strong dependence for the charged particle emitting channels may be

present. If the full explanation for these entrance channel effects is to be found, complete data including the excitation energy dependence of the emission of charged particles, and in particular of α 's, must be made available. The high detection efficiency of the Dwarf Ball was shown to be invaluable for bringing out the low cross section charged-particle emitting channels.

This past July we completed an experiment and measured an excitation function for the system $^{160}\text{Er}^*$ produced at 40, 65, and 75 MeV of excitation by $^{16}\text{O} + ^{144}\text{Nd}$ and $^{64}\text{Ni} + ^{96}\text{Zr}$ bombardments. We have measured charged particles in coincidence with discrete γ -rays employing the Dwarf Ball, 18 Compton Suppression Ge detectors, and the Spin Spectrometer. This experiment is now being analyzed.

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IIB3. Lifetimes of Subbarrier α Particles and Protons by the Atomic Clock Method – D.G. Sarantites, R.J. Charity, L. Gallamore [WU], J.R. Beene, M.L. Halbert, and R.L. Varner [ORNL].

The study of subbarrier emission of α particles provided us with a tool for investigating deformation effects in highly excited, rapidly rotating nuclei.¹ We pointed out in Ref. 1 that subbarrier α emission occurs from lower excitations (Fig. 7c in Ref. 1). Consequently, it is conceivable that a substantial fraction of the subbarrier α 's may originate from states close to the yrast line in competition with the statistical γ rays. Such emission was predicted by statistical model calculations some 23 years ago.² It is possible that irregularities in the level density near the yrast line may enhance this effect. A similar situation may be responsible for the structural effects on the proton spectra that we have observed³ and have been predicted⁴ in the region near ^{82}Sr .

The atomic clock method is based on the following idea. For α particle emissions faster than $4 \times 10^{-18}\text{s}$ the x-rays follow α -emission and therefore are associated with the atom of the daughter nucleus (Er in the present case). For α -particles emitted at times longer than the x-ray lifetime, the x-rays are characteristic of the atom associated with the compound nucleus (Yb in this case). The relative intensities of x-rays from Yb and Er in coincidence with α 's can thus be used to determine the fraction of the *delayed* α -particles and the corresponding mean lifetimes.

We had attempted such an experiment 6 years ago using 4 Si ($\Delta E, E$) telescopes with a total solid angle of 80 *msr* and 2 planar X-ray detectors inserted in the Spin Spectrometer. That experiment was limited severely by statistics and an upper limit of $\leq 20\%$ was placed

for the fraction of delayed α emission for all E_α energies. We used the reaction $^{64}\text{Ni} + ^{100}\text{Mo}$ at 250 MeV (a system studied in Ref. 1). For the ^{164}Yb compound system $\tau_K = 4 \times 10^{-18}\text{s}$ at $E_K = 52$ keV. According to preliminary calculations⁵ a K vacancy yield of $\sim 4\%$ is expected in the compound nucleus.

Observation of characteristic x-rays emitted during sequential proton evaporation from ^{112}Xe compound nuclei was recently reported by Azaiez *et al.*⁶. They used coincidences with a plastic scintillator 4π box, an x-ray detector at 0° to the beam and the "Chateau de Cristal"⁷.

Figure IIB3.1. Spectra of x-rays coincident with α -particles with $E_\alpha < 20$ MeV (thick histogram) and with $E_\alpha \geq 20$ MeV (thin histogram). The spectra are gated with $k_\gamma > 19$ from the reaction of 240 MeV $^{60}\text{Ni} + ^{100}\text{Mo}$. The two spectra are normalized to the same Er ($K_{\alpha_1} + K_{\alpha_2}$) x-rays. The statistically significant peak from the compound nucleus Yb K_{α_1} is highlighted by the filled area.

With the availability of the Dwarf Ball the statistics could be increased by a factor of 60 if only one x-ray detector is used. Several weeks ago we performed such an experiment. We employed an x-ray detector at 138° to the beam and recorded coincidences with the Dwarf Ball and the Spin Spectrometer. We employed the reaction $^{60}\text{Ni} + ^{100}\text{Mo}$ at 240 MeV, selected to maximize the ($^{60}\text{Ni}, \alpha 2n$) channel without appreciable 2α emission. During the experiment we were monitoring the x-ray spectra gated by $k_\gamma \geq 19$ and had total

coincidences with the Dwarf Ball and with gates on α -particles (lower and upper half of the energy scale) and on the protons. We collected data for 3.5 days. We have observed a *small Yb K_{α_1} x-ray peak* in the spectrum gated by the low energy α particles, which is absent from that gated by the high energy α 's. This is shown in Fig. IIB3.1. A small highlighted peak from the Yb compound nucleus is seen. It should be pointed out the better gating with lower α -energy and k_γ will enhance the peak to background. Significant background arises from γ -ray scattering both from the Dwarf Ball into the x-ray counter and from the x-ray counter into the NaI detectors neighboring the x-ray counter. It is expected that appropriate vetoing with the NaI detectors neighboring the x-ray counter will reduce the background by a factor of 2 – 3.

Figure IIB3.2. X-ray spectra coincident with any count in the Dwarf Ball (thin histogram) and with protons of any energy (thick histogram) recorded in the Dwarf Ball. A small peak labeled YB K_{α_1} is seen in the thick histogram, indicating possible slow proton emission.

In a manner similar to α emission, near and below the barrier proton evaporation may also have a slow component. In our online spectra we have observed compound nucleus x-rays in coincidence with protons. This is shown in Fig. IIB3.2. A small Yb K_{α_1} peak is seen in the thick histogram spectrum. The thin lines correspond to x-ray Dwarf Ball (DB) coincidences. Here the DB is sensitive to γ -rays, protons and α -particles. Consequently

the x-ray spectrum coincident with anything in the DB shows $_{70}\text{Yb}$, $_{69}\text{Tm}$ and $_{68}\text{Er}$ x-rays. Further analysis is required to confirm this observation of slow proton emission. Clean gates must be ensured in this analysis. The planned analysis is discussed in the accompanying proposal.

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IIB4. Very Large Deformations Observed at High Excitation Energies via GDR Studies – M. Thoennessen [MSU], J.R. Beene, F.E. Bertrand, C. Baktash, M.L. Halbert, D.J. Horen, D.C. Hensley, R.L. Varner [ORNL], D.G. Sarantites and D.W. Stracener [WU].

The γ -decay of the giant-dipole resonance (GDR) built on excited states has been found to be not only a useful tool for study of nuclear shape effects for nuclei as a function of excitation and spin,^{1,2} but it is also sensitive to reaction dynamics.^{3,4} For example, the reduction of the fission probability at the early stages of the decay of highly excited compound nuclei was reflected into an enhancement of GDR γ -rays preceeding fission.^{5,6} It was pointed out^{1,2} that the GDR does not necessarily measure the minimum of the underlying potential energy surface. It is, however, expected to be sensitive to the average of the deformation of the emitter over the short time scale of the GDR decay. In order to explore these effects we have made a simultaneous study of the GDR decay originating from a composite system when it undergoes fission or when it leads to fusion evaporation residues (ER).

In this work we measured GDR photons in coincidence with ER and with fission fragments for the reactions of 160 MeV $^{16}\text{O} + ^{159}\text{Tb}$, leading to ^{175}Ta at 123 MeV of excitation. We have found that the GDR spectrum coincident with ER is well represented by a standard calculation with small deformation. The shape and magnitude of the GDR spectrum in coincidence with the fission fragments cannot be reproduced by calculations with standard parameters of the post-fission and pre-fission contributions to the GDR. Even when a delay for fission is introduced via a friction coefficient ($\gamma \sim 10$) the shape of the observed GDR is not well reproduced by normal deformation. One must introduce a splitting in the GDR that would correspond to a $\beta \simeq 0.55$. Such a large deformation indicates that the observed GDR spectrum is at least sampling on the average the shape of the nucleus on the way to fission. A similar study of the GDR for fission of neutron deficient Pb isotopes with comparable fissility to this system produces GDR spectra with much smaller deformations ($\beta = 0.38$).⁶ Consequently it may be argued the the present experiment may be sensitive to additional structure effects the that persists at these moderate temperatures.

The abstract of a first draft of a letter is included as Appendix H.

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IIC. PRODUCTION AND STUDY OF HOT NUCLEI

IIC1. Production of Hot Nuclei – The Nuclear Level Density at High Excitations – A. Chbihi, L.G. Sobotka, N.G. Nicolis, D.G. Sarantites, D.W. Stracener, Z Majka [WU], D.C. Hensley, J.R. Beene and M.L Halbert [ORNL].

The simplest way to prepare highly excited nuclei is by means of fusion reactions. The decline of complete fusion in heavy-ion reactions as the relative velocity at contact exceeds $0.1c$ is well known. This is indicated by measurements of velocity distributions of evaporation residues¹ or by measurements of the fission fragment folding angle². Thus, the “degree” of incomplete fusion in a given reaction must be known in order to be able to reconstruct the excitation energy in such a reaction. We have employed this method in detail (see App. I for a reprint) in order to produce hot nuclei with known excitations up to 402 MeV for nuclei with mass $A \simeq 110$. 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 model³ 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 $\simeq A/8$. There are two reasons for this. The first is the influence of the diffuse surface of real nuclei,⁴ which would give $a = A/[14.61(1 + 4A^{-1/3})]$. The second one is the increase in effective mass of the nucleon^{5,6} 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 factor⁷ f_W 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 J and are shown in Fig. 2 of Appendix J.

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.*⁸, 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.

Figure IIC1.1. 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.

4 of Appendix J. 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 IIC1.2. 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. 6 (see text).

In these analyses the evaporation code EVAP was employed for the simulations (see the following section IIC2 and Appendix K.) 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. IIC1-1. 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 a failure of the optical model penetrabilities to account for the emission of these particles. We will return to this issue in the next Section of this report.

In summary, the level density constants $k = A/a$ extracted from our data are shown in Fig. IIC1-2, 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. 9 and the full circle from Ref. 8. The dashed curve is for a constant diffuseness $d = 0.7$ fm and the solid curve was obtained⁶ with $d = 0.7(1 + 0.01T^2)$ fm. Part of the difference between the value of Gonin *et al.*⁸ and our values may be due to differences in the diffuse surface between the $A =$

160 and $\simeq 110$ nuclei employed, respectively. We should point that in such a plot nuclei in different mass regions are compound without appropriate accounting of the surface effects. This may account for some of the variations, but in view of the large errors involved this comparison is still instructive.

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IIC2. Investigations of the Statistical Decay Modes of Highly Excited Compound Nuclei.– N.G. Nicolis, D.G. Sarantites, L.G. Sobotka and R.J. Charity

A great deal of insight into the decay properties of highly excited compound nuclei comes from comparisons of experimental data with the predictions of the statistical model. For the purpose of making a realistic description of these properties, we recently completed the development of an extended version of the Monte-Carlo statistical model evaporation code EVAP¹ (See Appendix K for a preprint). Important features of the code include:

- (a) An extended excitation energy range of validity, which makes possible calculations of excited systems eg. up to $E^* \sim 400$ MeV.
- (b) The consideration of decay channels involving n, p, d, t, α , ^3He and ^6Li emission.
- (c) The use of externally created transmission coefficients (T_ℓ), calculated for each individual nucleus and type of emitted particle.

Using the last feature, we recently studied² (see Appendix L for a preprint) the statistical deuteron and triton emission from highly excited compound nuclei, using different models for transmission coefficients.

In the statistical model description, the penetrability for particle emission is related to the one of the inverse (capture) process through the principle of detailed balance. The traditional method of calculating particle penetrabilities employs T_ℓ 's derived from an optical model (OM) calculation with standard parameters³. For many years, this method has been able to describe successfully the decay properties of compound nuclei for low to moderate excitation, for which n, p and α -emission are the most probable decay modes. Table I shows the total p, d, t and α cross sections observed in the reaction⁴ 121 MeV $^{14}\text{N} + ^{103}\text{Rh} \rightarrow ^{117}\text{Te}^*$ ($E^* = 107$ MeV). The calculated yields from EVAP using OM T_ℓ 's are also shown. They are in good agreement with the experimental values. Similarly,

Table I. Experimental⁴ and calculated cross sections of the evaporated charged particles in the reaction 121 MeV $^{14}\text{N} + ^{103}\text{Rh} \rightarrow ^{117}\text{Te}^*$ ($E^* = 107$ MeV).

Particle (ν)	σ_ν (mb)	σ_{calc} (mb) (OM T_ℓ)
p	1894 ± 190	1753.9
d	90 ± 14	135.5
t	21 ± 3	22.8
α	930 ± 90	1157.4

a good agreement has been found in the absolute magnitude and spectral shapes of the evaporative p, α , d and t spectra for this reaction².

Next, we applied the same approach to the description of particle multiplicities from equilibrated emitting sources observed in 25 MeV/u $^{28}\text{Si} + ^{100}\text{Mo}$ reactions^{5,6}. Fig. IIC2.1a shows the experimental n, p, α , d and t multiplicities as a function of the initial excitation energy of the emitting source. The lines represent the results of EVAP calculations. The solid, dash-dotted and dashed lines correspond to calculations with level density constants of A/11.0, A/8.5 and A/6.0, respectively. The neutron and proton multiplicity data are in favour of the A/11.0 calculation; a result consistent with the analysis of the high energy slopes of the corresponding evaporation spectra⁶. The alpha multiplicity data lie between the A/6.0 and A/11.0 calculations. However, the deuteron and triton multiplicities are systematically overpredicted, irrespective of the level density constant choice. This overprediction increases up to a factor of 2 or more as the level density constant becomes smaller. Although the trend of the calculations with the level density constant is understood on the general grounds of the statistical model, it has been impossible to reduce the calculated d and t yields with standard parameter changes².

Alexander, Magda and Landowne, recently reviewed the logical basis of using optical model (OM) T_ℓ 's in statistical model calculations⁷. A comparison of OM T_ℓ 's was made with the ones derived from an ingoing-wave boundary condition (IWBC) calculation. These T_ℓ 's give the transmission probability through the real potential barrier. It was pointed out that processes like transparency, shape resonances or peripheral absorption are normally present in the OM T_ℓ 's. These processes raise questions on the suitability of the OM T_ℓ 's in describing the inverse process of capture from an excited nucleus. It was suggested that simple barrier penetration T_ℓ 's, such as those of the IWBC model, may be more appropriate for use in statistical model calculations.

Following Ref. 7, we created a transmission coefficient set using the real part of the OM potentials³ and replaced the role of the imaginary parts with an ingoing-wave boundary condition. The statistical model calculations for the high-energy multiplicity data are shown in Fig. IIC2.1b. It is seen that the A/11.0 calculation reproduces closely the M_n ,

Figure IIC2.1. (a) Excitation energy dependence of n, p, d, t and α multiplicities (symbols) associated with equilibrated emissions from the reaction $701 \text{ MeV } ^{28}\text{Si} + ^{100}\text{Mo}$. The predictions of a statistical model calculation with optical model transmission coefficients and level density parameters of $a=A/10$, $A/8.5$, and $A/11$ are shown by the dashed, dash dotted and solid lines, respectively. (b) Same as in (a), but with transmission coefficients derived from the incoming wave boundary condition model. (c) Same as in (a), but with optical model transmission coefficients modified by the DRAF method for the deuterons and tritons as described in the text.

M_p and M_α data. The calculated d and t yields are still in excess of the experimental ones. However, the use of IWBC T_ℓ 's improves the discrepancies found with original the OM T_ℓ set. This improvement is attributed to some elimination of processes in the OM absorption which are not related to fusion. Therefore, it becomes desirable to examine transmission coefficient sets describing fusion of deuterons on different targets as candidates for the description of the emission properties of our systems.

In a recent study, West et al.⁸, measured excitation functions for the ground and an excited isomer state in the reaction $^{52}\text{Cr}(d, 2n)^{52}\text{Mn}^{g,m}$. They found that the assumption of equating the fusion cross section of $d + ^{52}\text{Cr}$ to the OM absorption (reaction) cross section fails to explain the observed cross sections. Subsequently, Mustafa et al.⁹, were able to describe the above data using σ_{fus} from a direct-reaction approach to fusion (DRAF) method¹¹. In the DRAF method, the fusion part of the reaction process is incorporated in the inner region of the imaginary part of the optical potential. The outer part is associated with incomplete fusion or direct reaction processes. This separation is achieved with the introduction of a *fusion radius*. A decomposition of the OM absorption cross section σ_{abs} into a complete fusion σ_{CF} and a direct interaction part σ_{DI} is then obtained: $\sigma_{abs} = \sigma_{CF} + \sigma_{DI}$. The usefulness of the method lies in the fact that once the fusion radius is determined, a description of the complete and direct interaction processes can be made on the same footing. Furthermore, it provides us with a method of creating T_ℓ 's related to the fusion part of the absorption process in the OM description. Using this method, Mastroleo et al.¹⁰, were able to describe the cross sections of various processes in $d + ^{93}\text{Nb}$ reactions; a reaction system with a mass similar to our emission systems.

A transmission coefficient set was created with OM T_ℓ 's for n, p and α -particles and DRAF T_ℓ 's for deuterons and tritons. A fusion radius for deuterons consistent with that of Ref. 10 and a radius of a similar magnitude for tritons was used. The corresponding statistical model calculations are compared to the data in Fig.IIC2.1c. For neutrons and protons we have a degree of agreement similar to that obtained with OM or IWBC T_ℓ 's. For deuterons and tritons, the agreement is now remarkably good. The small overprediction of M_α is not considered significant. In fact one should introduce a fusion radius for each particle, because direct reaction contributions are known to be present for all particle types. For example, when a fusion radius of 1.8fm was introduced for the α particles good agreement with experiment was obtained.

Some conclusions can be drawn from the comparisons of statistical model calculations with different transmission coefficient sets. The introduction of IWBC T_ℓ 's shows the existence of processes which are included in the description of OM absorption but are not related to fusion. One would like to eliminate these processes, in order to obtain a description of particle emission consistent with the principle of detailed balance. This is the task of the IWBC model. It seems that the direct-reaction type of processes in the OM T_ℓ 's represent a small fraction of the OM absorption cross section for neutrons, protons and alphas. This explains the success of the OM T_ℓ 's in statistical model calculations

where n , p and α -emissions dominate. However, this method seems to break down for deuterons and tritons whose emission becomes significant at high excitation energies. The present work shows that this breakdown is associated with the presence of non-fusion processes which involve a large fraction of the OM absorption cross section. The employed DRAF method provides a quantitative means of removing these processes and providing a transmission coefficient set consistent with the fusion process. Using this method, it became possible to restore overpredictions in the deuteron and triton emission yields of more than 50%, a result which could not be achieved by any other parameter change. The employed deuteron fusion radius parameter is consistent with a published analysis of fusion cross sections of deuteron induced reactions on a target similar to our emission systems¹⁰. This result, strengthens our confidence in the method. Unfortunately, little is known about the mass or energy-dependence of fusion radii which are derived from fusion cross sections. We believe that systematic studies of reactions induced by all particle types including deuterons and tritons are needed. This may provide valuable information for input parameters in the description of statistical n , p , d , t , and α emission from highly excited nuclei.

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5. A. Chbihi, L.G. Sobotka, Z. Majka, D.G. Sarantites, D.W. Stracener, V. Abenante, T.M. Semkow, N.G. Nicolis, D.C. Hensley, J.R. Beene and M.L. Halbert. *Phys. Rev. C* **43**, 652 (1991).
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9. M.G. Mustafa, T. Tamura and T. Udagawa, *Phys. Rev. C* **35**, 2077 (1987).
10. R.C. Mastroleo, T. Udagawa and M.G. Mustafa, *Phys. Rev. C* **42**, 683 (1990).
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IID. INCOMPLETE FUSION AND FRAGMENTATION REACTIONS

IID1. 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. Hensely, 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 published paper (Reprint is included as Appendix I).

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 I).
- (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).

IID2. The Mechanism for the Disassembly of Excited ^{16}O Projectiles into Four Alpha Particles – J. Barreto, R.J. Charity, L.G. Sobotka, D.C. Sarantites, D.W. Stracener, A. Chbihi, N.C. Nicolis [WU]R. Auble, C. Baktash, J.R. Beene, F. Bertrand, M. Halbert, D.C. Hensley, D. Horen, C. Ludermann, M. Thonnessen and R. Vanner [ORNL]

The decay of excited nuclei into many fragments is a topic of considerable interest at present. The models for explaining this type of decay include both prompt breakup and sequential emission of the fragments. It is important to find clear signatures for the

various modes of disassembly. Such a technique is to study the relative velocities between the fragments. If the fragments are initially in close proximity their subsequent interaction is dominated by the mutual Coulomb repulsion, which leads to a suppression of small relative velocities (relative emission angles). In contrast, for a sequential decay, the time intervals between emissions will be long and the fragments do not experience significant mutual interactions. Therefore the small relative velocities are not suppressed. Harmon *et. al*¹ have measured relative angles of α -particles produced in the disassembly of ^{16}O projectiles, and concluded that a sequential decay mechanism accounts for this decay.

In this work we also studied the breakup of ^{16}O into 4 α 's, but both our experimental approach and analysis had some new important features:

- (a) We employed a 4π coverage of the reaction, instead of only a forward array of detectors. This allowed us to make a significantly better characterization of the events identified by the forward wall as belonging to the $^{16}\text{O} \rightarrow 4\alpha$ process.
- (b) We have made more detailed simulations including prompt, sequential, fission then sequential, and sequential followed by fission. We have excluded the prompt mechanism and those including fission. The data are consistent only with a sequential decay for the excitation energies reached in this work.
- (c) We deduced the minimum time interval between emissions of the α -particles and found it to be of the order $3 \times 10^{-21}\text{s}$.

Our group provided the experimental data, which were acquired by D. Sarantites and D. Stracener in a summer visit at ORNL. The data analysis was done by J. Barreto and the simulations and interpretation by R. Charity.

1. Harmon *et. al.*, *Phys. Lett.* **B235**, 234 (1990). A preprint of this work was submitted for publication and a preprint is included as Appendix M

IID3. A 4π Approach to the Energy Division in the Reaction of 19.1 MeV/nucleon $^{48}\text{Ti} + ^{93}\text{Nb} - \text{V}$. Abenante, Z. Majka, A. Chbihi, D.G. Sarantites, R.J. Charity, D.W. Stracener, N.G. Nicolis [WU], D.C. Hensley, J.R. Beene and M.L. Halbert [ORNL].

In this work our objectives are:

- (1) to determine the relative importance of incomplete fusion and projectile fragmentation
- (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 for these intermediate energies account for most of the cross section.

In our previous work (Sect. IID1) 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 binary events by requiring that only one IMF is detected.

For the ^{48}Ti induced reactions, we selected the events that include detected IMF's. We find that these events have $\approx 85\%$ of the yield in 1 IMF $\approx 12\%$ in two IMF's, and the remainder in 3 or more IMF's.

Figure IID3.1. Angular distributions in the laboratory for the reconstructed primary PLF's that lead to the detected IMF Ne. The Z of the PLF is shown as ΣZ_i .

Assuming for the moment that the events with only one detected IMF are binary, we can proceed to reconstruct the primary projectile-like fragment from the forward detected particles. For each detected IMF in the 8° , 15° and 22° rings, the light-charged particles emitted in a $\sim 25^\circ$ cone are included in the reconstruction of the PLF from a vector addition of the momenta. This provides the velocity and energy of the PLF, which in turn is used via binary kinematics to obtain the total kinetic energy loss (TKEL), and the angular distribution of PLF's leading to each IMF. Then appropriate Z_{PLF} and TKEL gates are placed and the spectra from the various emitting sources are constructed and analyzed for multiplicities from which the energy sharing can be obtained.

This first order approximation neglected any fast, preequilibrium particles. These can be determined next, and a new iteration with reduced total available energy can be

made. This procedure seems to work. As an illustration we show in Fig. IID3.1 the angular distributions of all PLF's with Z from 13-22, when the detected IMF was Ne. In Fig. IID3.2 we show a density plot representing the velocity distribution along the PLF-TLF center-of-mass axis for α -particles and for a TKEL of 390 MeV from $Z_{PLF} = 16$. The TLF and PLF Coulomb circles are clearly seen. The extra intensity at the 4 o'clock direction is due to preequilibrium emission along the beam direction.

Figure IID3.2. Density plot of α particles emitted from the TLF and PLF ($Z_{PLF} = 16$) shown as a function of $v_{\perp}$ and $v_{\parallel}$ along the direction of the C.M. for the PLF-TLF emission. The beam is in the 4 o'clock direction.

Samples of the particle multiplicities deduced for the TLF emissions are shown in Fig. IID3.3 from fits of spectra of particles emitted at the backward angles. Fig. IID3.1(a) shows the proton multiplicities M_p as a function of the TKEL for the forward reconstructed Z_{PLF} . It is seen that for a given Z_{PLF} the M_p increases with increasing TKEL (Fig. IID3.3a), and for a given TKEL (or E_{avail}) M_p increases as Z_{PLF} decreases, i.e. as the transferred mass to the target increases its excitation energy also increases.

The particle multiplicities for the TLF can be converted to excitation energies via statistical model calculations that reproduce the measured multiplicities. The consistency

Figure IID3.3. (a) Proton multiplicities emitted from the TLF for selected ZPLF's as a function of the TKEL. (b) The same proton multiplicities as in (a) shown as a function of ZPL for selected gates on the available excitation energy (TKEL).

of the analysis will require to fit the forward spectra with a PLF and a preequilibrium component. A second iteration will be needed.

We are at present exploring the possibility of fitting the backward spectra for particle multiplicities and TLF velocities. If the fitted velocities for the TLF are smaller than the one from binary kinematics, they should be reflecting the energy removed by the preequilibrium component, and if so they can be used to determine the latter.

IID4. Dissipative Collisions of 28.2 MeV/nucleon ^{136}Xe with ^{207}Bi – Particle Multiplicity Correlations – S.P. Baldwin, B. Lott, B.M. Quednou, B.M. Szabo, W.U. Schröder, J. Töke, [U. Roch.], J. Barreto, R.J. Charity, L. Gallamore, D.G. Sarantites, L.G. Sobotka [WU], and R.T. de Souza [MSU].

In recent years studies of dissipative collisions between heavy ion of intermediate energy have employed 4π detection of either charged particles or of neutrons. Charged particle multiplicities characterize the elemental composition of the products and only sample the excitation energies involved, while neutrons provide a more complete determination of the

energy dissipation. The combined measurements can provide a complete characterization of the events, which would provide stringent tests of models dealing with particle production. We have recently completed the first of such combined measurements. Some preliminary results will be shown of what is the most complete study for reactions in the intermediate region.

Figure IID4.1. A contour plot of the detected total neutron multiplicity $\langle m_n \rangle$ as a function of the total charged-particle $\langle m_z \rangle$. The lines are from statistical model calculations for the various Z values indicated.

The reaction products from the reactions of $^{136}\text{Xe} + ^{207}\text{Bi}$ at 28.2 MeV/nucleon were detected with the Dwarf Ball and Wall and the University of Rochester Neutron Multiplicity Meter (NMM). The Dwarf system gives the energy and course position for p, d, t, ^3He , α and IMF's up to $Z \simeq 25$, while the NMM provided the neutron multiplicity from slow sources with an efficiency of $\approx 75\%$.

The simplest correlation to be examined involves that between the total neutron multiplicity $\langle m_n \rangle$ and the total charged-particle multiplicity $\langle m_z \rangle$. This is shown in Fig. IID4.1. Since the great majority of the events are peripheral and both projectile and target have very high Z 's one expects the bulk of such excitation to be dissipated by neutron emission.

Indeed, at low $\langle m_Z \rangle$ a large variation in $\langle m_n \rangle$ is observed. For the more central collisions, the charged-particle multiplicity or the neutron multiplicity are measures of the violence of the reaction. This is indeed observed (Fig. IID4.1) where the $\langle m_n \rangle$ and $\langle m_Z \rangle$ values increase in a correlated way for large multiplicities.

IID5. A Study of the Multiplicity Dependence of the High Energy Photon Production in a Heavy-Ion Reaction – L.G. Sobotka, L. Gallamore, A. Chbihi, D.G. Sarantites, D.W. Stracener [WU], W. Bauer, D.R. Bowman, N. Carlin, R.T. deSouza, C.K. Gelbke, W.G. Gong, S. Hannuschke, Y., D. Kim, W.G. Lynch, R. Ronnigen, M.B. Tsang, F. Zhu [MSU], J.R. Beene, M.L. Halbert and M. Thoennessen [ORNL].

This study of bremsstrahlung production as a function of charged-particle multiplicity was done at MSU using the Dwarf System and the ORNL BaF₂ γ -ray detection array. The experiment was analyzed by L.G. Sobotka and L. Gallamore and a paper was submitted for publication. The abstract is given below and a preprint is attached as Appendix N.

Abstract: The production of high energy photons in an intermediate energy heavy ion reaction (65 MeV/nucleon $^{40}\text{Ar} = ^{93}\text{Nb}$) is studied by characterizing the events, which produce the photons, by the forward and backward, light and heavy, charged particle production. While the absolute yield of high energy photons increases with increasing charged-particle multiplicity, the spectral shape is found to be almost independent of multiplicity. This indicates that the fundamental photon production mechanism is insensitive to the impact parameter but that the production process is more probable for the more violent central collisions. These data are compared to predictions of reaction simulations based on the Boltzmann-Uehling-Uhlenbeck equation. These calculations reproduce the overall yield of photons over 30 MeV but underpredict the inverse slope parameter. This comparison also suggests strong particle multiplicity fluctuations at fixed impact parameter.

III. INSTRUMENTATION AND ANALYSIS

IIIA. ADVANCES IN INSTRUMENTATION

IIIA1. The Dwarf Ball and Wall System – D.G. Sarantites, L.L. Wittmer, D.W. Stracener, J. Elson, R.J. Charity, and L.G. Sobotka [WU].

From experimental work presented in this report it has become clear that the Dwarf Ball and Wall (DBW) system is very well suited for low to intermediate energy reaction studies, and as a tool for spectroscopic studies via its channel selection capability. Furthermore, in the overlap area between these two fields, the so called “interface between structure and reactions”, the DBW system is capable of making the most significant contributions. For these reasons we are very much interested in improving the performance and counting rate capabilities of the DBW system most appropriate for these low energy studies. We have already begun changes both for the DBW detectors and for the associated electronics.

There are two areas for improvement of the DBW detectors. The first is the use of the DBW with Ge detectors, which are detecting discrete γ -rays through the DBW, that can cause absorption and scattering. The second is associated with the use of DBW with a low efficiency external trigger, i.e. a set of Ge detectors or an array of BaF₂ detectors etc., whereby the DBW is required to run at high rates.

The problem of absorption is easily corrected. If low energy γ -rays need to be counted one must remove some DBW detectors in front of corresponding Ge detectors. To remedy this problem in part we have constructed 18 DBW detectors with only 2mm CsI (instead of 4 and 8 mm) and have used them in a recent experiment. In addition it was thought that this would minimize the forward Compton scattering, which removes counts from the full energy peaks and increases the undesirable Compton background. To investigate this quantitatively, we have made measurements of the peak-to-total ratio for the Compton suppressed Ge detectors at HHIRF in the spin spectrometer, and of the magnitude of the Compton background after suppression.

In Fig. IIIA.1 we show Compton distributions from two Ge detectors suppressed with BGO shields. The top spectrum in each case is taken with a ⁶⁰Co source inside the Dwarf Ball and the bottom one with the source outside. The spectra are normalized to the same full energy peak area. It is seen that for the detector in (b) the increased Compton background goes up to ≈ 1.1 MeV whereas in (a) the increase is limited to energies below ≈ 500 keV. We do not understand the different behavior of these two detectors, but out of 18 detectors tested 6 showed the pattern in (a) and 12 that of (b). We then took out the CsI detector in front of a Ge detector and found that the increase in background was $\approx 2/3$ of what it was with the 2mm CsI detector in place. This clearly indicates that large angle scattering is responsible for the increase in the Compton background. To test this idea we shielded the antiCompton shield with a 6.0 mm and 2.5 cm thick Pb shields (not in very good geometry). The results are shown in Fig. IIIA1.2. It is clear that substantial

Figure IIIA1.1. Compton suppressed Ge spectra taken with a ^{60}Co source inside the Dwarf Ball (top spectra) and with the source outside the Dwarf Ball (bottom spectra) for two different Ge detectors (a) and (b) with BGO antiCompton shields. The compared spectra are normalized to the same peak area in each case. The peak maxima are off scale. The observed different behavior between the two detectors is not understood.

reduction of the extra background can be obtained by shielding the BGO suppressors. The improvement would be better if the Ge detectors could be collimated. Some of this can be accomplished by placing the Dwarf Ball in a smaller scattering chamber that will allow considerably better collimation than that used in Fig. IIIA1.2.

Along these lines a further reduction of the total DB mass is desirable. This can be done by either replacing all the CsI detectors (4 and 8 mm) with 2mm CsI ones or even by changing to fast-slow plastic phoswich elements.

The second aspect of the counting rate improvement is based on new features in our DBW electronics. Up to very recently we have been using the SLOW (integration of the current pulse from 0-400 ns) and the LONG (orTAIL, 1500-3000 ns) parameters for light charged-particle identification. While this gives good separation, it suffers from the LONG

Fig. IIIA1.2 Normalized Compton suppressed spectra to the same peak area. 1 = source outside the Dwarf Ball, 2 = source inside the DB with 2.5 cm Pb shield, 3 = source inside the DB with 6.0 mm Pb shield, and 4 = source inside the DB but with no shielding.

(7 μ s fall time) long time component, which at high rates gives a baseline shift. At present, we are exploring an alternative which will (a) provide the required particle identification (b) will permit a significant increase of the counting rate, and (c) will minimize pile-up. The earlier version of our discriminators provide individual ECL outputs with widths equal to the time over the discriminator threshold. These discriminators have a built in shaper with a selectable time constant. If this time is set to $\approx 2 \mu$ s, then the tails of the pulses from different types of particles will cross the discriminator level at different times because of the variation in the light from the two components of the CsI(Tl). This provides the desired pulse shape capability with a $\approx 2 \mu$ s shaping constant and allows performance at higher rates. We hope to increase the rates from 3-4 Kc/s to 15-20 Kc/s. This functionality will be accomplished with the use of the recently purchased LeCroy 2277 Multihit TDC's. These 32 channel real time TDC modules can register 16 hits per channel, which may be either on the negative or the positive going edges of the discriminator output signal. The time over threshold is then directly determined from the time difference between the first two hits (the first going negative and the second going positive). Subsequent hits will be due to recrossings of the threshold levels. These recrossings will be due to either statistical light fluctuations in the original signal (with short duration) or due to pile-up of another

pulse (long time difference). This new TDC thus will not only provide an easy new method for pulse shape discrimination, but it will permit pile-up rejection.

Another improvement in our DBW electronics and in the Mini Wall electronics (see the following section) is in the construction, debugging and use of a new set of 2-dimensional discriminators. A set of 8 16-channel modules were constructed from funds from this grant. They provide several new capabilities (a) computer controlled setting of thresholds (b) rejection of pulses narrower than ≈ 9 nsec (used for rejection of pulses due to electrons) (c) an adjustable time interval in which it does not re-fire, (d) 16-channel ECL outputs, and (e) an OR from any of the 16 channels (NIM output). The rejection of the electron pulses was found to be very valuable, because it allows us to lower the energy thresholds considerably. These modules, however, do not provide the time over threshold.

Fig. IIIA21.1 Graphic artist's view of the Washington University Mini Wall.

IIIA2. The Mini Wall– L. Gallamore, L.G. Sobotka, J.T. Hood, J. Elson, R.J. Charity, and D.G. Sarantites [WU].

As proposed last year we have undertaken and by now completed the construction of a high granularity hodoscope. This device named the Mini Wall was designed to be compatible with the MSU Mini Ball and to complement it because of the Mini Ball's lack of forward granularity which was only comparable to our Dwarf Wall. The Mini Wall, shown in Fig. IIIA2.1 consists of 128 fast plastic - CsI(Tl) phoswich elements. The fast plastic is typically 40 μm thick and the CsI(Tl) elements 3.0 cm thick. The device spans angles from 3.3. – 25.0.

Several changes and advances were made in the operation of the Mini Wall compared to the Dwarf System. The most important is the replacement of the singly gated 16-channel FERA ADC's with the Phillips 7176 individual channel gated ones. This was dictated by the larger distances which result in variations in flight times between any 16 signals. The second is the use of the the new 2-dimensional discriminators, described in some detail in the previous section. The last one is the use of the new LeCroy 2277 Multihit TDC's with new features also described in the previous section.

The new detectors of the Mini Wall have superior particle identification capabilities compared to the DBW. They are capable of not only separating p, d, t, ^3He and He from the intermediate mass fragments, but they also separate ^6Li , ^7Li , ^7Be and ^9Be . This is accomplished by use of higher Tl doping (1550-1900 ppm) in the CsI (Tl) crystals (from Hilger Analytical).

This project was masterminded by L. Sobotka with invaluable assistance from Larry Gallamore, with a helping hand from the remaining W.U. nuclear chemistry team. We have contributed the new 2-dimensional discriminators and the new multihit Lecroy TDC's from funds from this grant.

IIIB. COMPUTER FACILITY

IIIB1. The Nuclear Chemistry Computer Facility – J. Elson, D.G. Sarantites and L.G. Sobotka

As proposed this year we have made some improvements in our computer system. First we replaced a Vax Station 3500 with a Vax Station 3100 model from funds from this grant, and added another Vax Station 3100 model 76 (from L.G Sobotka's PYI grant). At present we have a local cluster of four 3100 Vax Stations (2 3100 model 76, one model 40 and one model 30). There are 5 2.3-Gbyte Exabyte systems available. The two model 76 work stations have two EXabyte drives each, and the model 40 has one Exabyte and a Cypher 6250/1500 streaming reel tape drive. The output drives include a Tektronix 4596 inkjet plotter and a QMS-S10 postscript laser printer. The massive storage capacity of the system includes 4.0 Gbytes on 5 SCSI disk drives. In order to run commercial graphics packages for publications we acquired an IBM PC clone (Gateway 2000 - 486 computer). This system will soon be added to the ethernet local cluster as a work station.

On the Software side, this year we brought to a satisfactory completion a data analysis and display package (1-dim and 2-dim) program called SNAP. This program utilizes the DEC Windows capabilities of the work stations for display and analysis of 2-dimensional and/or 1-dimensional spectral data. It is highly interactive via a mouse or in many instances with quick "Keys". The program is written in C and has already been exported to the University of Rochester.

Recently we acquired a TEK-4010 emulation package (XTERM) that emulates Tektronic graphics on the VMS Workstation. This display interface is extremely fast and allows us to run all our TEK based programs on the DEC windows work station.

Another acquisition is the previewer for the typesetting package TEX that runs on the work stations.

For the IBM PC's we have acquired the following packages (1) AXUM: a very versatile graphics package that includes multicurve plotting, contour, surface plots, etc. (2) *Mathematica* : A symbolic math package with powerful analytical and graphics capabilities, (3) PC-TEX with a previewer, (4) "Word and Mathtype for Windows (5) Excel for Windows and (6) Quattro Pro for windows.

IV. SCIENTIFIC AND TECHNICAL PERSONNEL

IVA. WASHINGTON UNIVERSITY PERSONNEL

The following Table summarizes the manpower effort by our group for the period indicated.

Person	Position	Effort During Last Year (months)	Effort During Last 3 Years (months)
D.G. Sarantites	P.I.	9	27
A. Chibihi	Research Associate	—	36
N.G. Nicolis	Research Associate	12	36
Z. Majka	Visiting Scientist	3	3
J. Barreto	Visiting Scientist	5	5
R.J. Charity	Research Professor	2	2
V. Abenante	Graduate Student	9	33
D. Stracener	Graduate Student	12	36
L. Gallamore	Graduate Student	—	1
L. Wittmer	Undergraduate	3	6
K. Myers	Software Specialist	2	10
J. Elson	Electronics Eng.	8	24
J.T. Hood	Design	3	7
Total (person months)		68	216
Total (person years)		5.7	18.0

Vincent Abenante, a fifth year graduate student has carried out essentially all his thesis work. Dan Stracener will be getting his Ph.D. at the end of this semester.

A new graduate student P.-F. Hua from the physics department has joined our group this semester.

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

IVB. COLLABORATIONS

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

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

We have started two new collaborations. One with the University of Rochester including Udo Schröder and J. Töke and the second with M. Riley and his group at the Florida State University.

V. PUBLICATIONS

VA. PAPERS PUBLISHED OR SUBMITTED (1988-1991)

1. "Statistical Emission of Deuterons and Tritons from Highly Excited Compound Nuclei." N.G. Nicolis, D.G. Sarantites, L.G. Sobotka, and R.L. Charity, Submitted for publication in *Phys. Rev. C*, August (1991).
2. "EVAP: A Monte Carlo Statistical Model Evaporation Code For High Energy Compound Nucleus Reactions." N.G. Nicolis, D.G. Sarantites, and J.R. Beene. Submitted for publication in *Computer Communications* (Aug. 1991).
3. "The Mechanism for the Disassembly of Excited ^{16}O Projectiles into Four Alphas." J. Barreto, R.J. Charity, L.G. Sobotka, D.G. Sarantites, D.W. Stracener, A. Chbihi, and N.G. Nicolis, Submitted for publication in *Phys. Rev. C* (July, 1991).
4. "A Study of the Particle Multiplicity Dependence of High Energy Photon Production in A Heavy-Ion Reaction", L.G. Sobotka, L. Gallamore, A. Chbihi, D.G. Sarantites, D.W. Stracener, [WU], W. Bauer, D.R. Bowman, N. Carlin, R.T. deSouza, C.K. Gelbke, W.G. Gong, S. Hannuschke, Y.D. Kim, W.G. Lynch, R. Ronningen, M.B. Tsang, and F. Zhu [MSU], J.R. Beene, M.L. Halbert, and M. Thoennessen [ORNL]. In press as Rapid Communication in *Phys. Rev. C*. (1991).
5. "Yield Decomposition and Excitation Energy Reconstruction in an Incomplete Fusion Reaction", A. Chbihi, L.G. Sobotka, Z. Majka, D.G. Sarantites, D.W. Stracener, V. Abenante, T.M. Semkow, N.G. Nicolis, D.C. Hensley, J.R. Beene and M.L. Halbert, *Phys. Rev. C* **43**, 652 (1991).
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8. "Alpha-Particles as Probes of Nuclear Shape and Structure Effects in Proton Evaporation Spectra", D.G. Sarantites, N.G. Nicolis, V. Abenante, Z. Majka, T.M. Semkow, C. Baktash, J.R. Beene, G. Garcia-Bermudez, M.L. Halbert, D.C. Hensley, N.R. Johnson, I.Y. Lee, F.K. McGowan, M.A. Riley, A. Virtanen and H.C. Griffin, in *Proceedings of the 'XXV Zakopane School of Physics'* (World Scientific, 1990), Vol.2, selected topics in nuclear structure, Eds. J. Styczen and Z. Stachura, (1990), p.180.

9. "Alpha-Particle Emission as a Probe of Nuclear Shapes and Structure Effects In Proton Evaporation Spectra" N.G. Nicolis, D.G. Sarantites, C. Baktash, V. Abenante, L.A. Adler, J.R. Beene, F.A. Dilmanian, G. Garcia-Bermudez, H.C. Griffin, M.L. Halbert, D.C. Hensley, N.R. Johnson, I.Y. Lee, Z. Majka, F.K. McGowan, M.A. Riley, T.M. Semkow, D.W. Stracener, and A. Virtanen, in Proceedings of the International Conference ' *Nuclear Structure in the Nineties* ', Oak Ridge, April, 1990, *Nucl. Phys.* **A520**, 153c (1990).
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12. "Dwarf Ball and Dwarf Wall: Design, Instrumentation and Response Characteristics of a 4π CsI(Tl) Plastic Phoswich Multidetector System for Light Charged-Particle and Intermediate Mass Fragment Spectrometry", D.W. Stracener, D.G. Sarantites, L.G. Sobotka, J. Elson, J.T. Hood, Z. Majka, V. Abenante, A. Chbihi, and D.C. Hensley, *Nucl. Instr. Meth.* **A294**, 485 (1990).
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15. "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, F. Zhu, L.G. Sobotka,

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28. "Comment on the 'Unexpected Large Deformations in $^{60}\text{Ni}^*$ Nuclei Produced in the Reaction 120 MeV $^{30}\text{Si} + ^{30}\text{Si}$ ", N.G. Nicolis and D.G. Sarantites, *Phys. Rev.* **C40**, 2422 (1989).

VB. INVITED PRESENTATIONS IN MEETINGS (1987–1990)

1. “Recent Results with the Dwarf Ball and Wall”, D.G. Sarantites, Invited Talk presented at the ‘*International Conference on Nuclear Physics with Advanced Techniques*’, Crete, Greece, June (1991).
2. “The Nuclear Level Density of Highly Excited Nuclei”, D.G. Sarantites, Invited talk presented at the American Chemical Society Symposium on ‘*Properties of Nuclei at High Spin*’, Atlanta, April, (1991).
3. “Incomplete Fusion and the Nuclear Level Density at High Excitations”, A. Chbihi, N.G. Nicolis, L.G. Sobotka, D.G. Sarantites, Z. Majka, D.W. Stracener, V. Abenante, T.M. Semkow, D.C. Hensley, J.R. Beene, and M.L. Halbert, Invited Talk presented at the *TASCC-90 Workshop*, Chalk River, July, 1990.
4. “Alpha-Particle Emission as a Probe of Nuclear Shapes and Structure Effects in Proton Evaporation Spectra”, N.G. Nicolis, D.G. Sarantites, C. Baktash, V. Abenante, L.A. Adler, J.R. Beene, F.A. Dilmanian, G. Garcia-Bermudez, H.C. Griffin, M.L. Halbert, D.C. Hensley, N.R. Johnson, I.Y. Lee, Z. Majka, F.K. McGowan, M.A. Riley, T.M. Semkow, D.W. Stracener and A. Virtanen, Invited Talk Presented at the International Conference on ‘*Nuclear Structure in the Nineties*’ Oak Ridge, April 23, 1990 (in press).
5. “Alpha-Particles as Probe of Nuclear Shape and Structure Effects in Proton Evaporation Spectra”, D.G. Sarantites, N.G. Nicolis, V. Abenante, Z. Majka, T.M. Semkow, C. Baktash, J.R. Beene, G. Garcia-Bermudez, M.L. Halbert, D.C. Hensley, N.R. Johnson, I.Y. Lee F.K. McGowan, M.A. Riley, A. Virtanen and H.C. Griffin, Invited Lecture presented at the ‘*XXV Zakopane School of Physics*’, Zakopane, Poland, May 6, 1990 (in press).
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8. “Disintegration of the Nuclear System Formed in the 45 MeV/nucleon $^{84}\text{Kr} + ^{159}\text{Tb}$ Reaction”, Z. Majka, L.G. Sobotka, D.W. Stracener, D.G. Sarantites, G. Auger, E.

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