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INVESTIGATIONS OF NUCLEAR STRUCTURE AND NUCLEAR REACTIONS INDUCED BY COMPLEX PROJECTILES

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Chapter 1

Overview

1.1 INTRODUCTION AND OVERVIEW

The research program of our group addresses 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) Reaction Mechanism Studies; 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 5. In the past 3 years we published 4 letters, 2 rapid communications and 8 full papers. Two full papers, 1 letter and 1 rapid communication have also been submitted. In addition, 4 invited talks have been delivered in professional conferences.

In the following, we highlight our accomplishments and advances in the five areas of our effort.

In the **first area**, we have undertaken a search for hyperdeformation in the mass 182 region. From a recent experiment we have constructed an E_γ - E_γ matrix mainly for ^{182}Hg . We have not been able to find evidence for hyperdeformation although a number of possible candidate transitions were seen that may have the appropriate spacing for the predicted large deformation. A new decay scheme for the high spin states in ^{182}Hg has been obtained which extends the ground band to $I = 20^+$ with four additional new side bands. This is an interesting nucleus because of the presence of several bands that indicate coexistence of oblate and prolate structures. Further analysis is in progress to complete this scheme and to assign spins.

An experiment was done with the HERA array to study ^{180}Hg , and ^{178}Pt using $(^{36}\text{Ar}, 4n)$ and $(^{36}\text{Ar}, \alpha 2n)$ reaction on ^{148}Sm . These data are being analyzed.

We have carried out a search for large deformation bands in ^{136}Pm and neighboring nuclei. Identical superdeformed bands have been found in the $A=150$ and $A=190$ regions, while searches for multiple SD bands in the $A=130$ region have up to now been overlooked. In our experiment we have used the Dwarf Ball as a channel selector. We have found a superdeformed band in ^{136}Pm . Its $J^{(2)}$ does not vary significantly with rotational frequency, unlike other large deformation bands in neighboring nuclei. This allows us to explain the underlying structure responsible for large deformation in this region. A rapid communication was published summarizing these findings.

The principal investigator participated in an experiment at the Eurogam facility in collaboration with the ORNL group in a continued search for superdeformation in ^{82}Sr . With

the impressive statistics of 4×10^9 triple coincidences, we were able to find the first evidence for a discrete superdeformed structure in this nucleus with a deformation of $\beta \approx 0.5$. Further interesting structures were observed indicating the first evidence for band termination in this region.

In the **second area** we include studies covering the interplay between reactions and structure. We have investigated in detail previous claims for the existence of strong entrance channel effects in the fusion of symmetric and asymmetric projectile-target combinations that are designed to produce compound nuclei at the same excitation energy (~ 52 MeV). Such effects appeared to violate the Bohr independence hypothesis for the formation and decay of compound nuclei. We found that, on one hand, in the decay of $^{164}\text{Yb}^*$ (formed by $^{16}\text{O} + ^{148}\text{Sm}$ and $^{64}\text{Ni} + ^{100}\text{Mo}$) by α xn emission, the previously observed differences are due to the breakup of ^{16}O into $^{12}\text{C} + \alpha$ prior to fusion, which is somewhat surprising for such low projectile energies (87 MeV for ^{16}O). This precludes compound nucleus formation at the same excitation energy and dismisses the differences as due to surprising entrance channel effects. The different behavior of the two systems is due to the reaction dynamics. On the other hand, for the xn exit channels, we find that the mappings from entrance orbital angular momentum to residue spin, then to γ -ray multiplicity, and finally to coincidence fold observed with the Spin Spectrometer, all involve broad distributions and are thus responsible for the rather strong previously reported entrance channel effects. This explains all the main features of the data without invoking any unexpected effects that might violate the Bohr independence hypothesis or the need to invoke structural influences due to the proximity of superdeformation. Simply, appropriate fusion models that lead to different initial compound nucleus spin distributions followed by appropriate statistical decay satisfactorily explain the main features of the data. This work was submitted for publication in the Physical Review.

On the latter subject, we note that under appropriate conditions the detailed fusion processes near the barrier exhibit observable differences, that depend on the fusing system. Thus for the above system $^{164}\text{Yb}^*$ formed at E^* of 49 MeV by the reactions $^{16}\text{O} + ^{148}\text{Sm}$ and $^{64}\text{Ni} + ^{100}\text{Mo}$ we measured high energy γ -rays from the decay of the giant dipole resonance. While standard statistical model calculations can describe the spectrum from the ^{16}O induced reaction, they fail to reproduce the spectra from the symmetric reaction induced by ^{64}Ni . Simple model calculations that include particle emission and γ -ray decay during the formation process, suggest that the observed differences may be related to a long fusion time in the more symmetric reaction. This work was recently published in a Physical Review letter.

A separate analysis of fusion reactions near and below-barrier was submitted to the Physical Review. In that work a consistent description of the formation and decay of $^{164}\text{Yb}^*$ in the fusion of $^{16}\text{O} + ^{148}\text{Sm}$ and $^{64}\text{Ni} + ^{100}\text{Mo}$ is presented in a bombarding energy range from near to well below the entrance channel Coulomb barrier. Fusion excitation functions and angular momentum distributions are described *well* with a recently proposed one-dimensional barrier penetration model with *energy-dependent* fusion barriers. This is equivalent to having a distribution of barriers for each bombardment energy. The main features of the fusion cross sections and angular momentum distributions in $^{64}\text{Ni} + ^{100}\text{Mo}$ are also reproduced with simplified coupled channel calculations. The statistical model accounts well for the decay of $^{164}\text{Yb}^*$ in the ^{16}O -induced reaction and for most of the data in the ^{64}Ni -induced reaction. The evaporation residue fractional cross sections as a function of the compound

nucleus excitation energy show trends that correlate with the low and high-spin regions of the compound nucleus angular momentum distributions populated in the two reactions.

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 $T = 1.8$ MeV and it is interpreted to be due to emission from the compound nucleus on the way to fission. This work was published in a Physical Review letter.

On a different but somewhat related problem, we know for sometime 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 xn 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 2×10^{-17} s, it provides a clock which shows that part of the α -emission is comparable or 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. In this work the x-ray atomic clock method provided a rough estimate of the characteristic emission time of α -particles from high-spin compound nuclei. The compound nucleus X-ray peak is very small, and therefore the uncertainties are large. Nevertheless, this is positive evidence that "slow" and last, or near last chance, α particle emission occurs in the de-excitation of high spin compound nuclei. The time scale for these emissions determined from the present work appear to be in some disagreement with statistical model estimates. However a quantitative comparison is not possible at this point since the absolute probability of creating a K-vacancy was not determined. A rapid communication was submitted on this subject.

Very recently we have carried out another atomic clock experiment aimed in establishing the time scale of fission. In that experiment atomic X rays were detected with a special Compton suppressed X-ray detector in coincidence with fission fragments. The aim was to observe characteristic X rays from the fissioning compound nucleus. These would be emitted if the K vacancies created in the fusion process are emitted prior to fission. The experiment was carried out at Atlas. The reaction system was $^{37}\text{Cl} + ^{209}\text{Bi}$ at 225 MeV. The experiment is being analyzed, from the on line monitoring of the run it was not clear whether a positive result was obtained.

We have further confirmed in new experiments the existence of significant shifts in the proton evaporation spectra when different rotational bands are populated by the (^{34}S , 2p2n) and by the (^{26}Mg , 2p2n) reaction leading to ^{82}Sr . A long paper is under preparation summarizing our results in detail.

In a separated experiment aimed to shed additional light on this problem, we employed a new concept of "total spectroscopy". We prepared ^{82}Sr via the (^{28}Si , 4p) reaction and detected all 4 protons with the Dwarf Ball and Wall, the γ -rays with the Spin Spectrometer

and the discrete γ -rays with 18 Compton suppressed Ge detectors. This allowed us to determine the excitation energy of the entry states in the residual nucleus without the use of the rather incomplete total γ -ray pulse height measurements. Again, we find differences in the proton spectra when the ground or the yrast bands are populated at high spin, but the magnitude of the differences is smaller compared to the (^{34}S , 2p2n) reaction. Furthermore, now we can determine the excitation energy distributions that lead to the yrast and ground bands of the ^{82}Sr nucleus at high spin. We find a substantial difference in these distributions. These effects cannot be ascribed to phase space arguments that do not include specific structural information. A satisfactory explanation of these effects is still lacking. A letter summarizing these findings has been prepared for Phys. Letters.

We further explored the concept of "total spectroscopy" and constructed the energy ordered proton spectra leading to the ^{82}Sr via the (^{28}Si , 4p) reaction. From statistical model calculations we have shown that an interesting correlation between the energy ordered and the time ordered spectra. Thus the lowest energy proton is for the most part the forth particle emitted in the cascade. Most interesting, however, is the utilization of the total spectroscopy concept to prepared cold highly spinning nuclei, with substantial population close to the yrast line. Furthermore, the subbarrier and thus the 4th chance protons show enhanced anisotropies. This provides additional evidence for stretched proton emission from states near the yrast line.

In a separate very recent experiment carried out at MSU, we studied the ground state two-proton decay of ^{12}O produced in the transfer reaction $^9\text{Be}(^{13}\text{O}, ^{12}\text{O})$. Triple coincidences (2p + ^{10}C) from the decay of ^{12}O were detected. In this experiment the RPMS (recoil products mass analyzer) were used to provide the secondary ^{13}O beam (≈ 3000 particles/sec). We hope to deduce the branching ratios for diproton decay (^2He emission), direct breakup, and sequential proton emission from the energy and angle correlations of the two protons. The ^{10}C was detected with a Silicon strip ΔE detector backed by four Si E detectors. The protons coincident with the ^{10}C fragments were detected with the Washington University MiniWall.

We have continued the analysis of earlier data leading to population of entry states in rate earth systems at energies well above the barrier and a publication is under preparation.

In the **third area** we produced hot nuclei and studied 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 over predicted 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 pursued this work further and have shown in a recent paper that a description of the deuteron and triton multiplicities and spectra 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.

We have continued improvements of the statistical evaporation code EVAP. We have extended the code to include 14 particle decay channels: n , p , α , d , t , ${}^3\text{He}$, ${}^6\text{Li}$, ${}^9\text{Be}$, ${}^{11}\text{B}$, ${}^{12}\text{C}$, ${}^{14}\text{N}$, ${}^{16}\text{O}$, ${}^{19}\text{F}$, and ${}^{20}\text{Ne}$. In these calculations for the first 7 particle modes optical model transmission coefficients are used, and parabolic penetrabilities are used for the remaining emitted particles.

In a separate investigation we have examined the intermediate fragment emission as a probe of the thermal properties of highly excited compound nuclei. Particular attention was given to the low energy part of the IMF spectra which are shown to be much more sensitive to the barriers for hot nuclei compared to the light particle emission.

We have made a systematic study of transmission coefficients obtained via the incoming wave boundary condition (IWBC). These were compared with those from the optical model. We found excess cross section for neutron emission predicted by the IWBC which cannot be justified in terms of existing data. The IWBC model was introduced in an attempt to eliminate processes like transparency, shape resonances or peripheral absorption which are expected to be present in the optical model but not in the inverse cross section for emission from excited nuclei. We have been able to study the percentage of transparency contributions in the optical model absorption cross section for alpha particles. The transparency was found to increase with bombarding energy.

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 ${}^{16}\text{O}$ into four α -particles and of ${}^{28}\text{Si}$ 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 dissipative collisions of ${}^{124}\text{Xe}$ with ${}^{207}\text{Bi}$ at 28.2 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. Furthermore, for any degree of dissipation, the velocity distributions of charged particles are found to be characteristic of sequential emission following binary collisions. The average correlation between multiplicities of neutrons and charged particles can be understood with the same reaction scenario. The energy dissipation appears to be approximately only one-half of the available entrance channel kinetic energy.

In the **last area** of instrumentation and analysis, we have made substantial progress. We have completed the design and are currently constructing a new 4π device the "MICROBALL", the next generation of the Dwarf Ball. It is based on 96 CsI(Tl) scintillators with silicon photodiode readout. A proposal for the construction of this device was submitted to the Department of Energy and was funded this year. The device will be ready for use by late fall in conjunction with the early implementation of the GAMMASPHERE. The

MICROBALL is designed to have: (1) a solid angle coverage of 98% of 4π for good channel identification, (2) minimal mass to substantially reduce degradation of the peak to total ratio of the GAMMASPHERE Ge detectors, (3) adequate segmentation that will distribute the counting rate among detectors and allow the device to keep up with the high event rates of GAMMASPHERE, (4) a segmentation increasing in the forward direction to allow measurement of angular distributions of light charged particles, (5) a reasonably good energy resolution for measuring particle spectra, (6) excellent gain stability, (7) excellent temperature stability, and (8) a very compact set of integrated electronics modules that will permit an extremely convenient and rapid setup for data acquisition.

We have designed and constructed a low cost channel selecting device, capable of enhancing the xn channels by tagging and removing charged-particle channels and fission. It consists of a scintillator tube made of four fast-plastic segments with light collection at one end. It has high rate capability, but it cannot identify the particle channels. The device was utilized very successfully in two spectroscopy experiments. Its characteristics were described in a NIM paper. It will be superseded shortly by the MICROBALL. We intend to give the "Tube" to the FSU group for some collaborative research.

We have designed and purchased a novel X-ray detector for timing nuclear processes such as α emission and fission by the atomic clock method.

Two 16-channel LeCroy CAMAC CFD's were acquired and used in the fission X-ray clock experiment. A new set of 4 multihit TDC have been acquired ordered and have been used in several experiments 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 several substantial improvements in our computer system. We have added a new DEC APX Vax station based on the new Alpha chip. This is now part of the Nuclear Chemistry local area cluster. We added a fast 1.2 Gb system disk and a second 2.4 Gb disk. A high density helical tape drive (4.8 Gb Exabyte) is on order. We have begun converting some of our special software for the Alpha work station.

We have developed new data analysis graphics software for Motiv windows. We have also acquired a second PC/486 computer to run commercial graphics packages that allow us to prepare better quality and faster graphics and to acquire data via the CAMAC interface or as a pulse-height analyzer.

We have developed a new data compression package that permits one- and two-dimensional histograms to be stored on disk with high compression. This increases the I/O speed and saves typically another factor of 3 over our previous compression scheme.

Chapter 2

Scientific Results

2.1 NUCLEAR STRUCTURE AT HIGH SPIN

The central theme of the new and exciting nuclear structure physics at high spin centers on the richness of coexistence of a variety of nuclear shapes often observed in the same nucleus. The wealth of information on the highly deformed (termed superdeformed, SD) nuclei with axes ratios near 2:1 that has been recently obtained with multi detector arrays attests to this.

Exciting prospects of finding predicted pear-shaped nuclei with axes ratios near 3:1 (termed “hyperdeformed”, HD) are in the horizon particularly with the modern arrays such as GAMMASPHERE that are coming on line.

There are some other aspects of the high spin physics that are related to the role played by the deformation driving higher ℓ orbits that are coming from above the Fermi level. These intruder orbitals play a crucial role in stabilizing the very deformed structures. At very high spins normal deformation bands are known to terminate due to complete alignment of all the orbitals participating in the configuration for each band. Do SD bands terminate, and if so at what spin?

Superdeformed structures have been found in the actinides, the Hg region, the rare earths, and the mass 130 region. In this sequence the deformation driving Coulomb repulsion constantly diminishes and the stabilization of the large deformations comes from rotational stretching coupled with the influence of single particle gaps at large deformations. We have very recently obtained the first evidence for a discrete SD band structure in ^{82}Sr . Here, the Coulomb repulsion is minimal and yet the delicate balance of the spherical and deformation driving forces does lead to a stable SD structure in this light mass region.

Below we give a more detailed account of several of the above issues of high spin physics. Here we note that we have been working to build the MICROBALL in order to facilitate and enhance the capabilities of GAMMASPHERE for studying these exotic nuclear structures. Although a good part of these studies can be addressed by GAMMASPHERE alone, using (HI, xn) reactions, a significant fraction of these effects are predicted to occur in sufficiently neutron deficient or light mass systems. For the latter charged particle emission becomes very important, while for the heavier systems fission competes strongly and limits the population of high spin states. When charged particle emission becomes important, automatically the number of exit channels increases by several fold. This is particularly true when one must raise the excitation energy in order to bring in more angular momentum in the compound nucleus. This large fragmentation of the fusion cross section means that detailed conventional

Figure 2.1: Nilsson diagram from Ref. [4]. The general features of the diagram are valid for protons as well as neutrons in the $A = 80 - 100$ region. Regions of low level density for large deformations are indicated.

spectroscopic studies are hampered by large backgrounds due to the competing exit channels. In this case, channels selection becomes crucial in reducing the background and allowing detailed study of these weakly populated structures.

For all these cases, the MICROBALL can very effectively provide the desired channel selection without significantly affecting the quality of the Ge γ -ray spectra. The systems we have studied thus far (see sections below) are a prelude to a program that we will undertake by using the MICROBALL in conjunction with the GAMMASPHERE.

2.1.1 Superdeformation and Band Termination in ^{82}Sr

(D.M. Cullen, C. Baktash, J.D. Garrett, C.J. Gross, N.R. Johnson, W. Nazarewicz [ORNL], J. Simpson [Daresbury], D.W. Stracener, D.G. Sarantites [WU], I. Ragnarsson [Lund].)

For some mass regions with prospects for exciting nuclear structure physics (especially at high spins), discrete γ -ray spectroscopy is difficult due to the emission of protons, neutrons,

and alpha particles from the compound system with comparable probabilities. Such a region certainly is around mass 80 - 100 ($Z < 50$).

The $A = 80 - 100$ region (including $^{78-82}\text{Sr}$, $^{82-86}\text{Zr}$, $^{81-85}\text{Y}$, $^{93-98}\text{Ru}$ and others) is interesting because of a very rich pattern of nuclear shapes (excitations), shape coexistence, rapid shape transitions, and high K oblate bands (see Ref. [1]). The most exciting aspect of further work on these nuclei would be a search for a new island of superdeformation (SD) at $A \leq 100$, predicted in Refs. [2, 3]. After numerous experiments for finding superdeformation in the $A \approx 80$ region we finally succeeded in observing it (see discussion below).

The richness of the physics in this region is shown by the following aspects. The microscopic structure of the nuclei at the lower end of the region, at $A \sim 80$, is determined by the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ and $g_{9/2}$ orbitals. At the higher end, at about $A \sim 100$, and/or for strongly deformed (e.g. SD) shapes the $h_{11/2}$ and perhaps the $i_{13/2}$ orbitals are expected to play an important role. Special features of the mass region compared to other regions (e.g. $A = 150 - 170$) are a noticeably lower level density of single particle states (see e.g. ref. [3]) and the fact that protons and neutrons occupy essentially the same potentials (orbitals). These are responsible for the aforementioned shape varieties and changes as a function of particle number and spin, and are an important part of the following considerations.

Mean-field calculations [2, 3, 4] show large subshell closures at 2:1 shapes ($\beta_2 \approx 0.6$) for particle numbers N (or Z) = 32, 44, 64, 86 (see Fig. 2.1 for example). Thus, another island of superdeformed rotational nuclei is expected for $A \lesssim 100$.

Another aspect of the physics in this region is the understanding of the systematics of the band terminating states. These states, which mark the terminal point of transition from collective rotation to non collective, single-particle motion, are very sensitive to the positions of the high-j single-particle levels in the energy spectra. In an extensive set of calculations of the high-spin properties of the $A=80$ nuclei, Nazarewicz has predicted the occurrence of these states in several Sr isotopes.

The earlier experiments:

According to the calculations, the SD states in $A = 80 - 100$ nuclei become energetically favored at relatively moderate spins ($I \geq 40$), i.e. about 10 spin units lower than in superdeformed nuclei of the $A = 150$ region. Furthermore, these structures would have a much better chance to survive the competition with fission than the candidates in the heavier mass regions. Unlike the heavier systems where fission limits the population of high spin states, in this mass region copious α particle emission depletes to some extent the highest spins. Further reasons that SD has not been found here, although seriously sought for with early generation γ -ray detection arrays, is that there is a large exit channel fragmentation coupled with large Doppler broadening due to the large recoil velocities. Despite the fact that state of the art charged particle discrimination (e.g. Dwarf Ball) has already been used (e.g. for $^{52}\text{Cr}(^{34}\text{S}, 2p2n)^{82}\text{Sr}$ [6]), the selection power of our present detector systems seems still not to be sufficient for achieving that goal.

Search for superdeformation in ^{82}Sr has been made in a number of experiments. The first two were carried out at HHIRF using the Dwarf Ball-Wall system for channel selection and the Spin Spectrometer with 18 Compton suppressed Ge detectors and were part of the PhD thesis of Dan Stracener [7]. The reactions used were (a) $^{52}\text{Cr}(^{34}\text{S}, 2p2n)$ at 130 MeV

and (b) $^{60}\text{Ni}(^{26}\text{Mg}, 2p2n)$ at 110 MeV. A weak ridge-valley structure in the continuum E_γ - E_α matrix was observed that corresponds to a rigid rotor with $\beta_2 = 0.55$ [6, 7]. A discrete band

Figure 2.2: Decay scheme for ^{82}Sr from [7].

associated with this structure has not been observed.

A detailed decay scheme that included up to 8 rotational bands with a variety of shapes ranging from oblate to triaxial and prolate have been identified. The early scheme is shown in Fig. 2.2.

The EUROGAM Experiment:

The third search was made using the EUROGAM array at Daresbury [8]. Again the ridge-valley structure was found to be more prominent than before due to the increased sensitivity of 45 large Compton suppressed Ge detectors. Finally, a week discrete superdeformed structure in ^{82}Sr was observed and in addition new information on band termination in ^{82}Sr was

Figure 2.3: New decay scheme for ^{82}Sr from the Eurogam experiment. [8]

observed (see below).

High-spin states were populated in ^{82}Sr in the $^{56}\text{Fe}(^{30}\text{Si}, 2p2n)$ reaction at a beam energy of 128 MeV. The ^{30}Si beam was produced by the NSF tandem accelerator at Daresbury Laboratory, and the γ -rays were detected with the 45 Compton Suppressed Ge-multidetector array, EUROGAM. Collimators were placed in front of the near 90° detectors to limit the Doppler broadening due to the moving recoils. The target consisted of one $315 \mu\text{g}/\text{cm}^2$ self-

Figure 2.4: Spectrum of γ -rays in coincidence with the 1540 keV gate in ^{82}Sr .

supporting metal ^{56}Fe foil. A raw Ge-fold threshold of 5 was set on the γ - γ coincidence data to enhance the high multiplicity events. The coincidence data rate was determined by the maximum singles rate of $\approx (1.0-1.5) \cdot 10^4$ c/s, which corresponded to the raw Ge fast-trigger event rate of $\approx 5.3\text{K}$ per sec. A total of 4×10^9 γ - γ events were recorded in 9 shifts. The Ge detectors were calibrated with radioactive sources both before and after the experiment. Source data were taken with ^{152}Eu as well as $^{88}\text{Y} + ^{133}\text{Ba}$ in coincidence mode.

In these data each of the six rotational bands observed in previous studies [6, 7] of ^{82}Sr have been extended to higher spins, see Figs. 2.2, 2.3. In particular the negative-parity oblate collective band, (band 1 in Fig. 2.3), has been extended by one transition, 2097 keV, at spin $26^- \hbar$.

For the band 3 which has spins intermediate to those of band 1, band 2, a new state decaying by a 2542-keV transition was added at spin $29^- \hbar$. The ground-state band, (band 6), was not extended in this work. However, the two bands that were only previously known with two- and four transitions, (bands 7 and 8), have been increased to much higher spins. Band 7 now has three new transitions, the 1081-, 1313- and 1493-keV γ -rays. Band 5 has the addition of a 1230-keV dipole transition at the bandhead, which changes the spin assignment for the band to be 9^- from the previous work. Four new transitions at 1502-, 1508-, 1777- and 1972-keV have been added to give 25^- as the maximum spin state in this band. The ordering of the highest transitions in the positive-parity band, (band 9), has also

been changed from the previous work. The top three transitions are now measured to be the 1871-, 2152- and 2415-keV γ -rays, extending its maximum spin state to $28^+\hbar$.

With the higher resolving power of the Eurogam array we were expecting to populate these bands to a much higher rotational frequency. After one shift of beam time, we were able to observe the highest-spin states recorded in the known [6, 7] ^{82}Sr level scheme. However,

Figure 2.5: (a) Ridge structure showing the superdeformation in ^{82}Sr . (b) Preliminary spectrum of the discrete transitions observed to form the superdeformed band in ^{82}Sr .

after an additional nine shifts we were only able to extend these high-spin states by the few transitions discussed above. Upon closer inspection it was observed that these collective rotational bands were terminating, their intensity fragmenting to the competing single-particle states. Band 1 was observed to fork at the 18^- state to another sequence of three transitions (1625-, 1739- and 1981-keV) in a parallel cascade. Band 2 was also observed to fork at spin 21^- to another state at 13959 keV. No other states were observed to feed this state.

Fig. 2.4 illustrates the fragmentation of the γ -ray intensity of the transitions as the band terminates. The low-spin yrast band, (band 6), was observed to split into two other bands, bands 5 and 7, at spin 8^+ . Furthermore, the new extension to band 6 was also observed to fragment with a 1543-keV γ -ray. The positive parity band, (band 9), was also observed to fragment at spin 18^+ into a parallel cascade with several transitions which terminates at spin 23^+ .

In addition, we find evidence that band 4 is actually the signature partner to band 1 with a moderate signature splitting. In this case the dipole transitions linking these bands are weak and in one direction only. (The multipolarity of the γ -ray transitions was determined from DCO measurements.) We also observe a new rotational sequence of four transitions which is strongly coupled to band 9 and is assumed to be its signature partner rotational band. Indeed dipole transitions are observed to connect the two bands in both directions.

Qualitatively one may understand why rotational bands in ^{82}Sr terminate at $30\hbar$ as both the number of valence shell nucleons and the angular momentum available for each nucleon ($g9/2$) is limited. Band termination is also suggested by the irregularity of the new branches; not simple band crossing by another rotational band.

One other feature observed in these data is evidence for superdeformation. The large deformed shell gaps at $Z=38$ and $N=44$ reduce the pairing correlations for these well deformed nuclei and allows them to behave as near rigid rotors. Indeed theoretical cranking model calculations [3] predict the coexistence of collective prolate, oblate, triaxial and SD shapes along with non-collective "Band terminating" states.

Close analysis of the triples background subtracted matrix, gated on the rotational bands in ^{82}Sr shows evidence for superdeformation. Ridges are observed parallel to the central valley which have a spacing of ≈ 300 keV which is appropriate for SD bands in the mass 80 region with $\beta \approx 0.5$. These ridges were first observed in [6], however, in those data the ridges were only reported to extend from 1800- to ≈ 2200 -keV, about 3-SD transitions. In the present data we observe ridges that extend from 1800- to 2600-keV, allowing for about 5 or 6 SD transitions in a cascade. The ridge structure is seen in Fig. 2.5(a). In addition, a discrete line structure was found with up to 9 transitions (1304, 1460, 1612, 1759, 1912, 2063, 2205, 2345 and 2493 keV). The average spacing is 151 keV which corresponds to deformation parameter $\beta \approx 0.5$. A "very preliminary" spectrum of the discrete structure is shown in Fig. 2.5(b). The discrete lines correspond to a population of $\approx 0.4\%$ of the $2p2n$ channel. Note that the peaks are very broad.

Despite this success, it would be important to repeat this experiment with an advanced detector setup such as Gammasphere augmented with the Microball in order to cleanup and possibly identify the connecting transitions.

We gratefully acknowledge the useful discussions with J. Döring and Dave Radford for the use of the Escl8r code.

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(P-F. Hua, D.G. Sarantites, J. Barreto, A. Kirov L. Sobotka [WU], C. Bakdash, I.Y. Lee, J.D. Garrett, N.R. Johnson, F.K. McGowan, D.Cullen [ORNL]).

Following the initial discovery of discrete superdeformed bands in ^{132}Ce and ^{152}Dy [1] 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.

2.1.2 Search for Hyperdeformation in the $A \approx 180$ Region

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Figure 2.6: Calculated potential energy surfaces at $h\omega = 0$, [3], for ^{170}Hg , ^{180}Hg , ^{190}Hg and ^{200}Hg as a function of β_2 and β_3 . The loci of the minima are shown by the solid dots.

which has led to the remarkable discovery of “identical” SD bands in neighboring nuclei.[2]

An even more exciting possibility is the observation of even larger deformations with $\beta = 0.8-1.0$ ($\sim 3:1$ axes ratio, “hyperdeformation, HD). Hyperdeformed structures have been predicted to exist in a number of regions at different spins and excitation energies. Usually the hyperdeformation is predicted for very high spins $\sim 80\hbar$, where the fission barrier vanishes. Very recently, state of the art calculations by Nazarewicz have predicted systematically hyperdeformation at low excitations in the light Hg isotopes.[3] The potential energy surfaces in the β_2 vs. β_3 plane at zero rotational frequency are shown in Fig. 2.6, and the excitation energy of the minimum is shown as a function of neutron number in Fig. 2.6. A minimum at $\beta_2 \sim 0.8$ is predicted in ^{180}Hg at ~ 6.5 MeV of excitation.

Figure 2.7: Calculated excitation energies [3] of the second minima in the potential energy surface for the Hg isotopes. For each set the values of β_2 and β_3 are shown.

Such a shape at low excitation would correspond to spin $\sim 30-35$ and may survive fission. Based on this prediction, we decided to undertake a search for a large deformation band structure in ^{182}Hg . For this purpose we chose the reaction $^{154}\text{Gd}(^{32}\text{S}, 4n)^{182}\text{Hg}$.

Statistical model estimates of the cross sections indicated only ~ 30 mb for the $4n$ channel, 200 mb of fission and the remaining 150 mb in charged particle channels. Based on this we designed a special particle counter that would allow us to tag and veto the charged-particle and fission channels. This counter was made from fast plastic scintillator and had the shape of a tube segmented in 4. The performance of this detector is described in the Section 3.3 and in Appendix 6.5. The experiment was performed at the HHIRF with the compact Ge array. A total of 12 Compton suppressed Ge detectors were used in the Compact Ball configuration. Four additional anti-Compton shields and four inserted BaF_2 detectors

served as a multiplicity filter to select high multiplicity events. The charged-particle channels to a considerable extent the fission events were identified.

In the above arrangement it was possible to construct a high multiplicity $E_\gamma - E_\gamma$ matrix from which the charged-particle channels and fission were removed. This matrix was then examined for sequences of γ -rays corresponding to the expected energies. Although we found some candidates for these transitions (only 4-5) transitions, we could not unambiguously establish the rotational character of these structures. We are still analyzing the data, but at present we can place an upper limit at the 1% level for the population of a hyperdeformed structure.

This work was done in collaboration with the ORNL group, while the data analysis was done primarily by P.F. Hua and the P.I.

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2.1.3 Structure of and Identical Bands in ^{182}Hg and ^{178}Pt .

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The structure of Hg and Pt nuclei offers a variety of interesting features because of the coexistence of a variety of nuclear shapes. The proximity of these nuclei to the $Z=82$ proton closed shell drives them to have spherical shapes in their ground state. The systematics of the 2^+ states attest to this. However, as we move toward the neutron deficient region, $N = 118-102$, well deformed structures appear in these nuclei.

Very little is known at this time about the structure in ^{182}Hg [1]. The experiment described in Section 2.1.2 was analyzed to construct a detailed decay scheme for ^{182}Hg . Analysis of the data from the $E_\gamma - E_\gamma$ matrix provided us with a detailed decay scheme shown in Fig. 2.8. Five additional decay sequences have been identified and directly connected to the ground state yrast band. Only levels up to 10^+ or 12^+ in the yrast band were previously known [1]. We extended the ground state band (GSB) up to spin 20^+ . Further analysis is in progress to establish the level spins sequences from angular correlation information.

Another experiment was carried with the HERA array at LBL and the "Tube" [2]. Here we employed the reaction $^{148}\text{Sm}(^{36}\text{Ar}, xpyn)^{178}\text{Pt}, ^{180}\text{Hg}$ at 165 MeV. The transitions in ^{178}Pt were isolated by gating on one charged particle (an α), in the pulse-height spectrum of the "Tube". The GSB transition sequence in ^{178}Pt was extended to higher spins (20^+) than previously known [3]. Part of the ^{178}Pt decay scheme is shown in Fig. 2.8.

It is interesting and important to notice that the GSB's for ^{182}Hg and ^{178}Pt have six transitions whose energies are close enough to be identical in Casten's definition [4]. The average difference of the identical transitions between these two bands is about 5 keV. If the moments of inertia were scaled as $A^{5/3}$, the difference should be 25 keV for the mass 180 region. The identical bands could be understood in the sense that ^{178}Pt and ^{182}Hg have their

Figure 2.8: Preliminary decay schemes for ^{182}Hg and ^{178}Pt from this work.

masses differing by 4, like those correlated in the identical band correlations pointed out by Casten [4].

If we compare the GSBs in ^{178}Pt and ^{182}Hg carefully, we find that the 261 keV transition of ^{182}Hg probably should not be considered as an inter band transition as it was done in Ref. [1]. Furthermore the bottom transition and the transitions above the identical are quite different in these two bands. The 170 keV transition in ^{178}Pt is the $2^+ \rightarrow 0^+$ member of these bands. In contrast the 351 keV transition in ^{182}Hg could not be a member of the ground state rotational band. This can be seen from a plot of the band energy as a function of spin shown in Fig. 2.9. The level energies can be represented reasonably well by Ejiri's formula [5]

$$E(I) = A \cdot I(I + 1) + B \cdot I \quad (2.1)$$

which fits the data better than fit in Ref. [3]. Therefore, the difference between these two bands must be related somehow to their intrinsic nuclear structure, such as the coexistence

of a spherical shape and a reasonably well deformed nuclear shape.

At present it is not clear how to interpret these identical bands, and the question of why are the bottom transitions and those above the identical region so different in the two nuclei. However if we notice that all the identical bands from ^{156}Dy to ^{180}Os [4] are identical only before or after the backbending region, we might understand these two GSB bands by relating some structural change near the bottom of ^{182}Hg to the alignment processes that are responsible for backbending.

Figure 2.9: Experimental ground state band energies in ^{182}Hg (open squares) and ^{178}Pt (open circles). The lines are fits of the data to the Ejiri formula of Eq. 2.1.

This work was done in collaboration with the ORNL group, while the data analysis and interpretation was done by P.F. Hua. This work is part of the PhD thesis of Peng-Fei Hua.

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2.1.4 A Highly Deformed Band in ^{136}Pm and the Anomalous $h_{11/2}$ Proton Crossing in the $A \sim 135$ Superdeformed Region

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The dynamical moments of inertia ($J^{(2)}$) of superdeformed (SD) bands in the $A \sim 150$ Gd-Dy and $A \sim 190$ Hg-Pb regions are fairly well reproduced by standard cranking calculations [1, 2]. However, for the superdeformed or highly deformed $A \sim 135$ Ce-Nd Sm region, this is not true at all, and has presented a theoretical puzzle for some time. Several theoretical suggestions in terms of quenched proton pairing [3] and a strong residual proton-neutron interaction [4, 5] have been proposed.

Figure 2.10: Summed coincidence spectrum for the highly deformed band observed in ^{136}Pm . Energies are given to the nearest keV. Known contaminant lines from ^{131}Ce , ^{136}Sm are indicated by a filled triangle.

Up to the present time in the $A \sim 135$ region highly deformed bands have been observed almost exclusively in even- Z nuclei, i.e. $^{131,132}\text{Ce}$ [6, 7, 8], $^{133,135,136,137}\text{Nd}$ [12, 10, 11], $^{135,137}\text{Sm}$ [3, 14, 19, 16, 15] and $^{139,141}\text{Gd}$ [20, 21]. Only in ^{130}La [22] has a highly deformed band been observed in an odd- Z nucleus. Unfortunately this band, since it is only observed at very high frequency ($\hbar\omega > 0.4$ MeV), is not able to contribute significantly to the understanding of the anomalous $J^{(2)}$ dependence on rotational frequency, which centers around the behavior of

the lowest $h_{11/2}$ proton levels near $\hbar\omega = 0.4$ MeV [3, 4, 5, 13]. The aim of the present work was to observe a highly deformed band in the $N=75$ odd- Z nucleus ^{136}Pm which lies in the middle of this region.

We performed an experiment at the Holifield Heavy Ion Research Facility at Oak Ridge to search for this superdeformed band. 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 $1n$, $2pn$, αn , $p\alpha n$, 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 280×10^6 γ - γ -charged particle coincidences were recorded. Additional statistics were accumulated in another experiment carried out at FSU using 9 Compton suppressed Ge detectors and a 28 element BGO sum energy/multiplicity ball.

Figure 2.11: Plot of the dynamical moment of inertia $J^{(2)}$ against the rotational frequency $\hbar\omega$ for highly deformed bands observed in $N=75$ isotopes. Note that the rise in $J^{(2)}$ above $\hbar\omega = 0.3$ MeV for Nd, Sm, and Gd bands compared to the downsloping or nearly constant value for Pm.

Figure 2.10 shows a summed coincidence spectrum for the highly deformed Pm band observed in both experiments. The band is assigned to ^{136}Pm from observed coincidence relationships with low spin yrast transitions in ^{136}Pm [25] and also excitation function information from the two experiments. The measured intensity of the band is ~ 5 -8% of the ^{136}Pm channel and closely follows the intensity pattern with increasing spin observed for

other highly deformed bands in this region. At the present time no firm connections linking the highly deformed band to the normal deformed levels have been established.

In odd-N nuclei in the $A \sim 135$ region the highly deformed structures occur by having a single neutron occupying the $[660]1/2 i_{13/2}$ orbital [13]. In ^{136}Pm the odd-proton is expected to occupy the favored $h_{11/2}$ signature ($\alpha = -1/2$) level. Thus, the yrast highly deformed band is expected to have even spin values with the configuration $\pi(h_{11/2})^1 \otimes \nu(i_{13/2})^1$. TRS calculations predict a deformation of $\beta_2 \sim 0.33$, $\gamma \sim 0$ for the highly deformed minimum compared to $\beta_2 \sim 0.20$, $\gamma \sim -20^\circ$ values for the normal deformed low spin yrast structures [24]. Since it is the $i_{13/2}$ neutron which plays the dominant deformation driving role, the deformations for all the $N=75$ isotones are expected to be rather similar. This expectation is supported by the measured quadrupole moments, see Ref. [15].

As mentioned above, the “anomalous” $J^{(2)}$ behavior in this region, centers around the $h_{11/2}$ proton alignment expected to take place around $\hbar\omega \sim 0.4$ MeV. If our configuration assignment to the ^{136}Pm band is correct then this troublesome crossing should be blocked. The observed $J^{(2)}$ for ^{136}Pm shown in Fig. 2.11 β supports this interpretation, where for $\hbar\omega \sim 0.3-0.5$ MeV the band is falling to a near constant value. On the other hand the even- Z $N=75$ isotones ^{135}Nd , ^{137}Sm and ^{139}Gd display significant increases in their $J^{(2)}$ behavior throughout this frequency range, see Fig. 2.11. These data indicate that the $h_{11/2}$ proton crossing is indeed taking place in the even- Z $N=75$ nuclei (and presumably other even- Z highly deformed nuclei in this region) but with a much stronger interaction strength than predicted by standard cranking calculations. Thus we can rule out the suggestion that proton pairing has been quenched at a very low frequency ($\hbar\omega < 0.2$ MeV) in these highly deformed bands [3]. Our results would support the proposal of Wyss and Johnson [4] for a strong residual proton-neutron interaction between the $\pi h_{11/2}$ and $\nu i_{13/2}$ orbitals which has the effect of shifting the $\pi h_{11/2}$ crossing to slightly higher frequency and causing a much stronger mixing between the crossing bands in the even- Z $N=75$ nuclei. However we would suggest that this may not be the only possible explanation. We would also suggest that the sharp increases in $J^{(2)}$ observed at very low frequency in the highly deformed bands (see Fig. 2.11) are not due to the paired to unpaired phase transition but simply reflect the mixing with other levels of similar (π, α) which help initiate the decay out of the highly deformed bands.

This work was done in collaboration with Mark Riley’s group and the ORNL group and was published in the Physical Review as a rapid communication (see Appendix S for a reprint).

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2.1.5 Quantitative Studies of the Continuum γ -ray Correlations in ^{170}Hf

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This work is a complete study which was recently published in Phys. Rev. C (See Appendix M). Bellow is the abstract from this work.

Abstract: We have studied the two-dimensional energy correlation of the continuum γ rays in ^{170}Hf produced in a heavy-ion fusion reaction. The γ rays were measured with an array of Compton-suppressed Ge detectors and the Spin Spectrometer. A quantitative analysis has been carried out on the properties of the peaks and dips in the correlation spectra. The results indicate the existence of at least two widths in the γ -ray energy distribution: a narrow width of about 20 keV, most likely originating from decay along different discrete bands near the yrast line, and a wide width of about 200 keV from mixed states at higher excitation energy. Theoretical calculations including the effect of level mixing fluctuations in the rotational frequency and moment of inertia give results in general agreement with experiment.

This work was done in collaboration with the ORNL group, while the data analysis and interpretation was done primarily by I.Y. Lee at ORNL.

2.2 STUDIES AT THE INTERFACE BETWEEN STRUCTURE AND REACTIONS

2.2.1 Search for Entrance Channel Effects in the Particle Decay of the ^{164}Yb Compound Nucleus at $E^* \approx 54$ MeV

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We recently completed a study of the decay of the compound nucleus $^{164}\text{Yb}^*$ formed at 54 MeV of excitation energy using heavy-ion fusion reactions with different entrance channel mass asymmetries [1]. The purpose of this study was to investigate the existence of an entrance channel dependence in the compound nucleus decay. Claims for such an entrance channel effect were made in the work of Ruckelshausen *et al.* [2] who studied the decay of the compound nucleus $^{156}\text{Er}^*$ ($E^* = 47$ MeV) produced in the reactions $^{12}\text{C} + ^{144}\text{Sm}$ and $^{64}\text{Ni} + ^{92}\text{Zr}$. In the study of Ruckelshausen *et al.* evaporation residue angular momentum distributions were deduced from data obtained with the Heidelberg Crystal Ball [2]. These distributions were transformed into compound nucleus angular momentum distributions. Strong differences in the α xn and high spin xn populations were observed in the two reactions. For the xn channels, in particular, the ratio of the 2n/3n cross sections as a function of the compound nucleus spin was found to depend on the entrance channel suggesting that there is "memory" during the particle evaporation process.

In order to shed some light into this subject, we performed a detailed study of the decay of the nearby compound nucleus ^{164}Yb formed at the initial excitation energy of $E^* \approx 54$ MeV in the reactions $^{16}\text{O} + ^{148}\text{Sm}$ and $^{64}\text{Ni} + ^{100}\text{Mo}$. Energy and angular distributions of the emitted light charged particles were measured with the Dwarf Ball that provided a nearly 4π detection. Evaporation residue γ -ray fold distributions and total γ -ray information were obtained with the Spin Spectrometer. These measurements were made in coincidence with discrete γ -transitions in the evaporation residues detected by an array of 18 Compton-suppressed Ge detectors. The γ -ray fold distributions combined with the energy and angular distributions of the emitted charged particles provided a complete set of data for the comparison of the two reactions.

In the $^{64}\text{Ni} + ^{100}\text{Mo}$ system, the α 2n and α 3n angular distributions were found to be symmetric around $\theta_{CM} = 90^\circ$. This pattern indicated emission from a fully equilibrated compound nucleus. However, in the $^{16}\text{O} + ^{148}\text{Sm}$ system, both of these channels showed rather different patterns with an extra forward component. It was further established that the excess of forward emitted α 's is related with the most energetic emitted particles and corresponds to low γ -ray folds. This non-equilibrium component was associated with an incomplete fusion process in which the ^{16}O projectile breaks up into $^{12}\text{C} + \alpha$, followed by fusion of the ^{12}C with the target nucleus. The subsequent decay of the resulting $^{160}\text{Er}^*$ by 2 or 3 neutron emission contributes to the α 2n and α 3n channels under study. Specifically, it results in shifts of the γ -ray multiplicity distributions to values lower than those associated with the equilibrium decay of $^{164}\text{Yb}^*$. Indeed, a downward shift of these distributions was observed in a comparison with the ones of the ^{64}Ni -induced reaction.

The above finding provided a rational explanation to the previously reported differences in the evaporation residue spin distributions involving αxn emission. In previous studies, the strongest entrance channel mass asymmetry was achieved in ^{12}C -bombardments; i.e. using a projectile that is even more prone to incomplete fusion.

In the present work apparent differences in the γ -ray fold distributions of the xn channels populated in the two reactions were also observed, which if converted into spin distributions as was done in Ref. [2] most likely would show unexpected entrance channel effects, in agreement with the previous reports on the decay of $^{156}\text{Er}^*$. We have opted a different approach in trying to understand the experimental observations. First we obtain a realistic fusion model that provides initial spin distributions with which statistical model calculations reproduce well all the exit channel cross sections. Then with these ℓ -distributions as input, we calculate the spin distributions in the compound nucleus and in each evaporation residue (ER). We note that these transformations involve broad mappings. Then for each ER we calculate via the statistical model the corresponding γ -ray multiplicity distributions through another mapping involving broad distributions. Finally, we calculate the coincidence fold distributions by folding the measured Spin Spectrometer responses to the calculated M_γ distributions through another broad mapping and only then we compare with the experimental k_γ distributions.

When the above analysis was done for the symmetric and asymmetric entrance channels all the essential features of the data are explained and there is no reason to assume that the Bohr independence hypothesis may be violated or that influences from nearby superdeformation [2] may be needed to explain the data.

More specifically, for the $^{16}\text{O} + ^{148}\text{Sm}$ reaction, a good description of the γ -ray fold distributions of the xn channels was obtained. Discrepancies in the reproduction of the αxn distributions were attributed to the above mentioned incomplete fusion mechanism. An improved description resulted after the inclusion of the component from the deexcitation of incompletely fused ^{16}O with ^{148}Sm , obtained with the model of Wilczyński[3]. The majority of the $^{64}\text{Ni} + ^{100}\text{Mo}$ data was also reproduced by the statistical model, although the degree of agreement was not as good as in the $^{16}\text{O} + ^{148}\text{Sm}$ reaction.

Summarizing, the description of the compound nucleus decay with the statistical model indicated that most of the experimental features can be understood without the need to resort to strong structural influences on the deexcitation of the compound nucleus by particle emission. We therefore conclude that no reason other than the difference in the primary spin distributions is responsible for the observed differences in the decay of $^{164}\text{Yb}^*$ populated in the above two reactions.

This work has been written in a paper submitted to Phys. Rev. C, and a preprint is given in Appendix 6.1.

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2.2.2 Formation and Decay of $^{164}\text{Yb}^*$ in Near and Below-Barrier Fusion Reactions

(N.G.Nicolis and D.G. Sarantites)

The process of subbarrier fusion between medium to heavy-mass nuclei has attracted a great deal of interest in recent years. Numerous experimental observations have established that although the near-barrier fusion cross sections are described well by an one-dimensional barrier penetration model, the below-barrier cross sections may exceed these predictions by orders of magnitude. A related phenomenon is the broadening of the spin distributions observed in several systems that exhibit a subbarrier cross section enhancement [1]. The coupled-channels method has demonstrated the importance of coupling of the entrance channel to various inelastic and transfer degrees of freedom in the subbarrier fusion enhancement. It has also predicted the broadening of the spin distributions compared to the one-dimensional barrier penetration model [1].

A stringent test of the fusion models can be made in simultaneous comparisons with the fusion excitation functions and the moments of the spin distributions, whenever available. A systematic analysis of cross section and average angular momentum data was recently undertaken by DiGregorio and Stokstad [2]. The data were compared with a barrier penetration model including the effect of coupling to the low-lying inelastic channels. It was concluded that in most of the cases, the simplified coupled channel calculations that fit the cross sections also give a reasonable account of the measured angular momenta. A few exceptions occur in systems involving highly fissile compound nuclei as well as the most symmetric systems such as $^{64}\text{Ni} + ^{100}\text{Mo}$ and $^{80}\text{Se} + ^{80}\text{Se}$. In the latter systems, the theory was found to underestimate systematically the fusion cross section and the corresponding average angular momentum with decreasing bombarding energy.

The subbarrier fusion of $^{64}\text{Ni} + ^{100}\text{Mo}$ was studied first with the Oak Ridge Spin Spectrometer by M.L. Halbert *et al.* and has encountered serious difficulties in its interpretation [3]. Evaporation residue cross sections and γ -ray multiplicity distributions were measured for the dominant decay channels. The compound nucleus spin distributions were reconstructed from the γ -multiplicity distributions using statistical model estimates of the angular momentum removed by particle and γ -ray emission. Using the same model as DiGregorio and Stokstad, it was found that the excitation function cannot be reproduced with a priori coupling strengths. Increasing the coupling strengths to 1.5 times their expected values was found necessary to fit the cross sections. However, even with this modification the average angular momenta were still underestimated. The data set of Ref. [3] provide one of the most complete subbarrier fusion measurements available to date for a heavy and nearly symmetric entrance channel. Therefore, it is not surprising that the observed effects have initiated several theoretical investigations and comparative studies.

In principle, a coupled channels approach should be able to account for the experimental data once the appropriate coupling scheme is known. However, this procedure becomes

quite involved or even impractical when the number of contributing channels is large. It was shown recently by Mohanty *et al.* [4] that the results of a coupled channel calculation can be reproduced by a simple barrier penetration model with energy-dependent barriers. It was pointed out that the barrier heights should be expressed as a function of the radial kinetic energy at the barrier radius. Such an energy dependence is expected on the basis of a macroscopic model of shape evolutions describing fusion [5, 6].

We recently obtained a description of the reactions $^{64}\text{Ni} + ^{100}\text{Mo}$ and $^{16}\text{O} + ^{148}\text{Sm}$ through the model of Mohanty *et al.* [4]. Both reactions lead to the formation of the compound nucleus $^{164}\text{Yb}^*$. Previous evaporation residue cross section and spin distribution data [3, 8] were considered together with recent data on these reactions [9]. The bombarding energies range from near to well below the respective entrance channel Coulomb barriers. The analysis of the $^{64}\text{Ni} + ^{100}\text{Mo}$ reaction was facilitated with an energy-dependence of the fusion barriers extracted in this work from the experimental spin distributions. A good description of the fusion excitation function and of the first two moments of the compound nucleus spin distributions was obtained. Furthermore, the calculated spin distributions were found sufficient in reproducing, through the statistical model, the majority of the evaporation residue cross sections in both reactions. Using the asymmetric $^{16}\text{O} + ^{148}\text{Sm}$ reaction as a reference, it was realized that the nearly symmetric $^{64}\text{Ni} + ^{100}\text{Mo}$ system involves a much larger angular momentum transfer to the compound nucleus. This influences significantly the cross sections of the neutron evaporation channels. In particular, it leads to an enhancement of the fractional $2n$ and a suppression of the fractional $4n$ cross sections, for $^{64}\text{Ni} + ^{100}\text{Mo}$, in the bombarding energy range of the present study. Comparisons of the data with simplified coupled channel calculations were also made for $^{64}\text{Ni} + ^{100}\text{Mo}$. Most of the features of the available data were reproduced by including coupling strengths additional to the low-lying projectile and target inelastic excitation modes. We also point out that difficulties encountered in previous analyses are related to the neglect of target thickness effects. These effects should be considered in the analysis of fusion experiments involving thick targets as in the case of the $^{64}\text{Ni} + ^{100}\text{Mo}$ reaction.

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2.2.3 The “Unitarity Limit” in Near-Barrier Fusion Reactions

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In recent years considerable effort has been devoted to the study of the role played by the mass asymmetry degree of freedom in the entrance channel of fusion reactions. It has been established that, for the same compound nucleus excitation energy, more angular momentum is brought in by the nearly mass-symmetric entrance channel reactions, and it is in excess over one dimensional models predictions. Experimental studies involving

Figure 2.12: Compound nucleus angular momentum distributions for $^{64}\text{Ni} + ^{92}\text{Zr} \rightarrow ^{156}\text{Er}$ (top) and $^{64}\text{Ni} + ^{96}\text{Zr} \rightarrow ^{160}\text{Er}$ (bottom) from Ref. [5]. The histograms are reconstructed spin distributions. The dashed lines represent the unitarity limit.

nearly 4π γ -detector systems such as the Darmstadt-Heidelberg Crystal Ball, the Daresbury

TESSA2 and TESSA3 arrays and the Spin Spectrometer, have indeed contributed to the above conclusion [1, 2, 3]. The same conclusion was reached by Haas *et al.* [4], using a more standard method to measure the average angular momentum transfer as a function of the mass asymmetry of the entrance channel.

A remarkable feature is seen in Fig. 2.12 from the work of Kuhn *et al.* [5]: The reaction $^{64}\text{Ni} + ^{92}\text{Zr}$ appears to exhaust the “unitarity limit” (fusion $T_l = 1$) at the lower angular momenta, while for the $^{64}\text{Ni} + ^{96}\text{Zr}$ system the partial cross sections σ_l are significantly

Figure 2.13: Experimental coincidence γ -ray fold distributions for the xn exit channels from the reactions (a) 242 MeV $^{64}\text{Ni} + ^{96}\text{Zr} \rightarrow ^{160}\text{Er}$ (top), and (b) 87 MeV $^{16}\text{O} + ^{144}\text{Nd} \rightarrow ^{160}\text{Er}$ (bottom). Note the apparent large displacement of the distribution for the 3n exit channel.

below this limit, even for low partial waves. We note, however, that these distributions were normalized to cross sections from other measurements. The low T_l 's for the more neutron-rich system are due to the rather low evaporation-residue cross section of 133 ± 25 mb observed [4] at an incident energy of 1.07 times the Coulomb barrier V_B . In comparison, a cross section of 239 ± 36 mb [6] has been used for normalization for the more neutron-deficient $^{64}\text{Ni} + ^{92}\text{Zr}$ at $1.05V_B$. Yet more recent measurements by Stefanini *et al.* [7] indicate lower cross sections for the latter system, suggesting that unitarity limit for the reaction $^{64}\text{Ni} + ^{92}\text{Zr}$ is not reached either.

The above striking result if true, implies that a dramatic change in the reaction mechanism occurs when four more neutrons are added to the ^{92}Zr . However, it is worth mentioning here that the spin distributions in Kuhn *et al.* [5] were actually deduced from measured fold

residues distributions, using unfolding techniques which are best suited for the transformation of averages and not distributions. These consecutive unfoldings may give rise to misleading results, as we have shown in [3].

In view of these uncertainties we decided to investigate more carefully one of these systems by obtaining both the cross sections and the multiplicity distributions from the same experiment. Here we report on preliminary results obtained in a detailed study on the systems $^{64}\text{Ni} + ^{96}\text{Zr}$ and $^{16}\text{O} + ^{144}\text{Nd}$, forming $^{160}\text{Er}^*$ compound nuclei at nearly 55 MeV of excitation energy. The purpose of this work was two-fold: (a) to obtain a complete set of data in both energy and angular distributions of the emitted charged particles, combined with the γ -ray fold distributions of all reaction products and their relevant cross sections; (b) to study the influence of the entrance channel mass asymmetry in the decay of the ^{160}Er compound nucleus, using the same $M_\gamma \rightarrow k_\gamma$ folding technique as outlined in Ref. [3].

In this study, we detected light charged particles in 4π with the Dwarf Ball. Evaporation residue γ -ray fold distributions in coincidence with discrete γ transitions in the exit channel products were obtained with the Spin Spectrometer, in conjunction with an array of 18 Compton-suppressed Ge detectors that replaced 18 elements of the Spectrometer. Using the above setup, excitation functions were also measured for both reactions in a second experiment. Here we will concentrate only on preliminary results obtained at 55 MeV of excitation energy.

Figures 2.13(a) and (b) show the experimental γ -ray fold distributions for various xn channels as a function of k_{eff} , for the two reactions. Apart from the difference in the magnitude of the respective cross sections, the 4n-channel k_{eff} distributions have the same shape and peak position in both reactions. However, the one for the 3n channel is shifted to lower k_{eff} values by nearly 2.75 units in the $^{16}\text{O} + ^{144}\text{Nd}$ reaction (in Fig. 2.13 the 3n channel was not corrected and thus shows a 5.5 unit shift). The 2n channel shows also a pronounced effect, it is below the detection threshold in the $^{16}\text{O} + ^{144}\text{Nd}$ reaction, but has a measurable k_{eff} distribution in the $^{64}\text{Ni} + ^{96}\text{Zr}$ reaction, with its maximum around 25 units of k_{eff} . Another important feature observed in Fig. 2.13 is the broader total fold distribution of the xn channels ($\sum xn$, curve not shown) observed in the ^{64}Ni induced reactions, compared to those from the ^{16}O -induced reactions. These differences are similar and perhaps more pronounced compared to those reported in our previous work of Ref. [3], and show the influence of the entrance channel mass-asymmetry degree of freedom in the fusion process between two heavy nuclei.

The k_{eff} distributions for channels involving light-charged particles are currently being analyzed. However, these channels contribute with less than 10 % of the evaporation-residue cross sections and do not affect the trends shown in Fig. 2.13(a) and (b).

A preliminary search was carried on in the γ -ray spectra for singles events in the $^{64}\text{Ni} + ^{96}\text{Zr}$ reaction, in order to identify reaction channels that might compete with the fusion process in this system. So far, no other channels than those from evaporation residues have been identified in the γ -ray spectra. More restrictive constraints in the γ -ray spectra, fold distributions, and in the particles CM angular distribution are currently being imposed, in an attempt to identify those exit channels that compete with the fusion channel in the $^{64}\text{Ni} + ^{96}\text{Zr}$ reaction.

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2.2.4 Atomic Clocks in Nuclear Processes - Time scale of sub-barrier alpha emission.

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Abstract: The time scale for alpha particles emitted from Yb compound nuclei formed in the fusion reaction $250 \text{ MeV } ^{60}\text{Ni} + ^{100}\text{Mo}$ is determined from the probability that a K-vacancy, created on the incoming part of the collision, is filled prior to the emission of the α -particle. The mean lifetime of low energy α -particles populating high spin states, is extracted as a function of the probability of creating the K-vacancy.

Thirty years ago Gugelot [1] pointed out that one can calibrate the decay width (Γ_c) of a compound nucleus in terms of the K x-ray width (Γ_x) for atomic vacancies. All one has to do is prepare an atom with an excited nucleus and a K vacancy and then measure the branching ratio Γ_x/Γ_c . In practice, there are several problems in applying this idea. These include: the K-vacancy production probabilities P_K are low (of the order of 1%) for typical low energy fusion reactions, x-rays generated by internal conversion pose a serious background problem, and unlike atomic collisions below the Coulomb barrier, the x-rays must be detected in an environment with a large γ -ray flux which generates a significant background. Another important issue is the photon production from the filling of vacancies in a charged particle exit channel during the time after emission but before the emitted particle is well outside the K-shell Bohr radius (MO emission). Due to these problems, this old idea has met with success only recently [2, 3, 4].

This technique is best suited to the study of the lifetimes of last or near last chance decays of compound systems with $Z \geq 50$. Only under these conditions does the K-vacancy lifetime approach the compound nuclear lifetime. Two interesting topics for which this technique is quite promising are: 1) the study of slow fission components and 2) slow "yrast" α -particle emission. The former involves actinide nuclei for which the K-vacancy lifetime is less than 10^{-17} s and the latter, heavy rare earth nuclei with K-vacancy lifetimes between 10^{-16} and 10^{-17} seconds. The recent paper by Molitoris et al. [4] addresses the first of these topics and this work deals with the second.

Statistical model codes predict that the emission of α -particles competes with γ -ray emission at very low excitation energies when the nuclei are trapped near the yrast line at high to moderate spins. [5] Grover and Gilat even comment on this process in work published 25 years ago [6]. These early calculations, as well as more recent ones [7], predict that

these “stretched” and “last chance” α -particles would be emitted from states with lifetimes similar to the K-vacancy lifetime and therefore present an ideal application of the atomic clock method. The α -particle energies are low for these “last chance” particle emissions and - despite the angular momentum removed by the decay - tend to populate high spin states of the residue. The present work demonstrates that these long lived α -particle emitting states do exist, however their mean lifetime is shorter than predicted.

Figure 2.14: X-ray spectra gated on high gamma fold (k_γ) and low E_α energy (top histogram, offset by +100), high k_γ and high E_α (middle histogram), and low k_γ and low E_α (bottom histogram, offset by -100). The characteristic energies and intensities for K x-rays from ^{70}Yb and ^{68}Er are indicated by the arrows on the top and bottom of the figure, respectively.

The Holifield Heavy Ion facility at Oak Ridge National Laboratory was used to produce a beam of 250 MeV ^{60}Ni , which impinged upon a $711 \mu\text{g}/\text{cm}^2$ ^{100}Mo target. This reaction produces ^{160}Yb compound nuclei with a mean excitation energy of 59 MeV and angular momenta up to $\approx 57 \hbar$. The K-vacancy production probability for a non-retarded scattered trajectory is estimated to be 2% from scaling relations predicted with the semi classical calculations in the first Born approximation [8, 9], while the lifetime of Yb K-vacancies is estimated to be $\tau_x = 20 \times 10^{-18} \text{ s}$ [10], a value corroborated by the intrinsic line widths [11]. The x-rays were detected in a planar Ge detector positioned at 130° to the beam while α -particles were detected with the Dwarf Ball system[12] which covers close to 4π in solid angle. The Spin Spectrometer[13] was used to determine the γ -ray fold (k_γ) which is used for spin

selection. Three coaxial Ge detectors with Compton suppressors, replaced three elements of the Spin Spectrometer. These were used to determine the overall photon spectrum.

Figure 2.14 shows x-ray spectra with three different requirements on k_γ and the center-of-mass energy of the detected α particles, E_α . The upper histogram is generated with the selection of a low energy α -particle (the lower 1/2 of the E_α distribution, $E_\alpha < 17.5$ MeV) and the upper 1/3rd of the k_γ distribution. The middle histogram is constructed with the requirement that both k_γ and E_α be large, upper 1/3rd and 1/2 of the respective distributions, while the lower histogram utilizes the data with intermediate values of k_γ and low values of E_α . (The data with the lowest values of k_γ are not used as they are contaminated with reactions on C impurities in the target.) The three spectra have similar statistics and therefore are displayed with vertical offsets. The x-ray peaks from converted transitions in Er residues are the prominent features in all these spectra. What is also apparent are weak Yb x-ray peaks in the upper spectrum. The only Yb x-ray peak with clear statistical significance is K_{α_1} , however excess counts also occur at the energies corresponding to K_{α_2} and K_{β_1} energies. The arrows indicate the location and expected relative intensities of the x-rays. Within the statistical uncertainty, no evidence for these peaks is found in the other two spectra. This last observation fulfills our expectation that the slowest emissions will be from high spin states (to, a large extent, high spin residues) not too far above the yrast line.

The mean lifetime of the selected compound nuclei τ_c can be estimated from the known lifetime of a K-vacancy and the fraction of events which emit the CN x-ray,

$$f_{x,\alpha} = \frac{P_{x,\alpha}}{P_K} = \frac{\Gamma_x}{\Gamma_x + \Gamma_c} = \frac{\tau_c}{\tau_x + \tau_c}, \quad (2.2)$$

where $P_{x,\alpha}$ is the x-ray coincidence probability, corrected for the x-ray detection efficiency, the relative intensity of the x-ray branch (K_{α_1} in this case) and the fluorescence yield, per alpha particle. In this work the α -particle singles data were not recorded, thus the number of α -particles was estimated from the beam current and the estimated cross sections.

The extracted lifetime as a function of P_K is shown in Fig. 2.15. The thick line represents the most likely values and the thin lines give our estimate of the uncertainty of this measurement. If one assumes that P_K for the fusion trajectory is 1/2 of the value for the scattered trajectory, then the best estimate for the mean lifetime of the selected α -particle emitting states is $\approx 6 \times 10^{-18}$ s, as indicated by the arrows on Fig. 2.15. An independent method to estimate the mean lifetime of the selected α -particle emitting states is to use the relative magnitude of the Er K_{α_1} and Yb K_{α_1} yields. To this end, an average conversion coefficient for the cascades of interest was deduced by folding the efficiency corrected photon spectrum from the Ge detectors (for the selected event type) with calculated conversion coefficients[14]. The uncertainty of this procedure is due to the estimate of the multipolarity mix of the cascades of interest. Since we are interested in high spin cascades we have used 80% E2 and 20% E1. This procedure has a substantial uncertainty, especially if M1 transitions exist to any appreciable extent. However this procedure is useful because the uncertainties are independent of the α particle and x-ray detection efficiencies and the α particle cross sections, all of which enter into the uncertainty of the previous estimate. Needless to say, the result still depends on the value of P_K for fusion.

This folding results in an estimate that $\approx 20\%$ of the selected cascades (high k_γ fold and low E_α) have a converted photon. Using a value of $P_K = 1\%$, we can expect a Yb K_{α_1} yield

which is at least a factor of 20 smaller than the Er K_{α_1} yield. The Er K_{α_1} yield is 3376 ± 235 counts above the background. The value of 20%, leads to the expectation of roughly 170 counts above the background in the Yb K_{α_1} peak in the limit of long τ_c . The observed 96 ± 36 counts indicates that τ_c is close to τ_x or $\approx 20 \times 10^{-18}$. This lifetime is 3 times longer than our previous estimate, but not inconsistent with it considering the approximations involved. Furthermore, this time scale, $\approx 10^{-17}$, is more than two orders of magnitude longer than the time required for an α -particle to reach the Bohr orbit radius. This indicates that MO emission is not probable in this case. (The product of the K transition frequency and the lifetime of the compound nucleus, $\omega_K \tau_c$, is several 100 for our best estimate assuming $P_K \approx 1\%$.)

Figure 2.15: Estimated mean lifetimes of the selected compound nuclei (those which emit a low energy α -particle and possess high angular momentum) prior to the emission of the x-ray. The lifetime is given as a function of the K-vacancy production probability. The thick line indicates the most likely values while the region between the thin lines represent the values within the estimated uncertainty of the present measurement. This estimate considers the statistical uncertainty of the yield of CN x-rays and the uncertainty of the total α particle cross section.

Statistical model calculations with the code EVAP [7] yields an estimate of $\sim 5 \times 10^{-17}$ s for the lifetime of the states consistent with the requirements used to select the data shown in the top histogram in Fig. 2.14, (lower portion of the E_α distribution and upper portion of the residual spin distribution.). This is long compared experiment but the errors are large.

In this work the x-ray atomic clock method was used to provide a rough estimate of the characteristic emission time of α -particles from high spin compound nuclei. The compound nucleus x-ray peak is very small, and therefore the uncertainties are large. Nevertheless, this is positive evidence that “slow” and last, or near last chance, α particle emission occurs in the de-excitation of high spin compound nuclei. The time scale for these emissions determined from the present work appear to be in some disagreement with statistical model estimates. However a quantitative comparison is not possible at this point since the absolute probability of creating a K-vacancy was not determined. As a final point, we would like to mention that the work reported here can be substantially improved upon. The use of Compton suppressors for the x-ray detector would reduce the background by a factor of ≈ 2 .

With the GAMMASPHERE augmented by a number of x-ray counters and the addition of the MICROBALL, such experiments can be made quantitative. The K-vacancy production probabilities will be measured, and this will allow a systematic study of the time scales for particle emission to be done in a model independent way.

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2.2.5 Time Scale of Fission by the X-ray Clock Method

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Recent experiments have indicated that the fission process is inherently slow. Large multiplicities of pre-fission neutrons,[1] light charged particles[2] and γ -rays[3] have been observed relative to the predictions of the statistical model. These measurements are consistent with minimum fission times of 10^{-20} – 10^{-19} seconds.

Such slow times can be interpreted in terms of the diffusion model of fission first considered by Kramers.[4] In this model, the equilibrium flux of systems over their saddle-point configuration is reduced from the statistical model prediction for very large and very small nuclear viscosities. Also it has been proposed[5, 6] that it takes a non-zero delay time before

this equilibrium rate is achieved. Before this time, the fission decay rate is suppressed allowing large multiplicities of light particles to be emitted. Both the reduction of the equilibrium rate and the delay time are dependent on the nuclear viscosity.

It may be interesting to attempt to establish the time scale of fission by another more direct method, and to see whether there is an excitation energy dependence of the fission times. A fission delay would greatly inhibit first chance fission at high excitation energies.

In view of the success of the atomic X-ray method for the subbarrier α emission (See Section 2.2.4) and the recent paper by Molitoris *et al.* [7] it was found appealing to attempt to study the time scale for fission by means of the K X-ray clock method. Again, the basic idea is to measure K X-rays in coincidence with fission fragments and look for the compound nucleus X-rays. If these are observed then fission in these events occurred after the X-rays were emitted, thus establishing a time scale for comparison. If the K-shell vacancy production probability is known then the fraction of 'delayed' fissions can be calculated. The fissioning system must be carefully chosen to allow (a) the experimental determination of the K-vacancy production probability and to have sufficiently short X-ray mean decay time.

An appropriate choice may be a heavy system such as $^{37}\text{Cl} + ^{197}\text{Au}$ or $^{37}\text{Cl} + ^{207}\text{Bi}$ at 70 MeV of initial excitation. Here we may expect a K-vacancy production probability of $\sim 0.2\%$ (see discussion in Sect. 2.2.4). This small probability makes the X-ray clock experiments difficult, since the efficiency of setting up the clock is very small. In the systems of interest the target is sufficiently heavy so that the probability of carrying a K-vacancy from a previous atomic collision is negligible. In subbarrier atomic studies one must only contend with the continuum MO background, which is in itself fascinating. On the other hand, when the object is to time nuclear processes, the background from γ rays and conversion generated X rays creates additional uninteresting and potentially confusing background. Distinguishing the conversion X-rays from the direct atomic X-rays is difficult, however the different time scales involved can be used to suppress the conversion X-rays by the shadow blocking technique. Aside from the conversion confusion, the main problem is detecting X-rays in an intense γ ray environment.

The γ generated background in the X-ray region (60-110 keV) has two components: low energy γ rays and Compton photons. Low energy γ rays with multipolarity other than E1 in this energy region will be slow enough to shadow block. If shadow blocking is employed, the major background will be the Compton photons. Therefore effective Compton suppression is extremely important. Due to experimental difficulties, neither of our previous experiments made use of Compton suppression on the X-ray detectors. In our future experiments we will not only use Compton suppression, but also use an X-ray detector which dramatically improves the suppression as compared to standard designs.

The standard planar Ge detectors used for X-ray detection are mounted in the same way as are the true long cylindrical Ge detectors. That is, with the axis of the thin Ge wafer in line with the cold finger which connects it to the cryostat. This geometry prevents the placement of any scintillation veto element directly behind the Ge crystal. Needless to say, this is the most important region to have suppression. No planar Ge detector design on the market allowed for the placement of a suppression element in the 0° region, so we designed one. (See Fig. 3.9 of the progress report). The axis of the crystal is perpendicular to the

cryostat. The can has a rectangular cross section of 1" by 2", with the axis of the crystal along the 1" dimension.

This design was simulated with GEANT [8] before placing the order for this detector. Some of the simulations are shown in Fig. 3.10 of the progress report. The initial photon distribution was chosen to resemble that from fission (but without any structure) with the addition of 2 parts per 10,000 K X-rays. This input spectrum is shown as the top curve in both parts (a) and (b) of the figure. The "raw" spectrum from this detector, with a 1 mm absorber placed in front of the active region, is also shown in both parts of the figure as the middle curve. The bottom curves are the Compton suppressed spectra from a) an Argonne type - full suppressor and b) a simple 3"x3" NaI(Tl) placed behind the Ge. The value of the full suppressor is clearly seen. In addition, the effect of suppressing directly behind the active element is also seen in that the small 3"x3" all by itself provides significant suppression.

A 800 mm² detector of this design has been delivered from ORTEC. We have obtained a 530 eV full width at half maximum at 122 keV. The experiment was done at Argonne at the Atlas Facility.

For the ³⁷Cl + ¹⁹⁷Au system the K X-ray mean lifetime is 3.2×10^{-18} s (calculated as $\tau = \hbar/\Delta E$, with $\Delta E = 208$ eV). This means that this method would be only sensitive to the longer components of the decay by fission. The experiment was done by detecting the fission fragments with a Si strip detector (16 strips along the x and 16 along the y axis) located near 90° in the laboratory. The Compton suppressed x-ray detector was also located at 90° and viewed the target through a recoil shadow collimator that prevented the evaporation residues a few mm down stream to be seen by the detector.

Initially a ²⁰⁹Bi target was used, but it could only take a few particle nAmps of beam before melting. Later in the run a ¹⁹⁷Au target was used. In this case we found an interfering γ -ray at exactly the $K_{\alpha 2}$ energy for the compound nucleus. At that point we switched back to the ²⁰⁹Bi target. The statistics were very limited, however some weak possible peak appears in the X-ray spectrum coincident with fission fragments. The data are being analyzed by Niel Robertson in L. Sobotka's group. In all likelihood this experiment would be repeated and plans for this are outlined in the proposal.

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2.2.6 Nuclear Structure Effects in Proton Evaporation Spectra

(D.W. Stracener, D.G. Sarantites, N.G. Nicolis, [WU], C. Baktash, J.R. Beene, N.R. Johnson, M.L. Halbert, D.C. Hensley, F.K. McGowan, I-Y. Lee [ORNL], and M.A. Riley, [FSU].)

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 and the recent report of a structure with even larger deformation (*hyperdeformation* with axis ratio $\sim 3:1$) for rare earth nuclei at high spins that are near the stability limit against fission[1]. Since superdeformed nuclei are produced in very small yields in heavy-ion

Figure 2.16: Proton energy spectra coincident with different rotational bands in ^{82}Sr . (see Fig. 2.2 for the decay scheme). The ground band spectrum is the sum of 3 gates (on transitions from 2^+ , 4^+ , and 6^+). 'Band 1' is a sum of 3 gates (on transitions from 14^- , 16^- , and 18^-). 'Band 3' is a sum of 4 gates (on transitions from 11, 13, 17, and 23). 'Band 4' is a sum of 2 gates (on transitions from 10^+ and 14^+). 'Band 7' is a sum of 4 gates (on transitions from 14^+ , 16^+ , 18^+ , and 20^+). The spectra are normalized to the same area for comparison and a few typical error bars are shown. The reaction was (^{24}Mg , $2n2p$).

fusion reactions, it is important to understand the mechanisms for populating these local

minima, if ways of producing hyperdeformed nuclei are to be found and their mechanism understood.

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 or by simple reduction of the fissility of the evaporation residues in the process of the compound nucleus de-excitation. 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. [2, 3] 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. These possibilities are supported by a recent report by the Chalk River group for the popu-

Figure 2.17: Angular distribution coefficients of protons coincident with the indicated rotational bands at spin 14^+ as a function of proton energy. It is seen that below the barrier (≈ 6 MeV) the A_2 coefficients associated with the yrast band 7 are considerably larger compared to those of the ground band. (The band numbers are from Fig. 2.2).

lation of a hyperdeformed structure by a (HI,p4n) reaction [4]. Related to this is might be the issue of structural influences on the shapes of the proton evaporation spectra. Although the particle emission may be very important in stabilizing the evaporation residues against fission, the shapes of the spectra do not appear to be influenced by the population of normal

or superdeformed states, although the angular distributions seem to be more sensitive [5].

In an early search for such influences we have observed a dependence of the shape proton spectra on the nature of the rotational bands populated in the final nucleus [6]. The origin of these effects, however, does not seem to be connected with the magnitude of the deformation of nucleus being populated. We do not fully understand their origin but they probably have something to do with the location in (E^*, I) space of the highest resolved or unresolved states that lead to each band.

Figure 2.18: (a) Density plot of the proton emitting states calculated with EVAP for the reaction $^{52}\text{Cr}(^{34}\text{S}, 2p2n)^{82}\text{Sr}$ reaction at 130 MeV. A γ -ray multiplicity selection $M_\gamma \geq 11$ 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.

Here we summarize the observations and conclusions of the results from Ref. [6, 7] and discuss recent measurement and calculations supporting these observations:

1. As expected, the proton spectra from the $(^{34}\text{S}, 2p2n)$ reaction coincident with the ground state $2^+ \rightarrow 0^+$ transition show a strong angular momentum dependence (see Fig. 2a in Ref. [6]) that can be understood in terms of phase space arguments from a statistical model calculation.
2. The proton spectra coincident with high spin states in a given rotational band have the same shape (see Fig. 3b in Ref. [6]).
3. Significant 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 in energy, respectively, when compared to the two other bands. These shifts are significant, but smaller than those associated with the spin effects seen in γ -ray multiplicity gating. Figure 2.16 shows a comparison of the proton spectra from Ref. [7] coincident with transitions from 4 bands in ^{82}Sr . The largest shift is ≈ 0.5 MeV.

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. This is shown in Fig. 2.17 (from [7]).
5. The γ -ray multiplicity distributions 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 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 rotational bands in ^{82}Sr , and in particular the yrast band, are populated by near yrast to near yrast proton emission, which significantly restricts the washing out by the statistical γ -rays of the correlation of the proton spectrum with the populated bands. This explanation is further supported by the stronger anisotropies observed (result 4 above) and by the statistical model calculations which suggest that 59% of the cascades involve a proton as the fourth emitted particle in the (^{34}S , $2n2p$) reaction. This is shown in Fig. 2.18(a) where the population of 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 to a large extent associated with the fourth chance emission. This is clearly seen in Fig. 2.18(b) where a density map is shown of the proton energy as a function of the excitation energy of the proton emitting states.

It is worth noting that in the ^{82}Sr case, proton emission from near-yrast states may be associated with a predicted mechanism based on instability toward nucleon emission of large spins, connected with the population of $h_{11/2}$ resonance states in nuclei in this region. [8] 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 confirmed them in two improved follow up experiments in which ^{82}Sr was produced in the reactions $^{60}\text{Ni}(^{26}\text{Mg}, 2p2n)$ at 110 MeV and the $^{58}\text{Ni}(^{28}\text{Si}, 4p)$ at 130 MeV.

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_γ) 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. The shapes of the γ -ray continuum spectra associated with the gates that show the proton shift are significantly different. Those associated with the yrast band show a softer statistical γ -ray component.

In conclusion we believe that stretched near the yrast line proton emission plays a role in the population of the high spin states in these bands and may influence the way the various bands are fed. Further experiments with the MICROBALL and GAMMASPHERE will help confirm and understand the origin of these effects. In particular, it will be possible to measure particle spectra with good statistics using $\gamma - \gamma$ - *particle* coincidences and placing 2-dimensional γ gates on specific bands.

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2.2.7 Nuclear Structure Dependent Entry-State Population by Total Spectroscopy

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In order to confirm and study further the effect discussed in the preceding subsection, we produced ^{82}Sr by a different reaction $^{58}\text{Ni}(^{28}\text{Si}, 4p)^{82}\text{Sr}$ at 130 MeV that matches the excitation energy and input angular momentum of the earlier studies. Here we employed a unique approach that we termed *Total Spectroscopy*, [1] which relies on the detection of all four protons leading to the residual nucleus of interest.

While the structure dependent energy shifts [2, 3] in the proton spectra were as large as 0.5 MeV, such effects were claimed [4] to be smaller than 160 keV in the reactions $^{58}\text{Ni}(^{29}\text{Si}, 2pn)^{84}\text{Zr}$ and $^{58}\text{Ni}(^{29}\text{Si}, 2p\alpha)^{81}\text{Sr}$ leading to different nuclei, or smaller than 1.0 MeV for the same reaction $^{58}\text{Ni}(^{28}\text{Si}, 4p)^{82}\text{Sr}$ [5].

By identifying the 4 protons in 4π and measuring their energies we can determine directly the excitation energy of the entry states from where the γ -cascades initiate. The detection system used included the *Dwarfs Ball and Wall*, the *Spin Spectrometer*, and 18 Compton suppressed Ge(Li) detectors. This setup allowed us to perform Total Spectroscopy in ^{82}Sr by measuring (a) the discrete transitions identifying the various rotational bands, (b) the γ -ray multiplicity (a measure of the input spin of the entry states), and (c) the excitation energy

Figure 2.19: Contour plots of E^* vs. k_γ after emission of $4p$ (solid lines) and of $4pn$ (dashed lines) coincident with transitions in ^{82}Sr and ^{81}Sr , respectively.

of the entry states by directly measuring all the protons. This approach is considerably more accurate than the total γ -ray pulse height, that is used commonly with devices like the Spin Spectrometer, which is incomplete due to limited efficiency.

Although the compound nucleus excitation energies and spin distributions were closely matched in the $(\text{HI}, 2p2n)$ and $(\text{HI}, 4p)$ reactions that produce ^{82}Sr , the $4p$ and $2p2n$ emissions are quite different in that the two extra protons remove on the average more spin than the two neutrons. This was found in the experimental entry lines in the total pulse height H_γ vs. γ -fold k_γ , where the $4p$ entry line lies above that from the $2p2n$ reactions.

This difference suggests that the structure dependent shifts in the proton spectra might be smaller in the $4p$ reaction compared to those from the $2p2n$ reaction. Thus, we might expect the band structure should exhibit a weaker connection to the entry region for the $4p$ case compared to the $2p2n$. The same argument would most probably apply for other reactions in which upper limits for structure effects were placed, since those reactions have predominantly emission of charged particles in the exit channels: $3p$, $2p\alpha$, and $2pn$ [5, 4].

We should emphasize here that in all this work the chosen gates select only the bands

from the channel of interest and they do not contain any contamination that can produce the observed effects.

Despite the fact that the decay mechanisms in the 4p and 2p2n reactions are different we still see a shift in the proton spectra depending on which band is populated at high spins.

Perhaps the best way to illustrate these structure effects is to construct an experimental entry region in (E_{rem}^*, k_γ) space for ^{82}Sr , where E_{rem}^* is the remaining or available energy after particle emission, in the following way. Assuming that all protons are emitted prior to

Figure 2.20: Excitation energy distributions for $k_\gamma \geq 13$ coincident with 4p and the $14^+ \rightarrow 12^+$ transitions in band 4 (open points) and band 7 (closed points). An average shift of 310 keV is observed.

γ -rays, then E^* can be set equal to E_{rem}^* (obtained from the four proton energies by energy conservation). In the earlier work differences in the proton spectra were seen only when the gating transitions had spins 14^+ or higher for the bands 4 and 7 (see decay scheme in Fig. 2.2).

In order to demonstrate the power of the total spectroscopy, we show in Fig. 2.19 (solid lines) a contour plot of E_{rem}^* vs. k_γ for gating on 4 protons and on the $2^+ \rightarrow 0^+$ transition in ^{82}Sr . The dashed-line contours correspond to gates on 4 protons and 4 transitions from three bands of ^{81}Sr , the 4pn product. The elevated position of the ^{81}Sr contours reflects the fact that the energy removed by the neutron is not measured. This displacement helps identify any contamination when gates are placed on weak high spin transitions in ^{82}Sr . This method is considerably more sensitive for identifying small contaminations compared to gating on the γ - γ matrix and examining the coincident Ge spectra, a check that was also done.

The contour maps of E_{rem}^* vs. k_γ that give the entry populations associated with the $14^+ \rightarrow 12^+$ transitions in bands 4 and 7 (see Fig. 2.2) were found to be different. The map of band 7 shifts mainly toward higher E_{rem}^* values. Here instead of the contour maps, we show their projections on the E_{rem}^* axis after gating on k_γ . These projections are shown in Fig. 2.20 and were obtained by requiring that only 4p be detected, and that $k_\gamma \geq 13$. A downward shift of 310 ± 50 keV, on the average, is observed for band 7 compared to band 4. Of course, this energy shift can be displayed in terms of differences in the proton energy spectra, which would be smaller. This is shown in Fig. 2.21 where a centroid shift of 100 ± 50 keV is observed.

Figure 2.21: Proton energy spectra coincident with 4p and the $14^+ \rightarrow 12^+$ transitions in bands 4 (open symbols) and 7 (closed symbols) for a $k_\gamma \geq 13$ gate. A centroid shift of 100 ± 50 keV is seen.

This shift is surprising because band 7 is the yrast one (see Fig. 2.3 where it is shown as band 9) and in principle has more phase space available for its population, which would tend to make the proton spectrum associated with it harder.

The origin of the observed energy shifts cannot be associated with simple statistical model analyses that do not explicitly include nuclear structure effects. For example, in the region where the yrast band (band 7 in [6]) is populated (spins > 14) it has more phase space available compared to the ground band (band 4 in Fig. 2.2) and yet it is populated from higher excitations (the proton spectra shift down in energy). Similar arguments apply for the behavior of the odd spin band (band 3 in Fig. 2.2). Apparently, some fractionation in the feeding of the bands occurs in a non statistical way that is influenced by the detailed structure at the high spins where the feeding occurs. The recent observation[8] of band

termination on top of band 7 and the presence of the superdeformed band in ^{82}Sr may well have a bearing to the observed behavior.

In summary, the high sensitivity associated with the direct measurement of excitation energy via the *Total Spectrometry* concept, permitted us to observe small but significant differences in the feeding of various rotational bands in ^{82}Sr that appear to reflect the nuclear structure at the high spins where the population occurs. We should make it clear that the observed effect does not invariably imply that all proton emissions are influenced by nuclear structure, except perhaps for the last chance emission which may occur near the yrast line and thus be influenced by the distribution of available states governed by structure.

A preliminary preprint for this work is given in Appendix 6.7.

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2.2.8 Preparation of Cold Highly Spinning Nuclei by Total Spectrometry.

(A. Kirov, D.G. Sarantites, J. Barreto, N.G. Nicolis, D.W. Stracener, R.J. Charity, L.G. Sobotka [WU], D.C. Hensly, C. Baktash, J.R. Beene, and M.L. Halbert [ORNL]).

Phase space considerations coupled with *Total Spectrometry* indicate that the first chance emission (first proton) is on the average more energetic than the second, the second chance proton more energetic than the third, etc. Experimentally, we cannot time order these very fast emissions, but we certainly can order them according to energy. So it is very interesting to examine the correlation between energy ordered and time ordered spectra.

Energy-ordered proton spectra from the reaction $^{58}\text{Ni}(^{28}\text{Si}, 4p)^{82}\text{Sr}$ observed in coincidence with the $14^+ \rightarrow 12^+$ transitions in bands 4 and 7 (of Fig. 2.2) are shown in Fig. 2.22(a). The energy ordering of the spectra bears an interesting correlation to the time ordering of the four emitted protons. To illustrate this correlation we show in Figs. 2.22(b) and (c) the energy and time ordered proton spectra from a Monte Carlo simulation of the spectra for this reaction using the code EVAP [1]. From this comparison we see clearly that in the subbarrier region, the spectrum of the lowest energy proton is associated with the last chance emission. In contrast, the highest and second highest energy-ordered spectra do not uniquely correspond to first and second chance emission, because of the significant overlap seen in Fig. 2.22(c) although a general sequencing trend is apparent for the average.

Figure 2.22: (a) Energy-ordered experimental proton spectra coincident with $4p$, $k_\gamma \geq 13$ and the $14^+ \rightarrow 12^+$ transitions in band 4 (thin lines) and band 7 (thick lines) in ^{82}Sr . The total proton spectra are also shown. The energy shifts are seen in both the ordered and the total spectra; (b) and (c) Energy- and time-ordered proton spectra for the $4p$ channel from a Monte Carlo simulation of the reaction with the evaporation code EVAP[7]. It is seen that the 4th chance protons are strongly correlated with the lowest energy protons.

Figure 2.23: Entry lines in (E^*, k_{γ}) space in coincidence with the sum of the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, and $6^+ \rightarrow 4^+$ transitions in ^{82}Sr . The closed circles have no other gate. The open squares show the entry line with an additional requirement that the highest $E_{\gamma} \leq 1.3$ MeV. The closed squares in addition to the above two gates require that the highest energy proton have $E_p \geq 11$ MeV. Thus at the highest multiplicities the cooling is of the order of 5 MeV! At this point the entry line crosses the yrast line.

Here we note that the structure dependent downward displacements of the spectra from band 7 (thick lines) compared to band 4 (thin lines) are also quite apparent in Fig. 2.22.

We found an interesting way of preparing cold highly spinning nuclei by combining h_{γ} , k_{γ} , and $\sum E_p$ gating, which is more powerful than H_{γ} , k_{γ} gating alone. The power of the *total spectrometry* is so great that it provides several ways for accomplishing this. We will intrigue the reader by offering what might appear as the unorthodox way of doing this. We will create a unique type of gating that we will term *phase space* gating. Three gates were placed in the event-by-event analysis on the parameters of choice as follows (a) Select the highest energy γ -ray emitted in each event as detected by the Spin Spectrometer and select the portion below the most probable pulse height (its lowest 1/3, this is nearly the same as placing a low gate on the total H_{γ}), (b) Select the proton with highest energy and place a gate on the upper 1/2 of it (this is an enhanced gating condition that lowers the excitation energy), and (c) place a gate on the upper 1/3 of the k_{γ} distribution. We have done this on the $^{58}\text{Ni}(^{28}\text{Si}, 4p)^{82}\text{Sr}$ reaction with an additional set of gates on the sum of the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, and $6^+ \rightarrow 4^+$ transitions in ^{82}Sr and imposed the additional condition that only 4 protons were detected. This procedure selects residual nuclei populated after particle decay close to the yrast line and at high spins. To demonstrate this we show Fig. 2.23 experimental

Figure 2.24: Angular distribution coefficients A_2 for the emission of each energy ordered proton. The open circles correspond to a gating on 4 protons, on $k_\gamma > 13$, and on the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, and $6^+ \rightarrow 4^+$ transitions in the ground band. A monotonic decrease in anisotropy is seen as one progresses from the highest to the lowest energy proton. The closed circles have the additional combined *phase space* gating that highest energy proton have $E_{p+} \geq 11$ MeV, and that the highest energy γ -ray have $E_{\gamma+} \leq 2$ MeV. Now the highest and lowest energy protons have stronger anisotropies.

entry lines (E_{rem}^* vs. k_γ) under several gating conditions. The closed circles have no other gate except the discrete transitions and the 4p requirement. The open squares show the cooling due to the additional requirement that the highest energy γ -ray in the event has $E_\gamma \leq 1.3$ MeV. The closed squares have the additional requirement that the highest energy proton has $E_p \geq 11$ MeV. The lines from the discrete transitions are also shown and define the yrast line for this nucleus. We used the decay scheme for ^{82}Sr to obtain the multiplicity and then corrected those values for the response of the Spin Spectrometer. Notice that the *cooling* provided by this combined *phase space* gating scheme is ≈ 5 MeV !

We note that the above combined *phase space* gating indeed places the excitation of the selected evaporation residues near the yrast line. If this were the case, then the anisotropies associated with the lowest energy protons and the level feeding patterns should reflect this. The feeding patterns indicate a small increase in the preferential population of the highest spins.

Figure 2.24 gives the angular distribution coefficients A_2 obtained by fitting the energy

integrated angular distributions for the emission of each energy ordered proton to the function : $W(\theta) = A_0 \cdot [1 + A_2 \cdot P_2(\cos \theta)]$. The open circles correspond to a gating on 4 protons on $k_\gamma > 13$, and on the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, and $6^+ \rightarrow 4^+$ transitions in the ground band. A monotonic decrease in anisotropy is seen as one progresses from the highest to the lowest energy proton. The open-square data have the additional combined *phase space* gating, namely that highest energy proton have $E_{p_1} \geq 11$ MeV, and that the highest energy γ -ray have $E_{\gamma_1} \leq 2$ MeV. Now the highest and lowest energy protons indicate stronger anisotropies, although the uncertainties are large. In any event this is precisely what we expect. The high energy requirement on the highest energy proton, simply leads to higher partial ℓ -wave proton emission. From our discussion of the energy ordered proton spectra above, we learned that the lowest energy proton is also for the most part (the subbarrier region) also the last to be emitted. The high energy requirement placed on the highest energy proton shifts, by virtue of energy conservation, the energy spectra of the 2nd, 3rd, and 4th protons to lower energies. Now the 4th proton spectrum contains a larger fraction of the last emission. If these are near yrast line emissions then the anisotropy (A_2 coefficient) should increase because they must be to a large part stretched and thus involve again higher ℓ -waves, and this is what the data suggest.

Clearly, we would like to use the power of the *total spectrometry* for high spin spectroscopy and for reaction mechanism studies. This may provide valuable detailed understanding of the role of excitation energy and spin in reactions near the barrier.

We will also leave it to the reader's imagination to see how one can use the *phase space* gating scheme to prepare cold nuclei for reaction channels like (H1, 3pn).

The above work will be submitted shortly in the Physical Review Letters.

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2.2.9 A Study of the Two-Proton Decay of ^{12}O .

(R.A. Kryger, A.Azhari, M. Hellstrom, T. Kubo, D.J. Morissey, B.S. Sherrill, R. Pfaff, E. Ramakrishnan, M. Thoennessen, J. Wigner, S. Yokoyama, B. Young [MSU], R.J. Charity, J. Dempsey, A. Kirov, N. Robertson, L.G. Sobotka, and D.G. Sarantites [W.U.]

There is considerable experimental and theoretical interest in exotic nuclear decay modes because they can provide unique tests of our understanding of nuclear structure. One example of such a decay mode, the ground state two-proton decay, was predicted over thirty years ago as a decay mode for nuclei which are bound (or at least strongly inhibited) to one proton decay but unbound to two-proton emission [1, 2].

A particularly interesting feature of 2p decay is that it is thought to occur through three different mechanisms: diproton (^2He) emission, direct two-proton decay, and sequential proton emission (if possible) [2]. Diproton emission occurs when the nucleus emits a correlated pair of protons in a configuration which promptly breaks up after penetrating the nuclear barrier. Although the ^2He line shape is rather broad [3], the energy-dependence of the Coulomb barrier penetrability strongly favors the emission of diprotons with nearly the maximum available kinetic energy. This result leads to substantial angular correlations between the emitted protons when the total decay energy of the parent nucleus is not too

Figure 2.25: Expected relative angle distributions for p-p emission for sequential (top panel), direct breakup (middle panel) and diproton emission (bottom panel).

large. Direct breakup occurs when the two protons independently penetrate the nuclear barrier. In this case, the mutual barrier penetrability is maximized for protons with equal energies, corresponding to $\frac{1}{2}$ of the total decay energy. In sequential emission the two protons are emitted through an intermediate state in the nucleus ${}^A_{Z-1}X$. In the latter two processes, no (or only very weak) angular correlations are expected between the emitted protons. The competition between these 2p decay modes is driven by the barrier penetrabilities of single protons and ${}^2\text{He}$ nuclei, the spectroscopic factor for formation of diproton in the parent nucleus, and the energies and widths of the decaying state and any intermediate states [2].

Although several β -delayed 2p emitters have been studied in recent years [4, 5, 6], (in these cases the 2p decay proceeds through an excited state of the β -daughter nucleus), no ground state 2p emitters have yet been directly observed. Furthermore, these β -delayed 2p decays have all been found to be consistent with 100% sequential emission. Recent mass excess data and shell model calculations suggest several candidates for ground state 2p decay including ${}^8\text{C}$, ${}^{12}\text{O}$, ${}^{16}\text{Ne}$, ${}^{42}\text{Cr}$, ${}^{45}\text{Fe}$, ${}^{48}\text{Ni}$, and ${}^{49}\text{Ni}$ [7]. All of these nuclei are difficult to study because they are far from the line of stability, and the lighter ones in particular are known to decay very quickly (10^{-21} seconds).

The experimental information on these nuclei is rather sparse, mostly obtained through

Figure 2.26: Simulated energy difference between the two protons in the reconstructed C.M. system for direct (bottom panel) and sequential emission (top panel).

Q-value measurements using low cross-section reactions such as (^4He , ^8He) and (π^+ , π^+) [8, 9, 10]. With the availability of radioactive beams at the NSCL, it is now possible to study some of these nuclei via single-particle transfer reactions.

As an initial case, we studied the 2p decay of ^{12}O produced in the reaction $^9\text{Be}(^{13}\text{O}, ^{12}\text{O})$. The mass excess of ^{12}O is known to be 32.06 ± 0.04 MeV [10] which indicates that ^{12}O is unbound to 2p emission by 1.78 MeV. The lowest known state of ^{11}N is at a mass excess of 25.23 ± 0.10 MeV [10] implying that ^{12}O is proton bound by 0.46 MeV. However, this ^{11}N state is thought to be the first excited state, with the anticipated ground state at a mass excess of 24.9 ± 0.2 MeV [10]. The width of the ^{12}O ground state is 400 ± 250 keV so that some sequential proton emission through a low-lying ^{11}N ground state may be possible. The diproton branching ratio was estimated to be $(60 \pm 30)\%$, although no direct measurement of this quantity exists.

The experiment consisted of a coincidence measurement of two protons and the residual ^{10}C nucleus with sufficient energy and angle resolution to construct the invariant mass of the $2p + ^{10}\text{C}$ system and the CM emission angles of the two protons. The invariant mass will be used to separate ground state ^{12}O decays from possible higher-lying states in ^{12}O or other breakup reactions of ^{13}O . The diproton branching ratio, as well as branching ratios for direct

emission and sequential emission, can be determined from energy and angular correlations between the two protons.

A Monte Carlo simulation was performed of the response of the experimental setup to ^{12}O two-proton decays to determine the sensitivity to the quantities of interest. Simulations were carried out for each of the three decay mechanisms modeling the experimental setup described in the following section. The anticipated energy resolution and angular granularity of the proton and fragment detectors were included, as was the effect of energy-loss in the target and beam emittance (estimated from [12]). One finds that the resolution in the total decay energy of the ^{12}O system, as calculated from the simulated "experimental" momenta of the two protons and the ^{10}C fragment, is approximately 450 keV (FWHM). While this resolution is not good enough to improve upon the known mass of ^{12}O , it does allow the ground state to be separated from possible higher-lying excited states of ^{12}O ($E^* \geq 1$ MeV).

Figure 2.25 shows the reconstructed distributions of the relative angle between the two proton momenta in the CM system for each of the simulated 2p decay modes. The proton and CM momenta were determined from the "measured" $2p + ^{10}\text{C}$ lab momenta (including all resolution effects). One sees that the angular distribution of the direct 2p breakup and sequential emission decay modes are isotropic as expected. The angular distribution for the diproton decay mode, on the other hand, is peaked near small angles and is quite distinct from the distributions of the other two cases. Based upon these results (and an estimated 4000 measured events) we anticipate a sensitivity to the diproton branching ratio of $\leq 5\%$. For sequential emission, one can use the CM energy difference between the two detected protons. Direct 2p breakup favors equal energy protons, while the energies of sequentially emitted protons are determined by the energy and width of the parent and intermediate states, and the single proton penetrability probabilities. Figure 2.26 shows the simulated energy difference between the two protons (in the reconstructed CM system) for direct and sequential emission. The ^{11}N ground state was taken at a mass excess of 24.9 MeV (see above) for the sequential emission calculation. The simulations show that the energy difference for the sequential emission process peaks at approximately 0.6 MeV, well above the peak for the direct breakup case. In this case, we expected the separation to be sensitive to levels on the order of 20%.

Secondary ^{13}O beam and its isotones (^{12}N and ^{11}C) with an energy of ~ 35 MeV/A, produced in the A1200 by fragmentation of 80 MeV/A ^{16}O primary beam on an Al target, was transported and mass analyzed through the recoil products mass analyzer (RPMS) and then focused onto a ^9Be transfer-target. A PPAC detector and thin-plastic timing detector positioned upstream of the ^9Be target served to determine the position of the incident beam and allowed further isotope identification by time-of-flight of the impurities in the secondary beam. Heavy-ion reaction products (^{10}C , as well as the transmitted beam) were detected in a Si-CsI telescope consisting of a 5 cm square double-sided ΔE Si strip detector (16 strips/side) backed by a set of 4 Si E stopping detectors. This Si detector was placed approximately 50 cm from the ^9Be target, providing an angular resolution of 0.4° and an energy resolution of better than 0.5% [12]. Isotopic identification of the reaction products was determined by energy-loss, total energy, and time-of-flight.

Coincident protons were detected in the Washington University MINIWALL array of CsI detectors. The wall was placed at a distance of 60 cm from the target, spanning the entire angular range between 2.6° and 13.0° with respect to the beam. The angular separation

between adjacent CsI detectors is approximately 2° . Protons were identified by pulse-shape discrimination with an energy resolution of 2%.

A rate of 2000-3000 particles/sec of ^{13}O were obtained after the RPMS. The incident ^{13}O nuclei had an energy of 40 MeV/A. Assuming a single-neutron transfer cross section of 5 mb [13], a ^9Be target thickness of 60 mg/cm², and a simulation-based $2p + ^{10}\text{C}$ detection efficiency of 70%, we expect a coincidence rate of 60 counts/hour. Data were acquired for 4 days. A considerable number of C -p-p coincidences were recorded. Detailed data analysis will show whether the observed protons show the required correlation for diproton emission.

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2.2.10 Entry State Population in Fusion Reactions.

(N.G. Nicolis, K. Honkanen, and D.G. Sarantites)

The transfer of orbital angular momentum into intrinsic spin of the reaction products plays an important role in the study of reaction mechanisms. For fusion reactions, spin distributions and associated excitation energy distributions in the evaporation residues can be deduced from measurements of the populated entry states. Such measurements are 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 225 MeV $^{50}\text{Ti} + ^{130}\text{Te}$. The cross section and entry state population for the major exit (HI, xn) and (HI, α xn) channels were measured.

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 versions of the code PACE, we have initiated a re-examination of the above evaporation residue and entry state data. Results from preliminary calculations for both reactions are compared with the data in Fig. 1 and 2. In these calculations, we employed simple parameter sets involving rotating liquid drop with finite range corrections yrast lines and fission barriers.

Figure 2.27: Comparison of experimental (symbols) with the calculated (histograms) channel cross sections for the reactions 136 MeV $^{20}\text{Ne} + ^{146}\text{Nd}$ and 225 MeV $^{50}\text{Ti} + ^{130}\text{Te}$.

The symbols in Fig. 2.27 show the measured evaporation residue cross sections in the two reactions. Different channels are indicated by the type of the emitted particles. The results of the calculations are shown by the histograms. In both reactions, the cross sections are reproduced reasonably well by the calculation.

A reasonably good agreement is also obtained in the description of the shapes of the projected entry state distributions of the above channels. The solid lines of Fig. 2.28 shows the experimental entry state distributions projected according to the total γ -ray energy (E^*) and γ -ray multiplicity (M_γ). The dashed curves show the results of the calculation. The total γ -ray energy projections are reproduced relatively well in absolute magnitude and peak position. The γ -multiplicity projections agree well in shape. However, the calculated distributions were found to over predict the experimental ones by two and three units in the ^{20}Ne and ^{50}Ti -induced reactions, respectively. The dashed curves shown in Fig. 2.28, were shifted down by two and three 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 model calculation.

A possible improvement in these calculations may result from the use of liquid-drop yrast lines for the rotational energy in the level density calculations and yrast lines consistent with the experimental ones for the γ de-excitation part in the EVAP code. This possibility is being examined in detail and preliminary results are encouraging in improving the quantitative

Figure 2.28: Comparison between the experimental (solid lines) and the calculated γ -ray multiplicity and total γ -ray energy distributions (dashed lines) for the reactions $^{20}\text{Ne} + ^{146}\text{Nd}$ and $^{50}\text{Ti} + ^{130}\text{Te}$.

agreement with the experiment.

This work was done in collaboration with the ORNL group, while all the data analysis and interpretation was done the P.I. and N. Nicolis at WU.

2.3 FORMATION AND DECAY OF HOT NUCLEI

2.3.1 The Statistical Model Evaporation Code EVAP.

(N.G. Nicolis, D.G. Sarantites [WU], J.R. Beene [ORNL])

Statistical model calculations have become an indispensable tool for the interpretation of a wide variety of experimental data concerning the decay properties of highly excited compound nuclei. For the purpose of making a realistic description of these properties, we developed the Monte-Carlo statistical model evaporation code EVAP [1]. Important features of the code include:

- (a) The extended excitation energy range of validity, which makes possible calculations of highly excited systems e.g. up to $E^* \sim 500$ MeV.
- (b) The consideration of decay channels involving n, p, d, t, α , ${}^3\text{He}$ and ${}^6\text{Li}$ emission.
- (c) The use of externally created transmission coefficients (T_ℓ), calculated for each individual nucleus and type of emitted particle.
- (d) The ability of simulating decays from deformed emitters.
- (e) The choice between the Lang or the Gilbert and Cameron level density formalism. The effect of a temperature-dependent level density constant has also been tested (See the following section 2.3.2).

The usefulness of the above features has been highlighted in the studies of Refs. [2] and [3] concerning particle emission from deformed emitters and the statistical decay of deuterons and tritons from highly excited compound nuclei, respectively.

In most of the current applications we consider emissions of n, p, α , d, t, ${}^3\text{He}$ and ${}^6\text{Li}$. Current efforts include the extension of the code for the description of intermediate mass fragment emission and the population of particle bound excited states in the emitted fragments.

Test calculations are being performed involving 14 "particle" decay channels: n, p, α , d, t, ${}^3\text{He}$, ${}^6\text{Li}$, ${}^9\text{Be}$, ${}^{11}\text{B}$, ${}^{12}\text{C}$, ${}^{14}\text{N}$, ${}^{16}\text{O}$, ${}^{19}\text{F}$ and ${}^{20}\text{Ne}$. These calculations employ optical model transmission coefficients (T_ℓ) for the first 7 particle decay modes and parabolic model T_ℓ 's for all the subsequent modes. The parabolic model treatment will be replaced by a more realistic method in the later stages of the development.

Comparisons of the results with existing experimental data as well as the predictions of binary fragmentation models will be made in the following sections.

This work was done exclusively by N. Nicolis (this grant), with useful discussions with the nuclear chemistry group.

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2.3.2 Statistical Emission of Deuterons and Tritons from Highly Excited Compound Nuclei

(N.G. Nicolis, D.G. Sarantites, L.G. Sobotka, and R.J. Charity.)

We recently completed [1] the interpretation of a recent study concerning the behavior of the nuclear level density constant at high excitation energies as deduced from an analysis of particle evaporation spectra and associated multiplicities [2, 3]. The present study gave a solution to the over prediction of the experimental deuteron and triton evaporation yields by the statistical model employing standard parameters [3].

In Refs. [2] and [3], Chbihi *et al.* presented a study of the evaporation spectra of equilibrium sources produced in the reaction 701 MeV $^{28}\text{Si} + ^{100}\text{Mo}$. There we used two different methods to extract the level density constant at high excitation. It was found that in order to reproduce the slopes of the light particle spectra, the level density constant of the excited nuclei must have a value of $A/10 - A/11$ at temperatures of 3.5 to 5.5 MeV; a conclusion also reached by other authors [4]. However, statistical model calculations with a reduced level density constant lead to an over prediction (in some cases, by a factor of 2 or more) of the experimental deuteron and triton multiplicities. This is in contrast to the finding that the statistical model provides a satisfactory description of deuteron and triton emission from compound nuclei at low excitations [1, 3]. It was suggested that a more complicated parameter adjustment may be required to treat the decay of highly excited nuclei[3].

Figure 2.29(a) shows the experimental n, p, α , d and t multiplicities as a function of the initial excitation energy of the emitting source. The solid lines represent the results of EVAP calculations. These calculations were performed using reaction parameters simulating the experimental conditions [1]. They employ optical model transmission coefficients for particle emission and a temperature-dependent level density parameter $a = A/k(T)$ where:

$$k(T) = k(0) \times \frac{1.4}{1 + 0.4 \cdot \exp \left\{ - \left(\frac{T}{3} \right)^2 \right\}} \text{ MeV.}$$

This temperature dependence is based on the parameterization of Ormand *et al.* [5] and accounts for an inclusion of thermal and quantal fluctuations on a low temperature level density constant $k(0)$. Choosing $k(0) = 8.0$ brings consistency with the level density constants extracted from the analysis of the evaporative spectra of Ref. [3].

The neutron, proton and α -particle multiplicities are well reproduced in the whole excitation range ($100 \text{ MeV} \leq E^* \leq 405 \text{ MeV}$). However, the deuteron and triton multiplicities are systematically over predicted. This over prediction increases with excitation energy up to more than a factor of 2. The same trend was also observed in the simplified statistical model treatment of Ref. [3] where energy-independent level density constants were used.

Due to the high excitation energies involved, changes in the critical angular momentum for fusion do not greatly affect the calculated particle emission yields. Also, changes in the level density constant were shown inadequate to account for the observed discrepancies in the deuteron and triton yields [3]. However, another important factor that determines particle emission is the transmission coefficients.

In the statistical model description, the penetrability for particle emission is related

Figure 2.29: Experimental n , p , α , d , and t multiplicities (symbols) as a function of the excitation energy of the emitting source in reactions of 701 MeV ^{28}Si on ^{100}Mo . The solid lines show the predictions of the statistical model with a temperature dependent level density constant as described in the text. The three columns of panels show calculations with transmission coefficients: (a) from the optical model, (b) from the IWBC, and (c) from the optical model for n , p , α and the DRAF method for d and t emission.

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 parameters [6]. For many years, this method has been able to describe successfully the decay properties of low-excited compound nuclei for which n, p and α -emission are the most probable decay modes.

Alexander, Magda and Landowne, recently reviewed the logical basis of using optical model (OM) T_l 's in statistical model calculations [7]. 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 potentials [6] and replaced the role of the imaginary parts with an ingoing-wave boundary condition. The statistical model calculations for the multiplicity data are shown in Fig. 2.29(b). The neutron, proton and alpha multiplicity data are again well reproduced but the calculated d and t yields are still in excess of the experimental ones. However, the use of IWBC T_l 's reduces the discrepancies found with the original OM T_l set. This improvement is attributed to the 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 observable cross sections. Subsequently, Mustafa *et al.* [9], were able to describe the above data using σ_{fus} from the direct-reaction approach to fusion (DRAF) of Udagawa *et al.* [10]. 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 process 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.* [11] 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. The studies of Refs. [9] and [11] show that the direct interaction part is a sizable fraction of the OM absorption cross section in deuteron induced reactions.

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. [11] and a radius of a similar magnitude for tritons was used. The corresponding

Figure 2.30: Comparison between the calculated p, α , d, and t center of mass energy spectra (histograms) at the indicated excitation energies of the emitting source. The solid lines represent experimental slopes obtained from evaporative moving source fits.

statistical model calculations are compared with the data in Fig. 2.29(c). The calculation provides a good agreement of the experimental data in the whole excitation energy range. The small over prediction of M_α is not considered significant, given that the uncertainty in the atomic numbers of our emitting systems is ± 1 .

The same calculation produces particle energy spectra whose slopes are consistent with the experimental ones. In Fig. 2.30, the histograms show the calculated proton, alpha, deuteron and triton energy spectra in the center of mass system. The spectra have been displaced on the vertical axis for pictorial reasons. The initial excitation energies of the emitting sources are shown in the figure. The solid lines represent the slopes of the evaporative source fits to the data [3]. Our approach of using a temperature-dependent level density constant together with the introduction of DRAF T_l 's for deuterons and tritons produces a simultaneous description of the particle multiplicities and the slopes of the evaporation spectra.

Our analysis shows that the statistical model with optical model transmission coefficients for n, p, α , d and t emission systematically over predicts the deuteron and triton emission yields at high excitation energies (E^* up to 405 MeV). These discrepancies are attributed to absorption processes in the optical model inverse cross section which are not related to fusion. It seems that such processes 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, the optical model treatment breaks down for deuterons and tritons whose emission becomes more important at high excitation energies.

The present work demonstrates that the elimination of the direct interaction components from the OM absorption is necessary for a successful description of deuteron and triton emission in statistical model calculations. The DRAF method provides a quantitative means of isolating these processes and extracting a transmission coefficient set consistent with the fusion process. With this method, it became possible to reproduce the deuteron and triton emission yields from highly excited compound nuclei; a result which could not be achieved with any other statistical model parameter change. For deuteron emission in particular, the employed fusion radius is consistent with a deuteron fusion cross section analysis in the mass region of the present study. A global description of particle emission in 701 MeV reactions of ^{28}Si on ^{100}Mo reactions was given in the context of a temperature-dependent level density constant.

We believe that systematic studies of deuteron and triton induced reactions are needed in order to extract and systematize the fusion radii. This may provide valuable information for parameters to be used in the description of statistical deuteron and triton emission from highly excited nuclei.

This work was done exclusively by N. Nicolis (this grant), with useful discussions with the nuclear chemistry group, and was published in Phys. Rev. (see Appendix 6.4 for a reprint).

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2.3.3 Deuteron and Intermediate-Mass Fragment Emission as Probes of the Thermal Properties of Highly Excited Compound Nuclei

(N.G. Nicolis and D.G. Sarantites)

The Monte-Carlo nature of the code EVAP makes possible the study of a number of correlations between experimental and/or theoretical quantities thus providing insight into the evaporation process.

An example of a high energy deexcitation calculation is given in Fig. 2.31 for the reaction $441\text{MeV } ^{19}\text{F} + ^{100}\text{Mo} \rightarrow ^{119}\text{Sb}^* (373\text{ MeV})$. The figure shows contour plots on the excitation energy (E^*) versus angular momentum plane of the neutron, proton, alpha and deuteron emitting states. The numbers on the contours give the intensity of each level in arbitrary units. The corresponding particle multiplicities are also given. The calculation was performed with the parameters mentioned in the previous Section, i.e. DRAF T_l 's for deuterons and tritons and optical model T_l 's for the rest of the particles. The temperature-dependent level density constant of Ormand et al. [1] was also used.

The contour plots show that for neutron, proton and alpha emission, the low excitation states are more frequently sampled. The angular momentum dependence is stronger for alpha than it is for proton or neutron emission. This is a rather well known fact. However, the emission pattern for deuterons is different. Deuterons are emitted primarily from very high excitation states and have a weak angular momentum dependence. Emission of other energetically expensive modes like ^3He , t and ^6Li shows a similar pattern.

A consequence of this difference is reflected in the contribution of different (E^* , I) emitting states to the total particle emission spectrum for each decay mode. The thick lines of Figs. 2.32 and 2.33 show the calculated total center of mass spectra for n, p, α , d, t, ^3He and ^6Li emission. We have examined the contribution to these spectra from emitting states at different excitation energies by constructing the partial spectra gated by the excitation energy within the following E^* -windows: 0-100MeV (curve 4), 100-200MeV (curve 3), 200-300MeV (curve 2), and $E^* \geq 300\text{MeV}$ (curve 1). In all cases, the partial spectra corresponding to the highest excitation energies are the hardest. They correspond to energetic non-stretched

transitions which cool off the emitting nuclei. The closeness of the slopes of the curves 1 and 2 to the ones of the total spectra makes the total spectral slopes useful in the determination of the level density of highly excited nuclei. However, statistical correction factors are needed in the analysis of the evaporation spectra as was done in Ref. [2].

Figure 2.31: Calculated (E^*, I) distributions of the neutron, proton, α , and deuteron emitting states in the reaction $441 \text{ MeV } ^{19}\text{F} + ^{100}\text{Mo} \rightarrow ^{119}\text{Sb}^* (373 \text{ MeV})$.

Of interest are the low energy parts of the partial spectra compared to the total ones. Proton and alpha emission show a common behavior. The low energy parts of the total spectra are dominated by emissions originating from low-excitation energy states. These are stretched emissions that occur close to the yrast lines. This fact for alpha emission was brought up in the study of Ref. [3] where it was pointed out that low energy alpha emission probes the emission properties of nuclei at a finite but low excitation. One may conclude that neutron, proton and alpha spectra are not useful if we want to obtain information concerning the barrier properties of highly excited nuclei.

However, Figs. 2.32 and 2.33 show that the corresponding spectra for the rare (energetically costly) decay modes of d , t , ${}^3\text{He}$ and ${}^6\text{Li}$ emission, are almost free of low E^* emissions.

Figure 2.32: Calculated n , p , α , and d C.M. spectra from the reaction $441 \text{ MeV } {}^{19}\text{F} + {}^{100}\text{Mo} \rightarrow {}^{119}\text{Sb} (373 \text{ MeV})$ (thick lines). The numbered thin lines show the contributions to these spectra from emitting states in the excitation energy ranges given in the text.

This is a consequence of the fact that all of these emissions take place far from the yrast line.

Fleckner, Sauer and Mosel [4] have studied the excitation energy dependence of Coulomb-barriers in a folding model calculation using thermal Hartree Fock nuclear densities. For alpha emission from ${}^{208}\text{Pb}$ ($E^* \sim 500 \text{ MeV}$ or $T = 5 \text{ MeV}$) the barrier has been predicted to be lower by 0.7 MeV . At the same excitation, however, the barrier for ${}^{12}\text{C}$ emission is lowered by 1.7 MeV .

Our preliminary results indicate that a temperature effect in the barrier reduction for alpha emission would be unnoticed in the total spectrum. However, the barrier reduction in the evaporation spectra of heavier fragments such as ${}^{12}\text{C}$ could be pronounced.

The upgrading of EVAP to include emission of heavy fragments may give us quantitative estimates of such effects in order to establish the use of heavy fragment emission spectra as

probe of the evaporation barrier of highly excited compound nuclear systems.

Based on these predictions we have designed an experiment to use deuteron and triton emission as probes of early reaction dynamics for the system $^{60}\text{Ni} + ^{100}\text{Mo} \rightarrow ^{160}\text{Yb}^*$ (at 250

Figure 2.33: Same as in Fig. 2.32 for tritons ^3He and ^6Li .

and 300 MeV). This is described in some detail in the accompanying proposal.

This work was done exclusively by N. Nicolis (this grant), with useful discussions with the nuclear chemistry group. A short communication on these findings is under preparation.

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- [2] A. Chbihi, L.G. Sobotka, N.G. Nicolis, D.G. Sarantites, D.W. Stracener, Z. Majka, D.C. Hensley, J.R. Beene and M.L. Halbert. *Phys. Rev.* **C43**, 666 (1991).
- [3] N.G. Nicolis, D.G. Sarantites, L.A. Adler, F.A. Dilmanian, K. Honkanen, Z. Majka, L.G. Sobotka, Z. Li, T.M. Semkow, J.R. Beene, M.L. Halbert, D.C. Hensley, J.B. Natowitz, R.P. Schmitt, D. Fabris, G. Nebbia and G. Mouchaty. *Phys. Rev.* **C41**, 2118 (1990).
- [4] J. Fleckner, G. Sauer and U. Mosel, *Phys. Lett.* **65B**, 316 (1976).

Figure 2.35: Calculated inverse cross sections for neutrons, protons, and alpha particles for ^{117}Te . The thick lines correspond to the optical model and the thin ones to the IWBC model.

of the OM T_ℓ 's was made with the ones derived from an ingoing-wave boundary condition (IWBC) calculation [4]. The latter T_ℓ 's give the transmission probability through the real part of the optical model potential. The role of the imaginary potential is replaced by the ingoing-wave boundary condition. It was pointed out that processes like transparency, shape resonances or peripheral absorption are normally present in the OM T_ℓ 's. Such processes should not be included in a model describing the absorption of a particle by a nucleus, if one wishes to describe the process of particle emission with the same set of T_ℓ 's. Alexander *et al.* [3] suggested that T_ℓ 's arising from a strong absorption model such as the IWBC model may be more appropriate for use in statistical model calculations.

In our study of deuteron and triton emission from highly excited nuclei [5] we showed that the statistical model with OM T_ℓ 's describes satisfactorily the p, d, t, α emission spectra and cross sections in the reaction: 121 MeV $^{14}\text{N} + ^{103}\text{Rh} \rightarrow ^{117}\text{Te}^* (107\text{MeV})$. The effect of IWBC T_ℓ 's in the calculated particle multiplicities was tested at high excitation energies. In this Section, we make remarks concerning the detailed shape of the calculated energy spectra of the emitted particles using OM and IWBC T_ℓ 's.

In Fig. 2.34 we compare the calculated center of mass proton, alpha and deuteron spectra

with OM T_ℓ 's (thick lines) and IWBC T_ℓ 's created according to Ref. [3] (thin lines). In both cases, the slopes of the particle spectra seem to be similar for all particle types. Indeed the slopes of the evaporation spectra are determined mainly by the level densities, since the transmission coefficients approach a limiting value for high channel energies in both models. In the low energy region, no significant differences are seen in the spectral shapes for protons and deuterons. However for alpha particle emission, the low energy part of the spectrum calculated with IWBC T_ℓ 's shows a shift of ~ 1 MeV up in energy, compared to that obtained with OM T_ℓ 's.

The behavior of the low energy alpha emission is not related to a difference in the evaporation barriers for alpha emission. We have verified that the OM and IWBC barriers are similar for partial waves up to $\ell=10\hbar$. A detailed analysis of the events comprising the low energy spectra of Fig. 2.34 shows that the suppression of the low energy alpha emission in the IWBC model is due to: a) The suppression of high- ℓ partial waves for alpha emission, and b) The enhancement of low- ℓ partial waves for neutron and proton emission which enhances their competition with alpha emission at low excitation energies. These trends in the transmission coefficients have been shown in Ref. [3].

In a number of studies, the behavior of the low-energy particle spectra has been used in the interpretation of the properties of the emitting system. Therefore, the above difference in the calculated alpha energy spectra by the two models deserves further investigation. In Fig. 2.35 we show the neutron, proton and alpha inverse cross sections that lead to ^{117}Te . The thick lines correspond to the predictions of the optical and the thin ones to the IWBC model. For neutrons, the IWBC model overestimates the OM inverse cross section. Similarly, the proton inverse cross section is overestimated at high energies. The α inverse cross section is underestimated at all energies, but the effect is more significant at low energies.

Our OM calculations for neutrons have been compared and found consistent with the data of Ref. [6] as far as the total and absorption cross sections are concerned. It has to be noted that the optical model parameters of Ref. [6] have been used excessively in the past in Hauser-Feshbach calculations. Therefore, the excess of neutron cross sections predicted by the IWBC model cannot be justified in terms of the existing data. For protons, comparisons with excitation functions of proton induced reactions has to be made. The under prediction of the optical model cross section by the IWBC model is discussed further in following Section.

This work was done exclusively by N. Nicolis (this grant), with useful discussions with the nuclear chemistry group.

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- [3] J.M. Alexander, M.T. Magda and S. Landowne, Phys. Rev. **C42**, 1092 (1991).
- [4] G.H. Rawitscher, Nucl. Phys. **85**, 337 (1966).
- [5] N.G. Nicolis, D.G. Sarantites, L.G. Sobotka and R.J. Charity, Phys. Rev. **C45**, 2393 (1992).
- [6] F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1958).

Table 2.1: Alpha-particle inverse cross sections for ^{117}Te .

$E_{C.M.}(MeV)$	$\sigma_{OM}(mb)$	$\sigma_{IWBC}(mb)$	$\Delta(\%)$
8	0.0013	0.0004	-69.2
9	0.0279	0.0101	-63.8
10.0	0.3332	0.1537	-53.9
11.0	2.5539	1.4491	-43.3
12.0	13.603	9.2757	-31.8
13.0	51.633	41.254	-20.1
14.0	137.86	123.27	-10.6
15.0	266.63	252.01	-5.5
16.0	410.28	395.86	-3.5
18.0	676.73	658.59	-2.7
19.0	791.38	770.26	-2.7
20.0	894.14	869.74	-2.7
21.0	986.32	958.48	-2.8
22.0	1069.3	1037.9	-2.9
24.0	1212.0	1173.3	-3.2
26.0	1329.8	1283.8	-3.5
28.0	1428.5	1375.2	-3.7
30.0	1511.9	1451.8	-4.0

2.3.5 A Study of Transparency in the Optical Model

(N.G. Nicolis and D.G. Sarantites)

A comparison was made in Section 2.3.4 of the inverse alpha cross sections for ^{117}Te using optical model and IWBC transmission coefficients according to the prescription given in Ref. [1]. These inverse cross sections are compared in Table 2.1. We see that $\sigma(IWBC)$ underestimates $\sigma(OM)$ by a percentage that increases as the alpha particle energy decreases.

The introduction of the IWBC model was made in order to eliminate processes like transparency, shape resonances or peripheral absorption which are expected to be present in the OM T_ℓ 's. The interaction of alpha particles on different targets is usually well described with strong absorption models. One expects the optical model transparency to become stronger as the alpha particle energy increases. This is in contradiction with the trend between $\sigma(IWBC)$ and $\sigma(OM)$ seen in Table 2.1.

We have undertaken a study of the optical model transparency by calculating the quantum flux and divergence of alpha particles incident on different targets. Below, we describe briefly our method which we applied first in the case of alpha particle scattering on ^{42}Ca due to the detailed studies done in this system [2]. The starting point is the Schrödinger equation which for the motion of particles in a complex potential $U=V+iW$, with $W < 0$ is equivalent to the continuity equation with a sink term, i.e.

$$\frac{\partial}{\partial t}(\Psi^*\Psi) + \nabla \cdot \vec{J} = \frac{2}{\hbar} \Psi^* W \Psi \quad (2.3)$$

here $\vec{J}$ is the probability current density vector and Ψ is the (OM) wave function of the particle. The sink term represents the loss of particles per unit volume per unit time. Assuming a steady state and integrating Eq. 2.3 in a sufficiently large volume V of radius R (enclosing the nucleus) we get

$$\int_S J_\rho dS = 2\pi R^2 \int_0^\pi J_\rho \sin\theta d\theta = \frac{2}{\hbar} \int_V \Psi^* W \Psi dV \quad (2.4)$$

where we made use of the Stoke's theorem. The second term in Eq. 2.4 expresses the number of particles lost per unit time; J_ρ is the component of the probability current density vector normal to the integration surface S . It is negative for the ingoing and positive for the outgoing

Table 2.2: Parameters extracted in the analysis of the $\alpha+^{42}\text{Ca}$ system

$E_{C.M.}(MeV)$	R_0 (fm)	r_0 (fm)	σ_{OM} (mb)	σ_{DRAF} (mb)	$\Delta(\%)$
8.0	8.0	2.30	402.6	345.2	-14.3
10.0	7.9	2.27	702.2	614.7	-12.5
12.0	7.7	2.22	900.7	784.5	-12.9
15.0	7.5	2.16	1085.9	933.5	-14.0
20.0	7.2	2.07	1248.5	1034.9	-17.1

flux. Therefore, we can determine the radius at which we have reflections by examining the positive and negative contributions to this integral as a function of the distance from the center of the nucleus.

Figure 2.36: Radial component of the probability current density vector J_ρ for 15 MeV alphas on ^{42}Ca calculated at the matching radius as a function of the angle of incidence. (The beam enters at 180°).

Fig. 2.36 shows a calculation made for 15 MeV alphas on ^{42}Ca . The radial component J_r is shown as a function of the angle θ of the incident alpha particle. Here, J_r was calculated at the (matching) radius of $R = 11.3$ fm where the nuclear potential is negligible. The negative contribution is due to the incident beam. The positive one peaks around 90° and indicates the reflected flux. The integral of the curve in Fig. 2.36 gives us, according to Eq. 2.4, the absorbed flux.

Figure 2.37: Divergence of the probability current density (apart from a factor of $2/\hbar$) along the beam direction for 42 MeV alphas on ^{42}Ca . The beam is incident from the left.

Examination of the positive and negative contributions of the integral of Eq. 2.4 shows that they both increase monotonically as a function of the distance R . However, their sum tends asymptotically to the optical model absorption cross section. This behavior makes difficult the determination of the absolute magnitude of the reflected flux. The ratio of the negative to positive contributions decreases as a function of the distance. This way, we determine a distance R_0 at which reflections start. However, it would be unfair to assume that all of the flux for $r \geq R_0$ leads to reflections because some absorption of the reflective components may still occur. This has been inferred from the examination of divergence plots [3] similar to the one shown in Fig. 2.37.

Making the assumption that all flux for $r \geq R_0$ leads to reflections, we obtain an upper limit of the reflections in the optical model at a given energy. We then calculate the "true" optical model absorption cross section using the DRAF method [4] with R_0 as the fusion radius. The radius R_0 can be parameterized as $R_0 = r_0 A^{1/3}$. In our example of ^{42}Ca , the calculated $\sigma(OM)$, $\sigma(DRAF)$, and radius parameters r_0 are tabulated in Table 2.2 at selected energies. As expected, the radii at which reflections start decrease with increasing

Figure 2.38: Plot of the probability current density vector J for 42 MeV α + ^{42}Ca . The circles correspond to the 10% and the 90% of the central value of the imaginary potential. The outermost arrows were drawn at a distance equal to the matching radius where reflections are apparent.

particle energy. This results in a $\sigma(DRAF)$ value which is closer to $\sigma(OM)$ at lower energies.

A calculation of the azimuthal component J_θ gives the representation of the probability current density shown in Fig. 2.38. The figure is symmetric with respect to the horizontal axis. The circles in the figure show the 10 and 90% of the central value of the imaginary potential. The outermost arrows were drawn at a distance equal to the matching radius where reflections are strong. The magnitude of J gets smaller as the distance to the center decreases. This indicates absorption.

Summarizing, we have been able to study the percentage of transparency contributions in the optical model absorption cross section in the case of alpha particles. The transparency was found to increase with bombarding energy. The method will be applied next to the case of ^{117}Te .

This work was done exclusively by N. G. Nicolis, (this grant) with useful discussions with the Nuclear Chemistry group.

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2.4 REACTION MECHANISM STUDIES

2.4.1 The Mechanism for the Disassembly of Excited ^{16}O Projectiles into Four Alpha Particles

(R.J. Charity, J. Barreto, L.G. Sobotka, D.C. Sarantites, D.W. Stracener, A. Chbihi, and N.C. Nicolis [WU], R. Auble, C. Baktash, J.R. Beene, F. Bertrand, M. Halbert, D.C. Hensley, D. Horen, C. Ludermann, M. Thoennessen and R. Varner [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, which are summarized in the following abstract of a paper published in the Physical Review C. (see Appendix 6.10 for a reprint).

Abstract: The decay of excited ^{16}O projectiles into the four alpha particle exit channel has been investigated. The projectiles, with bombarding energies of $E/A = 25$ MeV, were excited through peripheral interactions with ^{159}Tb target nuclei. A 4π counter was used to detect both the projectile alpha particles and the light charged particles evaporated from the target nucleus. Criteria for selecting true $^{16}\text{O} \rightarrow 4\alpha$ events with the minimum contamination from incorrectly identified events were examined. The distribution of relative angles between the four alpha particles in their center of mass frame was compared to simulations of ^{16}O decay by sequential decay mechanisms. The relative angles were shown to be consistent with a sequential evaporation mechanism if a non-zero angular momentum is assumed for the excited projectile. The momentum distribution of the alpha particles in the reaction plane was examined and found to be anisotropic for high projectile excitation energies. This anisotropy was shown to be consistent with Coulomb interactions between the first emitted alpha particle and the target nucleus, which would indicate that the lifetime of the projectile is very short; on the order of 10^{-22} 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).

2.4.2 Evidence for Prompt Projectile Decay

(R.J. Charity, L.G. Sobotka, G. Van Buren, F.A. Tibbals, A.S. Kirov, J.L. Barreto, P.F. Hua, and D.G. Sarantites [WU], D.R. Bowman, M. Chartier, J. Dinius, C.K. Gelbke, D.O. Handzy, W.C. Hsi, M.A. Lisa, W.G. Lynch, D.F. Peasly, L. Phair, C. Schwarz, M.B. Tsang and C. Williams [MSU], D. Fox, and R.T. de Souza [Indiana U].)

We have continued the studies of projectile fragmentation in collaboration with Lee Sobotka's group. We investigated the disassembly of ^{24}Mg and ^{16}O projectiles at $E/A=60$ MeV impinging on a ^{197}Au target. The influence of the Coulomb field due to the target proximity on the velocities of the projectile fragments in the projectile rest frame was studied in detail. This is manifested as shifts of the longitudinal component of the velocities. The proton ($Z/A = 1$) velocity is shifted up more than that of the α particles ($Z/A = 0.5$).

This work is summarized in a Letter to be submitted for publication. The abstract is included below and a draft preprint is given in Appendix 6.11.

Abstract: Highly fragmented exit channels containing protons, alpha particles and ^3He fragments produced in the decay of excited ^{24}Mg projectiles have been detected. The longitudinal velocity spectra of the protons were shifted to higher velocities with respect to the spectra of the alpha particles. This shift is consistent with post-breakup Coulomb accelerations from the ^{197}Au target nuclei. It was determined that the protons were emitted from the projectile while it was still in contact with the target, or within $2 \times 10^{-22}\text{s}$ after they separated.

2.4.3 Binary Character of Highly Dissipative $^{209}\text{Bi} + ^{136}\text{Xe}$ Collisions at $E_{\text{lab}}/A = 28.2$ MeV.

(B. Lott, S.P. Baldwin, B.M. Szabo, B.M. Quednau, W.U. Schröder, J. Tőke [ROCH] L.G. Sobotka, J. Barreto, R. Charity, L. Gallimore, D.G. Sarantites, D.W. Stracener [WU], and R.T. de Souza [IU].)

An interesting question in recent years has been whether novel reaction mechanisms exist in intermediate energy heavy-ion collisions. Despite the many scenarios possible, the answer to this question is still unknown. In view of the fact that a considerable fraction of the reaction cross section bears the characteristics of partially damped inelastic reactions, it is clear that powerful reaction filters will be needed to resolve these issues.

For this purpose we combined simultaneously exclusive neutron and charged particle 4π measurements and studied the reaction $^{209}\text{Bi} + ^{136}\text{Xe}$ at 28.2 MeV/nucleon. The apparatus is shown in Fig. 2.39. The neutrons were recorded by the 900 l Gd-loaded liquid scintillator tank (University of Rochester), while the charged particles were detected by the WU Dwarf system.

The experimental joint multiplicity distribution between charged particles and neutrons is shown in Fig. 2.40. As would be expected for such a heavy system, for peripheral collisions predominantly neutrons are emitted. For more dissipative collisions charged particle emission becomes important. The stars in Fig. 2.40 are the result of GEMINI calculations for different total energy losses. The calculations were not corrected for the efficiency of the detector system. The last star corresponds to a total of 1.2 GeV. This energy is much less than

the total kinetic energy above the entrance channel Coulomb barrier (2.3 GeV). This would

Figure 2.39: The experimental setup.

Figure 2.40: Experimental joint multiplicity distribution (uncorrected for instrumental response) of neutrons and charged particles.

seem to suggest that damping is far from complete. Some support for this conclusion can

be found in the light particle invariant cross section plots which show blurred images of only moderately damped projectile and target sources (See Fig. 2 in Appendix 6.9). However, there are two reasons to doubt this conclusion. Firstly, we believe that use of GEMINI at this excitation energy region is inappropriate. Secondly, other studies which we have done (Sobotka's analysis of our GANIL data for the ^{84}Kr induced reactions at 45 MeV/A indicate that the larger the charge of the detected species, the greater the apparent damping. Therefore, the extent of damping is still an open question. However, it is clear that binary or entrance channel dominated dynamics persist in the energy region of this work.

B. Lott and S. Baldwin (from Rochester) have done the bulk of the analysis for this project. A significant portion of their work was done during a one month visit to Washington University. This work is contained in Phys. Rev. Letter [1]-(see Appendix 6.9 for a reprint)

- [1] B. Lott, S.P. Baldwin, B.M. Szabo, B.M. Quednau, W.U. Schröder, J. Töke, L.G. Sobotka, J. Barreto, R. Charity, L. Gallamore, D.G. Sarantites, D.W. Stracener and R.T. de Souza, Phys. Rev. Lett. **68**, 3141 (1992).

2.4.4 Particle 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, [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 6.16.

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 under predict the inverse slope parameter. This comparison also suggests strong particle multiplicity fluctuations at fixed impact parameter.

Chapter 3

Instrumentation and Analysis

3.1 “MICROBALL” A 4π CHANNEL SELECTION DEVICE FOR SPECTROSCOPIC AND NUCLEAR REACTION STUDIES WITH GAMMASPHERE

In the past few years our group at Washington University has concentrated on a variety of experiments that utilized the *Dwarf Ball* and *Wall*, a 4π charged-particle detection system, for reaction mechanism studies and as an exit-channel selection device for spectroscopic studies. Although the *Dwarf Ball* fits inside the GAMMASPHERE chamber, it has two serious disadvantages that cannot be remedied. These are (i) the serious deterioration of the peak to total ratio of the Ge spectra due to Compton scattering in originating from the large mass of the *Dwarf Ball*, and (ii) the limited stability at high counting rates, which renders particle identification by pulse shape discrimination difficult. The MICROBALL currently under construction will eliminate these difficulties and will provide several additional improvements that will permit its operation with the high data rates commensurate with the capabilities of GAMMASPHERE.

During the past eight months we have completed the mechanical design of the MICROBALL detection system and of the new electronics for signal processing. A recent in beam test of several detector elements has demonstrated the superior performance of the proposed system in terms of energy resolution, stability at low and high counting rates, excellent particle identification resolution, and operation with a very compact and economical system of electronics. The performance test has also established that we can build a second version of the MICROBALL with thicker elements that can stop more energetic particles for the purpose of reaction mechanism studies. The crucial feature was the ability to identify not only light-ion isotopes but some of the lighter intermediate fragments with good Z resolution.

3.1.1 Design Requirements

The design criteria for a 4π charged particle detection device are based on the physics capabilities that the device will address. In the present case we plan an optimal device that will accomplish exit channel selection by particle identification for the purpose of detailed spectroscopy with GAMMASPHERE without significant deterioration of the GAMMASPHERE performance. Automatically, this means that the reactions will be limited to near Coulomb barrier energies and thus only light ions of low energy need to be detected. This choice is

consistent with thin low mass detectors that are planned. On the other hand, for reaction mechanism studies one needs to stop more energetic light ions, which means thicker detectors. A compromise must be reached in this case. Since the MICROBALL construction is fairly inexpensive we propose to build two sets of detectors. The thinner set, to be termed the *spectroscopy* MICROBALL, will have the minimum possible mass for good channel selection. The thicker version, termed the *reaction* MICROBALL, will allow more energetic particles to be measured. In the latter case certain compromises in absorption and scattering will be made. However, for most anticipated reaction studies only particle- γ , or particle- γ - γ coincidences will be measured and the absorption losses will not be too severe. These two devices use the same support structure and electronics.

We can summarize the design requirements for the MICROBALL as follows:

1. Large solid angle coverage ($\simeq 98\%$ of 4π) for good channel identification. This condition is important when a weak channel such as (HI,p2n) needs to be selected in the presence of much stronger channels such as (HI,3p). Such large coverage can be achieved geometrically, but there are other factors that reduce the actual detection efficiency. For example, the device of choice should provide adequate particle identification at all particle energies. However, at large angles for more symmetric reactions and/or lighter compound systems the lowest energy α particles and protons cannot be completely distinguished, thus decreasing the identification efficiency somewhat.
2. Small total mass to minimize degradation of the peak to total ratio of the GAMMASPHERE Ge detectors. This is imperative for spectroscopic studies, but not as crucial for reaction mechanism studies.
3. Adequate segmentation to distribute nearly equally the counting rate among the detectors. This will allow the device to keep up with the high event rates of GAMMASPHERE.
4. Increasing segmentation with decreasing angle relative to the beam. This will allow angular distributions of light charged particles to be measured with nearly equal statistical quality at all angles.
5. Reasonably good energy resolution for measuring particle evaporation spectra.
6. Excellent gain stability with time and counting rate. This is very important in order to reduce significantly the data analysis time by eliminating the need of gain shift corrections in the off line analysis.
7. Excellent temperature stability. This is related to the gain stability of the device.
8. The device should be small enough to fit inside the GAMMASPHERE scattering chamber.

These diverse requirements limit severely the choice of the detector material and the geometrical design.

We have opted against the choice of Si as the detector material, because such a device would be impractical for high energy particle identification, where the $(\Delta E, E)$ method must be used since this is difficult to implement with high solid angle coverage. Furthermore, at

Figure 3.1: Schematic diagram showing a vertical section of the MICROBALL. The number of detectors for each ring are given with bold type. The azimuthal angle θ and the half angle are also given. In addition to the detectors facing the target, the light guides are shown as the dot filled trapezoids. The detectors are shown attached to the rings via the gold plated pins of the of the photodiodes. The device is shown to real scale.

low energies (for 1-4 MeV α) sub nanosecond timing must be used for particle identification by time of flight, and this is not possible at the present site of GAMMASPHERE.

We have chosen the CsI(Tl) scintillator as the detector material. Using a high T concentration, (1000 ppm) it is possible to achieve excellent PID resolution by pulse shape discrimination(PSD). Coupled with a Si photodiode readout of the scintillation light, these detectors satisfy very well all of the above criteria. It is well known that CsI(Tl) has two decay components. The first one has a mean decay time $\tau = 0.4\text{-}1.0 \mu\text{s}$, the amplitude and fall time of which depends on the particle type detected. The second component has a decay time of $7 \mu\text{s}$, which is independent of particle type. These two components can be used to distinguish between particle types by PSD methods. The long $7 \mu\text{s}$ component presents an important limitation for the CsI(Tl) detectors, because of its length it limits the counting rate that can be achieved without PID deterioration due to pile-up. To avoid this limitation we have opted to design the geometry of the MICROBALL in a way that equalizes the counting rate as much as possible among detectors at all angles.

The thickness of the CsI(Tl) scintillator is crucial to the performance of the two devices. The detector thicknesses were chosen on the basis of simulations of the GAMMASPHERE performance *coupled* with reasonable reaction kinematics calculations. These simulations are described in section 3.1.3.

3.1.2 Geometry and Characteristics of the MICROBALL

The geometry of the MICROBALL is determined by the counting rate considerations, and the packing limitations associated with the size of the Si photodiodes taking into account the light collection efficiency from the scintillators. We must emphasize that for each reaction studied there is always a best suited geometry. In order to make the device as versatile as possible a compromise solution must be chosen based on a “typical” reaction.

First, the counting rate considerations coupled with the desire to measure adequate particle angular distributions will be used to choose an appropriate segmentation for the device.

Let us assume a typical reaction that emits on the average 2 charged particles. Assume further a typical γ -ray multiplicity of 20 and an event rate that gives 10,000 c/sec per Ge detector in the GAMMASPHERE. The geometric coverage of the Ge detectors is $0.5 \cdot 4\pi$ for 110 detectors, while a typical triggering efficiency may be 0.95. Under these conditions the event rate is

$$Event\ Rate = \frac{10,000 \times 110}{20 \times 0.5 \times 0.95} = 1.16 \times 10^5\ events/sec.$$

If we limit the counting rate per CsI(Tl) detector to 2,500 c/sec, which is a comfortable rate with acceptable pile-up fraction (see discussion below), then

$$Number\ of\ Detectors = \frac{1.16 \times 10^5 \times 2}{2500} = 93.$$

For reasons of packing, we select a number of 96 for the detectors because it gives a convenient number of 6 electronic modules of 16 channels each. Under these conditions we

Table 3.1: Geometric Parameters of the MICROBALL.

Quantity/Ring	1	2	3	4	5	6	7	8	9
No. of Dets.	6	10	12	12	14	14	12	10	6
Distance(mm)	110	80	60	50	50	50	45	47	50
θ°	9.0	21.0	36.0	52.0	70.0	90.0	111.5	135.0	159.0
Half θ°	5.0	7.0	8.0	8.0	10.0	10.0	11.5	12.0	12.0
$(\Delta\Omega/4\pi) \times 100$	0.23	0.44	0.68	0.91	1.17	1.24	1.55	1.47	1.24
$\Delta\Omega/\Delta\Omega(9^\circ)$	1.0	1.92	3.00	4.02	5.13	5.46	6.80	6.47	5.47
Lite guide (mm)	8.0	7.5	6.0	6.0	6.0	7.0	7.0	7.5	8.0
$\mu\text{B-1 CsI}$ (mm)	2.5	2.5	2.0	2.0	1.5	1.5	1.5	1.0	1.0
Stops p (MeV)	24	24	21	21	18	18	18	14	14
$\mu\text{B-2 CsI}$ (mm)	9.0	7.0	6.0	6.0	5.0	5.0	4.0	3.5	3.0
Stops p (MeV)	50	43	39	39	35	35	31	29	26

can estimate the overall pile-up fraction to be $1.0 - (1.0 - 3 \cdot 10^{-5} \times 2.4 \cdot 10^3)^2 = 0.14$ or 14% for a typical 2 particle channel (20% for a 3 particle channel). It was assumed that a time interval of $-15 \rightarrow +15 \mu\text{s}$ is inspected for a second trigger for identifying a pile-up count. Since the pile-up is designed to be identified by our electronics, it will only entail rejection of only 14% of the 2 particle events. This should be compared with a rejection rate of 12% per Ge detector which, for example, amounts to a reduction by 48% of the 4-fold Ge coincidence events, which appear as 3-fold ones in the final version of Gammasphere !

A vertical section of the MICROBALL is shown to scale in Fig. 3.1 . There are 9 rings of detectors spanning the angular range between 4.0° and 171° relative to the beam. The parameters of the proposed MICROBALL are summarized in Table 3.1 . The distance of the detectors in each ring is given in the third row. The last 4 rows give the CsI(Tl) thicknesses for the two devices for spectroscopic and reaction studies, as well as the energies of proton that stop in the detectors.

The MICROBALL detectors will have the shape of an arc. This is preferred over a trapezoidal shape because a better packing arrangement can be achieved. In this way, there will be no shading of detectors by other detectors from the neighboring rings. The plastic rings that support the detectors are held by appropriate legs that move in a rail and can be placed at the exact distance by set pins. Each detector will be glued to its UV transparent light guide by a Bicon BC-600 epoxy glue, while the light guide will be attached firmly to the photodiode by a silicon RTV glue that remains sufficiently soft to allow decoupling from the diode by firmly applying a twisting force. The two diode leads serve to attach the detector to the ring via two plastic parallelepipeds and one supporting screw, making the removal of a detector easy.

The target is inserted at an angle of 80° to the beam between matching detectors in rings 5 and 6 which will be cut to make room for the target holder. In the early implementation the device will be inserted into place from the bottom of the chamber and will be supported by a bottom plate. The target or the phosphor will be inserted by breaking the vacuum. In the final arrangement a separate dedicated scattering chamber will be used and the target

Figure 3.2: Fraction of the scattered γ -rays relative to the direct ones impinging on a Ge detector as a function of the radius of the MICROBALL assuming a 2 mm thick CsI shell. (Courtesy J.R. Beene, ORNL).

will be inserted via an appropriate port at 80° to the beam. Up to two targets can be accommodated in the same target rod that can be inserted without breaking the vacuum.

For beam focusing one of the 135° detectors will be removed to allow viewing of the scintillator and then can be placed back. A plastic plate will be used at the top of the early implementation chamber to allow sighting, while in the complete GAMMASPHERE arrangement a 135° viewing port will be install in the scattering chamber.

3.1.3 Performance Simulations

In order to choose the characteristics of the MICROBALL in the best possible way, detailed simulations were carried out with the Monte Carlo code GEANT. [1] The full geometry of GAMMASPHERE was entered in the code GEANT and performance tests for γ -rays of various energies were done. The materials in the vicinity of the Ge detectors had to be reproduced well in order to obtain realistic values of the peak-to-total ratios as a function of energy.

Then the geometry of the MICROBALL was introduced in the code and was assumed to act as an absorber and scatterer. Calculations with different γ -ray energies were carried out and the results were examined. It was found that a reasonable typical thickness of ≈ 1.5 mm for the CsI(Tl) detectors would be adequate for the spectroscopy version of the MICROBALL.

Figure 3.2 shows the results of a simulation for the scattered γ -rays relative to the direct ones as a function of the radius of the MICROBALL. Clearly, one should make the device as large as possible, but above about a 7 cm radius further improvement is significantly

Table 3.2: GEANT simulation of the single γ -ray response of the GAMMASPHERE for three γ -ray energies. The numbers given are the Peak-to-Total ratios in a Ge detector and are averages of the 3 geometries of BGO shields. The statistical uncertainties in all the numbers are $\pm 2\%$.

Configuration	300 keV	600 keV	1200 keV
Gammasphere			
Unsuppressed	0.61	0.39	0.27
Own Shield	0.85	0.76	0.61
Own+Neighbor's Shield	0.86	0.81	0.71
GS+Microball			
Unsuppressed	0.58	0.38	0.26
Own Shield	0.81	0.70	0.58
Own+Neighbor's Shield	0.82	0.75	0.66
Peak Efficiency Loss	0.87	0.93	0.96
PTT Reduction by μB			
Unsuppressed	0.95	0.97	0.96
Own Shield	0.95	0.92	0.95
Own+Neighbor's Shield	0.95	0.93	0.93

reduced. From this simulation and from the limitations due to the size of the photodiodes and/or the size of the scattering chamber coupled with the efficiency of light collection we have chosen the radii of the rings to vary from 4.5 to 11.0 cm.

In Table 3.2 we give the results of a simulation for the Ge detectors of GAMMASPHERE to 300,600 and 1200 keV γ -rays for the following situations: (a) A Ge detector unsuppressed, (b) 1 Ge detector in the GAMMASPHERE suppressed only by its own BGO shield, and (c) 1 Ge detector in GAMMASPHERE suppressed with its own BGO plus BGO from the neighboring detectors. Also are given the situations (d), (e), and (f) as in (a), (b), and (c), respectively, but with the MICROBALL in place. The average peak efficiency loss due to the insertion of the MICROBALL is also given. The reduction of the PTT ratio for the three conditions and the three energies are also given.

The reduction of performance due to the assembling of the GAMMASPHERE is not shown here, but is found to be larger than that caused by the MICROBALL. In summary the loss of peak-to-total ratio due to the MICROBALL is approximately 0.95 ± 0.02 . This reduction is indeed minimal, especially when one realizes that additional reduction of the PTT ratio occurs when high multiplicity events are considered. These produce significant coincidence summing (~ 10 -15% depending on M_γ) and additional scattering. We are in the process of simulating these effects as a function of M_γ .

3.1.4 Performance Tests

Experimental tests were made for the purpose of selecting and fine tuning the performance characteristics of the MICROBALL detectors and their associated electronics. These

Figure 3.3: Energy spectrum from a ^{232}U α source. The energy resolution at the 8.78 MeV α peak corresponds to a FWHM of 240 keV.

Figure 3.4: Simulated pulse shapes assuming two input exponentials of the initial amplitudes of 20 to 1 with decay times of 0.7 and 7.0 μs . The solid line is the summed signal from both components, while the dashed line gives the response to the long component. This gives a relative light of 2:1 for the short and long component, respectively. The shaper RC constants were taken to be $\tau_0 = 1.3\mu s$. The long tail can be reduced by pole-zero cancelation and still preserve good PID resolution.

included (a) the energy resolution (b) the counting rate stability, (c) the particle identification resolution by pulse shape discrimination, and (d) temperature stability. The energy resolution is intimately coupled to the geometry of the detector assembly and the quality and design features of the associated electronics. The counting rate stability and the PID resolution depend only on the electronics, while the temperature stability is a function of the crystal and the electronics. These factors are discussed below.

Detector geometry and energy resolution.

We have carried out a series of tests aimed to determine the importance of the geometry of the light guides of the energy resolution of the MICROBALL detectors. The geometry of the entire MICROBALL was programmed in the computer so that the distance of the rings from the target and the thickness of and shape of the light guides could be easily calculated and varied.

Remembering that the detectors have the shape of portion of an arc, and that their area is approximately 3 to 4 times that of the $10.0 \times 10.0 \text{ mm}^2$ Si diode, we would need a matching light guide having an arc shape in one end and square at the other. For the purposes of these tests we approximated the detectors shapes with trapezoids of equal area. We used a highly doped CsI(Tl) with 1000 ppm in Tl, known to give optimal PID resolution[2] and prepared matching light guides. To insure that the tests reflect the effect of the geometry,

we scanned the crystals in 2 dimensions with a collimated α source and at the same time measured the energy resolution. We found certain relationship between the thickness and the shape of the light guide with the uniformity of response. We have achieved a uniformity better than 0.7% across the face of the detector and obtained an energy resolution of 2.7% (not a channel resolution) for 8.78 MeV α 's. This is indeed 2 times better than that achieved with the Dwarf Ball detectors, where photomultipliers are used. Taking into account the fact that the Si photodiodes have a quantum efficiency of $\simeq 80\%$ as compared to $\simeq 20\%$ for the phototubes, the improved energy resolution is in accord with the photon statistics, indicating that the losses due to geometry are similar for the two detector arrangements. The thickness of the light guides given in Table 3.1 were selected to optimize the resolution.

Figure 3.3 shows a typical spectrum of α particles measured with a detector approximating the ring-2 geometry and a 7 mm matching light guide using a ^{232}U α source. A charge sensitive preamplifier and a filtering shaper (see Sect. 4.2) were used in these measurements. It should be pointed out that in Fig. 3.3 the low energy broad structure is the composite of the beta groups with an average end point energy of ~ 2.4 MeV.

Furthermore, we have measured the noise and energy resolution as a function of cable length between the photodiode and the preamplifier. We tested 2 cables, an RG174 and a much thinner shielded cable with the same capacitance (1.0 pF/cm) per unit length. We found that for up to 1.8 m the resolution deteriorates slowly at a rate of $\approx (0.6\%)/\text{m}$. We plan to test other lower capacitance cables in order to optimize the energy resolution. For the full implementation a cable length of 1.2 m will be needed to place the preamplifiers outside the GAMMASPHERE shell.

Counting rate stability.

We have measured the counting rate stability with an $5\ \mu\text{Ci}\ ^{249}\text{Cf}$ α source that could be moved remotely to vary the rate. The stability as a function of rate depends entirely on the pole-zero compensation and base line restoration employed in the slow shaper of the electronics system. Several schemes were tried and the adopted one gave an impressive stability of $\leq 0.5\%$ between rates of 500 c/s and 12,000 c/s. No gain variation was observed below 5,000 c/s. For higher average energies the gain shift may be somewhat larger, but over the range of counting rates for which the device is designed no noticeable gain shifts are expected.

Timing resolution

The timing resolution of CsI(Tl) is limited due to the slow rise time (15 ns) and the small amplitudes. With the appreciable integration introduced in the preamplifier, a compromise has to be reached between timing resolution and energy threshold. In our tests we employed a fast peaking time of 600 ns in the constant fraction discriminator. We measured the timing resolution of the CsI detectors using a ^{246}Cf source that gives a 5.8 MeV α in coincidence with a 380 keV γ ray. A fast CsF detector was used for the fast channel. We obtained a FWHM of 55 ns. This can be improved to about 40 ns and still provide a triggering capability down to ~ 200 keV α particles without noise. For higher energy particles the timing resolution will be significantly better.

Figure 3.5: Scatter plot showing the PID resolution by pulse shape discrimination. (a) shows the separation of α particles and electrons or γ -rays from a source of ^{232}U . Our prototype preamplifier is used in this feeding a MSU shaper. (b) Separation of electrons, α particles and fission fragments by PSD. Our first prototype shaper is used in this measurement.

PID resolution by pulse-shape discrimination.

Good PID resolution is crucial to the performance of the MICROBALL. Therefore we have carried out extensive tests in order to obtain the best possible resolution. The PID resolution is critically dependent on the preamplifier and shaper used. A detailed description of the electronics is given in Sect. 3.2. Here we summarize the experimental results. The charge sensitive preamplifier employed integrates considerably the photodiode signals and produces pulses with a rise time of $\sim 1 \mu s$ and a decay time of $\sim 300 \mu s$. A low and high frequency filtering 2-stage shaper is employed to recover the two components of the CsI(Tl). An aperiodic pulse with the shape proportional to $x^4 \times e^{-4x}$ where $x = t/\tau_0$ is used. Tests with τ_0 values of 1.3 and 1.8 μs were made. The pulse shapes were simulated using a computer code that gives the output pulse of the actual shaper circuit for any input. Using input pulses with exponential decay times of 0.7 μs and 7.0 μs , we obtained the simulated pulse shapes that guide us as to where to place the gates for integrating the charge for the two components. In Fig. 3.4 we show the simulated pulse shapes corresponding to $\tau = 1.3 \mu s$ which gives a peaking time of 2.8 μs for the 0.7 μs component and $\sim 6 \mu s$ for the 7.0 μs component that shows a long tail. Remembering that the 7.0 μs component carries only a fraction ($\sim 1/2$) of the light of the shorter component we have used these relative intensities in the simulation in Fig. 3.4. The dashed curve is the long 7.0 μs component and the solid curve is the sum of the two. We conclude that the best place for the gates are near and on the left of the peak and at $\sim 12 \mu s$, respectively. However, the long tail produces pile-up. A good compromise is found by using the pole-zero compensation to reduce the tail and then move the tail gate up to about 10 μs .

We have been fine tuning the electronics to obtain the best PID resolution by measuring 2-dimensional distributions using a simultaneously an α -source of ^{232}U which provides several α -peaks with energies of 5.32, 5.684, 6.051, 6.287, 6.777, and 8.785 MeV, as well as β^- groups with end point energies of ~ 2.4 MeV. These α and β particles can be easily identified on the bench top by pulse shape discrimination (PSD). Two different shapers but similar in principle were compared in these experiments. An early version of the shaper for CsI PID by M. Maeir[3] (borrowed from MSU), was compared with a more recent design of the shaper also by M. Maeir. The latter was assembled at Washington University. We found out that the MSU version had about 30% better signal to noise ratio at the tail. Consequently, it gave somewhat better PID resolution. We understand the origin of the additional noise in our prototype and are in the process of replacing a crucial operational amplifier with another one having lower noise by a factor of about 7. This will improve significantly the PID resolution.

Typical PID resolutions from a ^{232}U source are shown in Fig. 3.5 where the abscissa is the E component (0.7 μs) and the ordinate is the tail. The α particle separation from the ($\beta^- + \gamma$) pulses is clearly seen down to very low energies. In the maps of Fig. 3.5 protons are expected to be located half between the α 's and the electrons, it is clearly seen that the proton- α separation at energies from $E_\alpha \geq 2.0$ MeV and $E_p \geq 1.0$ MeV is easily achieved. This indicates that the spectroscopy version of the MICROBALL is expected to work very well. In the panel (b) of Fig. 3.5 α particles and fission fragments from a ^{252}Cf source were mixed in with the ^{232}U . The direct identification of the fission fragments is also seen. Note that the CsI(Tl) scintillators are covered with 170 $\mu g/cm^2$ aluminized mylar that attenuates the energy of the fission fragment somewhat, but the large reduction in pulse height comes

Figure 3.6: Color scatter plot showing the PID resolution by pulse shape discrimination using a 2mm detector. The reaction was 300 MeV ^{20}Ne on ^{93}Nb . The p, d, t separation is clearly seen. The separation of α particles from the hydrogen isotopes is apparent for all energies. The proton punchthrough energy here is 21 MeV. Our prototype preamplifier and a complete channel of the new electronics was used to process the signals.

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Figure 3.7: Color scatter plot showing the PID resolution by pulse shape discrimination using a 6 mm detector. The reaction was 300 MeV ^{20}Ne on ^{93}Nb . The p, d, t separation is clearly seen. Separation of ^3He from α particles down to reasonably low energies is seen. The first line below the α line is the 2α line from the ^8Be breakup. The next line shows the Li ions detected and the lowest is the group of all heavier ions from B to Ne. The proton punchthrough energy here is 39 MeV. Our prototype preamplifier and a complete channel of the new electronics was used to process the signals.

from the strong light quenching in the CsI(Tl) from the high ionization density.

It remained to establish the suitability of the present crystal design and readout system for particle identification with the thicker prototype detectors of the MICROBALL. Here it is important to separate p, d, t, ^3He , α , Li, Be and perhaps heavier ions. For this purpose, we scheduled and carried out a test run at LBL. In order to identify any noise pickup we used the early implementation scattering chamber. The preamplifier was placed outside the chamber with a solid grounded connector feedthrough and a 60-cm RG174 cable between the diode and the preamplifier. We found that there were no ground loops and the preamplifier signal could be sent to the electronics area about 70 m away without any noticeable noise pickup.

We tested four different detectors. Two of these were trapezoidal 2 mm thick and had tapered light guides of 6 and 7 mm thick. The third one was 6 mm thick and had a 7 mm tapered light guide. The last one was a 2 mm thick CsI(Tl) $10\times 10\text{ mm}^2$ coupled directly to the photodiode also $10\times 10\text{ mm}^2$. We compared the MSU shaper and a complete module of the present design electronics with only one channel fully implemented. Different tests were made with varying gate widths and gate time positions. In all cases very good PID resolution was observed, but differences in performance were found depending on how the gating was done. The MSU shaper as expected showed slightly better PID resolution, but we had not replaced the op-amplifier with the quieter one yet.

We used a rather energetic reaction of 300 MeV ^{20}Ne on ^{93}Nb and placed the detectors between 25° and 70° . This reaction produced high energy p, d, t, ^3He , α , Li, Be ions at the forward angles. As expected the light ions had energies that exceeded the range in the 2 mm detectors. Consequently the light ions punched through but still were well identified. For energies near the Coulomb barrier only a very small fraction of the light ions will punch through.

In Figure 3.6 we show a color scatter plot from the 2 mm detector with the 7 mm light guide placed at 30° to the beam. The Washington University made electronics module (M. Maeir design) was used in taking these data. The excellent PID resolution is apparent. The proton punchthrough energy is 21 MeV. The complete separation of the hydrogen isotopes is clear. For clarity of presentation of the p, d, t resolution the single count points have been suppressed from the map. Otherwise the Li, Be, and heavier ions separation would be visible. Since the composite system has a $Z = 50$ for this reaction the emission Coulomb barrier is low and this gives lower energies in the spectra, while the energetic beam provides high temperatures and thus high energy tails in the proton spectra that punchthrough but still remain separated from electrons and/or γ -rays.

In Figure 3.7 we show a color scatter plot from the 6 mm CsI(Tl) detector placed at 25° to the beam. Again excellent PID resolution is seen. The data shown were also taken with the WU module. Now the proton punchthrough energy is 39 MeV and that of the deuterons 52 MeV. Reasonable ^3He - α separation is seen. One can clearly see the ^8Be breakup line into 2 α -particles (first line below the α line), then the Li and the remaining heavier species. This figure was cut at the triton punchthrough energy of 61 MeV so that the higher energies where the PID resolution continues to improve are not shown.

the feedthrough plate and preamplifier cylindrical container clear of the GAMMASPHERE detectors and support structure.

The preamplifier is a charge sensitive one [4] which includes significant integration to optimize the signal to noise ratio. The output pulses have a rise time of about 900 ns and a decay time of 300 μ s.

Integrated Electronics Modules

We have decided to combine all the functions of 16 detector channels in a one double width CAMAC module. Using compact CMOS technology we have demonstrated that we can accomplish this. The basic design of most of the components of this module was provided by M. Maeir of LBL. Some modifications were made by J. Elson at Washington University. A block diagram of the functions in the module is shown in Fig. 3.8 .

For each channel the module incorporates:

1. Pole-zero compensation. This is important for adjusting the tail of the pulse to minimize pile-up.
2. A two-stage aperiodic shaper. It is used to give the signals for energy and PID analysis. The time constant τ_0 for each module can be changed by replacing 16 capacitor plugs (with 5 capacitors on each one). This will permit reducing the pile up by using shorter τ_0 values for high counting rate applications at low energy at some expense of the PID resolution.
3. Computer selectable (via slow CAMAC) gain adjustment for each channel. This is done via a computer controlled attenuation resistor between the two stages of the shaper.
4. Base line restoration for gain stabilization against counting rate variations. No gain shift was observed with an α source for rates between 500 and 5000 c/s. For 14,000 c/s a downward shift of 0.6% was measured. For higher energies the gain shifts will be higher, but we point out that the device is designed to operate usually below 2,500 c/s.
5. A two-way DC coupled slow splitter providing the energy and the PID signals. The unattenuated branch will be used to place the tail gate for PID by PSD. The E signal is obtained from the attenuated branch the magnitude of which is determined by a plug-in resistor pack. These will most like be selected only once for optimal PID resolution. The DC coupling was found to be essential for achieving the desired counting rate stability.
6. A computer selectable monitor signal for the discriminator and energy signals of any specified channel. This is important for setting the gains and discriminator thresholds via a IBM PC computer. *This feature allows one to set up an experiment in 30-60 minutes !*
7. A fast shaper (peaking time 500 ns) and a differentiation used to produce a Nowlin type constant fraction discriminator output. [5] The peaking time had to be slowed

down considerably in order to allow triggering to low energies without excessive noise. The discriminator is cleared after a selectable period of time up to $20\ \mu\text{s}$. This should be set to exceed the period from the beginning of the fast discriminator to the end of the tail gate.

8. A OR circuit for the 16 channels of the CFD output is provided on a single LEMO connector. Its width is nominally set to 100 ns.
9. A multiplicity output on a LEMO connector. Its output level is adjustable and is set at 50 mV per fold.
10. A pile-up sensing circuit is incorporated that provides a bit per channel if another pulse appears for a period $-\Delta t \rightarrow +\Delta t$ around the event trigger time. The interval is selectable and must end past the end of the tail gate. The pile-up bit can then be used off line to identify events which include a pile-up in any detector.
11. A time-to-FERA converter for each channel. This section provides a pulse of adjustable amplitude with a width determined by a common start pulse and the individual delayed discriminator signals. The delay time is set to a maximum of 800 ns to accommodate any adjustable desirable range for time measurement. The Common start is derived from an overlap coincidence between the OR of all the CsI detectors and of all Ge or other external detectors and then is brought to each module via a LEMO input.

The module has one 16 pin input from the preamplifiers, 1 LEMO common start input, 4 LEMO outputs for the OR, the multiplicity, the discriminator monitor, and the energy monitor signals. In addition there are 4 16-channel multi pin output connectors for the energy, the tail for PID, the time, and the pile-up bits.

External Logic

The external logic is used to prepare the coincidence gates. We need to OR together the discriminator OR's, create an overlap coincidence with the Ge OR's in a way that the Ge determines the timing. This AND is then fanned out to each bank for the TFC start. In addition, a second overlap coincidence is made with the Ge OR's such that the CsI determines the time. This AND is then used to make the E and tail gates for all the FERA adc's.

Digitization and Readout

The MICROBALL signal digitization will be done with 18 FERA adc modules (LeCroy 4300B mod 610). There are 6 banks of 16 channels each. Each bank needs an energy, tail (PID), and a time signal adc. The time-to-FERA converter has been designed in our module. Two spare FERA modules will be needed, because from experience we know that there is some degree of failure in these units. The FERA's for the E, Tail analysis (PID), and the time will have different gate widths. Therefore, three FERA bus driver modules will be needed for handshaking and ECL bus readout.

The readout of the MICROBALL information in full GAMMASPHERE implementation will be done in the same way as the readout of the BGO detectors. For early implementation we

are examining a number of easy solutions. One is to use one CAMAC crate and use existing readout. A second is to use a VME bus and the FERA "faucet" system on loan from MSU. (Contributed by D.G. Sarantites, P.-F. Hua, J. Elson, J.R. Hood, W.U, and M.R. Maeir, LBL).

- [1] Simulation performed by L. Sobotka with the code GEANT
- [2] J. B. Birks, "Theory and Practice of scintillation counting" Pergamon Press, New York, 1964, p. 457.
- [3] W.G. Gong *et al.*, Nucl. Instr. Meth. **A268**, 190 (1988).
- [4] M. Ciric, J. Friese, H.J. Korner, and M.R. Maeir (IEEE), and private communication.
- [5] C.H. Nowlin, Rev. Sci. Instr. **63**, 2322 (1992).

3.2 A NOVEL X-RAY DETECTOR

In Sect. 2.2.3 we discussed the use of an atomic X-ray clock for measuring the lifetimes of subbarrier α -particle emission. The small probability of creating the K vacancy during the incoming atomic collision is only of the order of 1%, (see the section on this subject in the proposal.) This makes all such measurements difficult. In addition considerable background in the X-ray region of interest (40-100 keV) is created from the fusion or fission γ rays and their Compton scattering distributions. Further complication arises from X-rays following internal conversion. The latter can usually be eliminated by requiring coincidence with an α particle or fission fragment, depending on the particular interest at hand.

Figure 3.9: Design of the transversely mounted planar Ge X-ray detector.

Low energy γ rays with multiplicities other than E1 in the X-ray energy region will be slow enough to shadow block (see proposal). If shadow blocking is employed, the major

background will be the Compton photons. Therefore effective Compton suppression is extremely important. Due to experimental difficulties, our previous experiments did not make use of Compton suppression on the X-ray detectors. In our future experiments we will not only use Compton suppression, but also use an X-ray detector which significantly improves the suppression as compared to standard designs.

Figure 3.10: GEANT simulations of the transversely mounted planar Ge X-ray detector with both (a) an Argonne type suppressor and (b) a simple 3"x3" NaI(Tl) veto detector behind the active region. These simulations each have 2 parts of K X-rays to 10,000 parts of fission-like γ spectrum. A Cu absorber has been included to reduce the counting rate from the target X-rays, which have not been included in the simulation.

In the standard design of planar Ge X-ray detectors the crystal axis is radial and collinear with the cryostat. This geometry prevents the placement of any scintillation veto element directly behind the Ge crystal. Needless to say, this is the most important region to have suppression detectors. No planar Ge detector design on the market allowed for the placement of a suppression element in the 0° region, so we designed one.

Figure 3.9 shows our design. The axis of the crystal is perpendicular to the cryostat. The can has a rectangular cross section of 1" by 2", with the axis of the crystal along the 1" dimension.

This design was simulated with GEANT [1] before placing the order for this detector. Some of the simulations are shown in Fig. 3.10. The initial photon distribution was chosen

to resemble that from fission (but without any structure) with the addition of 2 parts per 10,000 K x-rays from the parent nucleus. This input spectrum is shown as the top curve in both parts a) and b). The "raw" spectrum from this detector, with a 1 mm Cu absorber placed in front of the active region, is also shown in both parts of the figure as the middle curve. The bottom curves are the Compton suppressed spectra from a) an Argonne type - full suppressor and b) a simple 3"x3" NaI(Tl) placed behind the Ge. The value of the full suppressor is clearly seen. In addition, the value of suppressing directly behind the active element is also seen, in that even a 3"x3" NaI(Tl) crystal provides some suppression. (The funds for this order were split between Sobotka's PYI award and this grant.)

A 800 mm² detector of this design has now been delivered from ORTEC. We have tested the detector and achieved resolution better than the manufacturer's specifications.

This detector was already used in the Fission Clock experiment at Argonne (See Sect. 2.2.5 of this report).

[1] R. Brun et al. GEANT3 Users Guide (Data Handling Division EE/84-1 CERN,1986)

3.3 "THE TUBE": A SIMPLE 4π DETECTOR FOR ENHANCING CHANNELS IN γ -RAY EXPERIMENTS

(P.F. Hua, J. Barreto, D.G. Sarantites, L.G. Sobotka [WU])

In the past year we designed and constructed an inexpensive channel enhancing detector with absolutely minimal mass. The device was used in two experiments, one at HHIRF and one at LBL. The device is described in detail in a NIM paper, a reprint of which is given in Appendix 6.5.

3.4 THE NUCLEAR CHEMISTRY COMPUTER FACILITY: HARDWARE

At present we have a local cluster of three 3100 Vax Stations (two 3100 model 76, and one model 30). Recently we added another Vax Station model AXP 400 based on the DEC alpha chip. We have installed a fast 1.2 Gb system disk and a 2.4 Gb data disk on the AXP work station.

There are five 2.3-Gbyte Exabyte helical tape 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 ink jet plotter and a QMS-810 postscript laser printer.

In addition to the new disks on the AXP work station, the massive storage capacity of the system includes 3.8 Gbytes on 5 SCSI disk drives.

In order to run commercial graphics packages for publications we acquired an IBM PC compatible (Gateway 2000 - 486 computer). This system was added to the ethernet local cluster as a work station. A second IBM PC/486 serves also as a data acquisition computer.

We can either use this in a pulse-height analyzer mode or as a multidimensional CAMAC based system.

3.5 ACQUISITION AND ANALYSIS SOFTWARE

For in house data acquisition for testing purposes we utilize an IBM PC/486 computer that can serve as a pulse height analyzer or as a multidimensional CAMAC based acquisition system. The following packages serve this purpose.

CAMDA :

This is a modified version of a GSI acquisition program that allows easy 1- or 2-dimensional data acquisition via any of the CAMAC modules that we presently own.

MAESTRO:

This is the ORTEC data acquisition and analysis program that runs in the MS Windows environment.

SNAP - A 1- and 2-dimensional Display and Analysis Program:

Last 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. This program was written by K. Myers (supported by this grant). At present we are converting and expanding this package to run on the AXP work station.

LZW - A new data compression package:

Recently we completed a new data compression package, that permits us to minimize the disk space required for storing large arrays of histogrammed data and accelerate histogram storage and retrieval from disk.

This package is most valuable in two aspects. Firstly, with the new high resolution arrays such as the Miniwall, several hundreds of 2048×2048 histograms need to be generated and stored for each experiment. Secondly, with the increased capability of the multi-Ge arrays such as Eurogam or Gammasphere multidimensional histograms with $(2048)^n$ or $(4096)^n$ where $n = 3, 4$ or 5 are forthcoming.

This package can be made to allow storage of such a histogram in 2-Gbyte disks currently available. Details of the performance of this package will be published in a NIM paper.

The LZW compression package has several advantages over the old package. Our new format compresses all forms of data, 1-D and 2-D spectra, XY files, and masks. It uses the same data identification fields as the old package, so no user programs need to be changed.

The old package removed zero data points from 2-D data only, while the new package compresses all data, zero and non-zero alike, using the Lempel-Ziv-Welch algorithm. This algorithm uses a simple method of recognizing patterns of symbols which recur in the data, and reducing the patterns to numbered symbols of varying length. The symbols start out at 9 bits, and can expand up to 16 bits, giving 32768 different symbols. These varying length strings are then packed into 8-bit bytes for storage. The old package kept the index of spectra at the end of the data, which caused the index to be destroyed whenever a spectrum was added. The updated index was then rewritten after the new spectrum was completely written to the file. This meant that the index did not exist during the writing of a new spectrum, so that if the program, computer, etc. failed to complete writing the spectrum, the entire file's contents were rendered useless. The LZW package places the index in a reserved space at the beginning of the file, and it is never in an inconsistent state. The new package achieves a substantial reduction in disk space, so that most files will be between 40-60% of their former size. The old package made seven passes through the data when compressing or expanding it, including reserving a big chunk of virtual memory to compress or expand into. If the spectrum does not fit in virtual memory, then the computer needed to page the spectrum in from disk seven times, causing extreme overhead. This has been a severe problem. The LZW package makes precisely one pass through the data, and reserves no intermediate memory for the compression/decompression, thereby greatly reducing paging activity. The sum of all channels was previously computed every time the data were read (taking up one pass through the data), we now store the sum in the index.

The LZW package has been successfully tested and its implementation has begun for some time. It is at present the only option of data disk storage in the WU nuclear chemistry group. An option is provided to allow storage of multidimensional arrays under predetermined indexed segmentation that will allow easy retrieval of subspaces for the purpose of creating gated or total projections from the matrices.

This package was written by Jon Elson under close consultation with the P.I.

DAMM - The ORNL 2-D display and analysis package:

We have acquired the ORNL graphics package DAMM and adopted it to our computer system. It has a number of desirable features that allow convenient gating of a 2-dimensional matrix. Software were written to permit us to write the matrices in the HHIRF format for use with DAMM.

Motif Window System:

Recently we converted all work stations to the widely accepted standard windowing system Motif. A new Tek 4010 emulation program has been installed under the Motif environment.

TEX, LATEX, REVTEX and Previewer:

Another acquisition is the previewer for the typesetting packages TEX, and LATEX, and REVTEX that runs on the work stations. The present document has been typeset on a PC/486 with Scientific Word , which is a WYSIWYG program that makes writing TeX or

LaTeX documents extremely easy.

IBM PC software packages:

1. AXUM: A very versatile graphics package that includes multi-curve plotting, contour surface plots, etc.
2. MATHEMATICA: A symbolic math package with powerful analytical and graphic capabilities.
3. MS WORD 2.0 and Mathtype for Windows.
4. EXCEL for Windows.
5. QUATTRO PRO for Windows.

Chapter 4

Personnel

4.1 WASHINGTON UNIVERSITY PERSONNEL

Table 4.1 summarizes the manpower effort by our group for the past three years.

Table 4.1: Personnel Effort for the past three years

Person	Position	Effort During Last Year (months)	Effort During Last 3 Years (months)
D.G. Sarantites	P.I.	9	27
N.G. Nicolis	Research Associate	12	36
J.L. Barreto	Visiting Professor	10	27
R.J. Charity	Research Professor	-	3
V. Abenate	Graduate Student	-	12
P.-F. Hua	Graduate Student	12	15
A. Kirov	Graduate Student	10	21
A. Kirov	Research Associate	2	2
D. W. Stracener	Graduate Student	9	33
L. Gallamore	Graduate Student	4	5
L.L. Wittmer	Undergraduate	-	3
J.E. Sarantites	Technician	2	2
K. Myers	Software Specialist	-	11
J. Elson	Electronics Engineer	8	24
J.T. Hood	Design Engineer	3	9
	Total (person months)	83	232
	Total (person years)	6.9	19.3

D. W. Stracener received his PhD degree the past May from Washington University and he presently doing postdoctoral work under J.R. Beene at ORNL.

A. Kirov received his PhD degree the past July from the University of Sofia, Bulgaria. Kirov used the work done at Washington University as part of his thesis work.

Larry Gallamore received his Masters Degree from Washington University and now he is employed.

We have enjoyed extensive collaboration with Lee Sobotka and Bob Charity.

4.2 COLLABORATIONS

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

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

We have continued our collaboration with M. Thoennessen in his new capacity as Professor at MSU.

We have also continued our collaboration with Udo Schroeder and J. Töke of the University of Rochester, and with M. Riley at Florida State University.

Chapter 5

Publications

5.1 PAPERS PUBLISHED OR SUBMITTED (1991-93)

1. "Search for Entrance Channel Effects in the Decay of the ^{164}Yb Compound Nucleus at $E^* \approx 54$ MeV." J. L. Barreto, N.G. Nicolis, D.G. Sarantites, R.J. Charity, L.G. Sobotka, D.W. Stracener, D.C. Hensley, J.R. Beene, C. Baktash, M.L. Halbert, and M. Thoennessen, Phys. Rev. C (submitted July 1993).
2. "Formation and Decay of $^{164}\text{Yb}^*$ in Near and Below-Barrier Fusion Reactions ." N.G. Nicolis and D.G. Sarantites, Phys. Rev. C (submitted July 1993).
3. "Atomic Clocks in Nuclear Processes - Time scale of subbarrier alpha emission." L. Gallamore, D.G. Sarantites, J.L. Barreto, R.J. Charity, L.G. Sobotka, J.R. Beene, M.L. Halbert, and R.L. Varner, Phys. Rev. C, (submitted August 1993).
4. "'The Tube': a Simple 4π detector for enhancing channels in γ -ray spectroscopy experiments." P.-F. Hua, D.G. Sarantites, L.G. Sobotka, J.L. Barreto and A. Kirov, Nucl. Instr. Meth. A**330**, 121 (1993).
5. "Evidence for Long Formation Times of Near-Barrier Fusion Reactions" M. Thoennessen, J.R. Beene, F.E. Bertrand, C. Baktash, M.L. Halbert, D.J. Horen, D.G. Sarantites, W. Spang, and D.W. Stracener, Phys. Rev. Lett. **70**, 4055 (1993).
6. "Highly Deformed Band in ^{136}Pm and the Anomalous Dynamical Moment of Inertia Behavior in the $A \sim 135$ Superdeformed Region" M.A. Riley, T. Petters, J. Shick, D.E. Archer, J. Döring, J.W. Holcomb, G.D. Johns, T.D. Johnson, O.N. Tekyi-Mensah, S.L. Tabor, P.C. Womble, V.A. Wood, C. Baktash, M.L. Halbert, D.C. Hensley, I.Y. Lee, R.J. Charity, D.G. Sarantites, L.L. Wittmer, J. Simpson, Phys. Rev. C**47**, R443 (1993).
7. "The Mechanism for the Disassembly of Excited ^{16}O Projectiles into Four Alpha Particles." R.J. Charity, J. Barreto, L.G. Sobotka, D.G. Sarantites, D.W. Stracener, A. Chbihi, N.G. Nicolis, R. Auble, C. Baktash, J.R. Beene, F. Bertrand, M. Halbert, D.C. Hensley, D.J. Horen, C. Ludemann, M. Thoennessen, and R. Varner, Phys. Rev. C**46**, 1951 (1992).
8. "Charged Particles as Probes to Study Entrance Channel Effects in the Composite System ^{164}Yb ." J.L. Barreto, D.G. Sarantites, R.J. Charity, N.G. Nicolis, L.G. Sobotka, D.W. Stracener, D.C. Hensley, J.R. Beene,

- M. Halbert, and C. Baktash, in *Proceedings of the 8th Winter Workshop on Nuclear Dynamics, Jackson Hole, Wyoming, Jan. 18-25 (1992)*, p. 8-13. World Scientific, W. Bauer and B. Back Eds.
9. "Statistical Emission of Deuterons and Tritons from Highly Excited Compound Nuclei." N.G. Nicolis, D.G. Sarantites, L.G. Sobotka, and R.L. Charity, *Phys. Rev. C* **45**, 2393 (1992).
 10. "Large Deformation in $A \sim 170$ Nuclei at High Excitation Energies", M. Thoennessen, J.R. Beene, F.E. Bertrand, C. Baktash, M.L. Halbert, D.J. Horen, D.C. Hensley, D.G. Sarantites, D.W. Stracener, W. Spang, and R.L. Varner, *Phys. Lett. B* **282**, 288 (1992).
 11. "Quantitative Studies of Continuum Gamma-ray Correlations in ^{170}Hf " I.Y. Lee, C. Baktash, J.R. Beene, M.L. Halbert, D.C. Hensley, N.R. Johnson, F.K. McGowan, M.A. Riley, and D.G. Sarantites, *Phys. Rev. C* **46**, 597 (1992).
 12. "Binary Character of Highly Dissipative $^{209}\text{Bi} + ^{136}\text{Xe}$ Collisions at $E/A=28.2$ MeV" - B. Lott, S.P. Baldwin, B.M. Szabo, B.M. Quednau, W.U. Schröder, J. Töke, L.G. Sobotka, J. Barreto, R. Charity, L. Gallamore, D.G. Sarantites, D.W. Stracener, and R.T. de Souza, *Phys. Rev. Lett.* , **68**, 3141 (1992).
 13. "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, 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, J.R. Beene, M.L. Halbert, and M. Thoennessen, *Phys. Rev. C* **44**, R2257 (1991).
 14. "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).
 15. "Determination of the Nuclear Level Density at High Excitation Energy" 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**, 666 (1991).
 16. "Shape Coexistence and Disappearance of Pairing Correlations in ^{82}Sr ." C. Baktash, G. Garcia-Bermudez, D.G. Sarantites, W. Nazarewicz, V. Abenante, J.R. Beene, H.C. Griffin, M.L. Halbert, D.C. Hensley, N.R. Johnson, I.Y. Lee, F.K. McGowan, M.A. Riley, D.W. Stracener, T.M. Semkow, and A. Virtanen, *Phys. Lett. B* **255**, 174 (1991).

5.2 INVITED PRESENTATIONS IN MEETINGS (1991-93)

1. "Structure Dependent Effects on Proton Energy Spectra by 'Total Spectroscopy'" D.G. Sarantites American Chemical Society Symposium in Honor of R.M. Diamond, Washington DC, April 1993.

2. "Entrance Channel Effects in Low Energy Fusion Reactions", Invited Talk presented at the ACS Symposium on Nuclear Shapes, Washington D.C. Aug. 23-28 (1992) by D.G. Sarantites, work done with J. Barreto, R.J. Charity, N.G. Nicolis, L.G. Sobotka, D.W. Stracener, J.R. Beene, M.L. Halbert, D.C. Hensley and C. Baktash.
3. "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).
4. "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).

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