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Abstract

This report presents a summary of research projects in the area of low energy nuclear reactions and structure, carried out between March 1, 2006 and October 31, 2009 which were supported by U.S. DOE grant number DE-FG52-06NA26187/A000.

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I Introduction

We describe here research into low-energy nuclear reactions and structure. The statistical properties of nuclei have been studied by measuring level densities and also calculating them theoretically. Our approach of measuring level densities via evaporation spectra is able to reach a very wide range of nuclei by using heavy ion beams (we expect to develop experiments using radioactive beams in the near future).

Another focus of the program has been on γ -ray strength functions. These clearly impact nuclear reactions, but they are much less understood than corresponding transmission coefficients for nucleons. We have begun investigations of a new approach, using γ - γ coincidences following radiative capture.

Finally, we have undertaken several measurements of cross sections involving light nuclei which are important in various applications. The ${}^9\text{Be}(\alpha, n)$ and $\text{B}(d, n)$ reactions have been measured at Ohio University, while neutron-induced reactions have been measured at Los Alamos (LANSCE).

II Research

II.A Study of gamma strength functions

We continued to study γ -strength functions below the particle separation threshold. This poorly studied energy region is responsible for γ -ray emission from nuclear reactions.

We use two experimental methods. The first one is based on the measurement of particle- γ -coincidences from $({}^3\text{He}, {}^3\text{He}' \gamma)$ and $({}^3\text{He}, \alpha \gamma)$ reactions [1]. We collaborate on these measurements with a group from Oslo University, and experiments are performed at the Cyclotron Laboratory of Oslo University.

For the past year we have been working on an analysis of data from the reaction ${}^{117}\text{Sn}({}^3\text{He}, {}^3\text{He}'){}^{117}\text{Sn}$. The Sn isotopes are interesting to study because recently, a resonance-like structure in the γ -strength function was observed in the ${}^{129-133}\text{Sn}$ and the ${}^{133,134}\text{Sb}$ isotopes using relativistic Coulomb excitation measurements in inverse kinematics [2, 3]. This E1-type pygmy resonance was located at γ -ray energies around 8 to 10 MeV, and was interpreted as excess neutrons oscillating against the core nucleons. The summed $B(E1) \uparrow$ strength of the pygmy resonance was found to be 3.2 and 1.9 e^2fm^2 for ${}^{130,132}\text{Sn}$, respectively, which correspond to $\approx 7\%$ and $\approx 4\%$ of the classical Thomas-Reiche-Kuhn (TRK) sum rule. As these measurements are restricted to excitation energies above the neutron separation energy, it is an open question whether additional strength may be found at lower energies.

The γ -strength function has been obtained for the ${}^{117}\text{Sn}$ nucleus by the Oslo method [1]. The experimental points have been compared to similar data points obtained from photoabsorption reactions and to the available models of γ -strength functions (see Figure II.1). We observe that the γ -strength function exhibits an abrupt change in slope at $E \approx 4.5$ MeV. It is clear from our analysis that extra strength is present below and above the neutron threshold in ${}^{117}\text{Sn}$. Our data show the functional form of the pygmy resonance below 8 MeV from low to high γ -ray energies for the first time. In addition, this resonance has not been experimentally measured in a stable, odd-A tin isotope before, and this has now been successfully done in ${}^{117}\text{Sn}$. This result has been published in

Physical Review Letters [4].

The other method which we are developing at the Edwards Accelerator Laboratory consists of measuring two-step γ -cascades populating low-lying levels of a product nucleus after proton capture reactions. Before, this method has only been used in thermal neutron capture experiments [5, 6]. One of the main difficulties of studying γ -transitions following the thermal neutron capture is that these γ -transitions undergo big Porter-Thomas fluctuations which introduce considerable uncertainties in a γ -ray spectrum and complicate its analysis. Using a neutron capture averaged over resonances would be a big advantage, however no such experiments have yet been done because of the small reaction cross section in the resonance region that requires a high efficiency spectrometer with a good energy resolution. Another drawback of this method is that the level density of a product nucleus has to be assumed or measured from an independent experiment.

At the Edwards Accelerator Laboratory we have measured cascade γ -transitions from the proton capture reaction on ^{59}Co . Protons with energies near or below the particle emission threshold can excite many resonances of a compound nucleus. The cross section of a low-energy proton capture is very small compared to neutron capture reactions, however the intensity of the available proton beam is much higher, and that makes such a type of experiments feasible. We used a beam of 1.85 MeV protons produced using the tandem accelerator of the Edwards Accelerator Laboratory at Ohio University. The reaction $^{59}\text{Co}(p, 2\gamma)^{60}\text{Ni}$ has been studied. The main motivation of this choice is that the level density of ^{60}Ni has been already measured by us from neutron evaporation spectra of $^{59}\text{Co}(d,n)$ and $^{58}\text{Fe}(^3\text{He},n)$ reactions [7]. We used a $1\mu\text{m}$ thick ^{nat}Co target. The estimated number of compound nuclear resonances excited in this reaction is about 70. Two Ge detectors have been used in coincidence to register cascade γ -transitions. The single γ -transitions have been recorded as well. The two-step γ -cascades populating the first excited 2^+ state of ^{60}Ni have been selected by gating on the corresponding sum peak ($E_{\gamma_1} + E_{\gamma_2}$) in the sum coincidence spectrum (see Refs. [8, 5] and references therein for details of the method). The spectrum of two-step γ -cascades populating the 2^+ level of the ^{60}Ni has been normalized to the intensity of the 1332 keV $2^+ \rightarrow 0^+$ single γ -transition measured from the same experiment. The shape and absolute scale of this spectrum is determined by both level density and γ -strength functions of ^{60}Ni . However, because the level density of ^{60}Ni has been obtained from the independent experiment [7], the γ -strength functions can be studied. We developed the simulation technique to extract both E1 and M1 γ -strength functions from the cascade spectrum (the paper has been accepted by Phys. Rev. C). It is shown that the low energy increase of the summed E1 + M1 strength function debated for the last few years most likely belongs to the M1

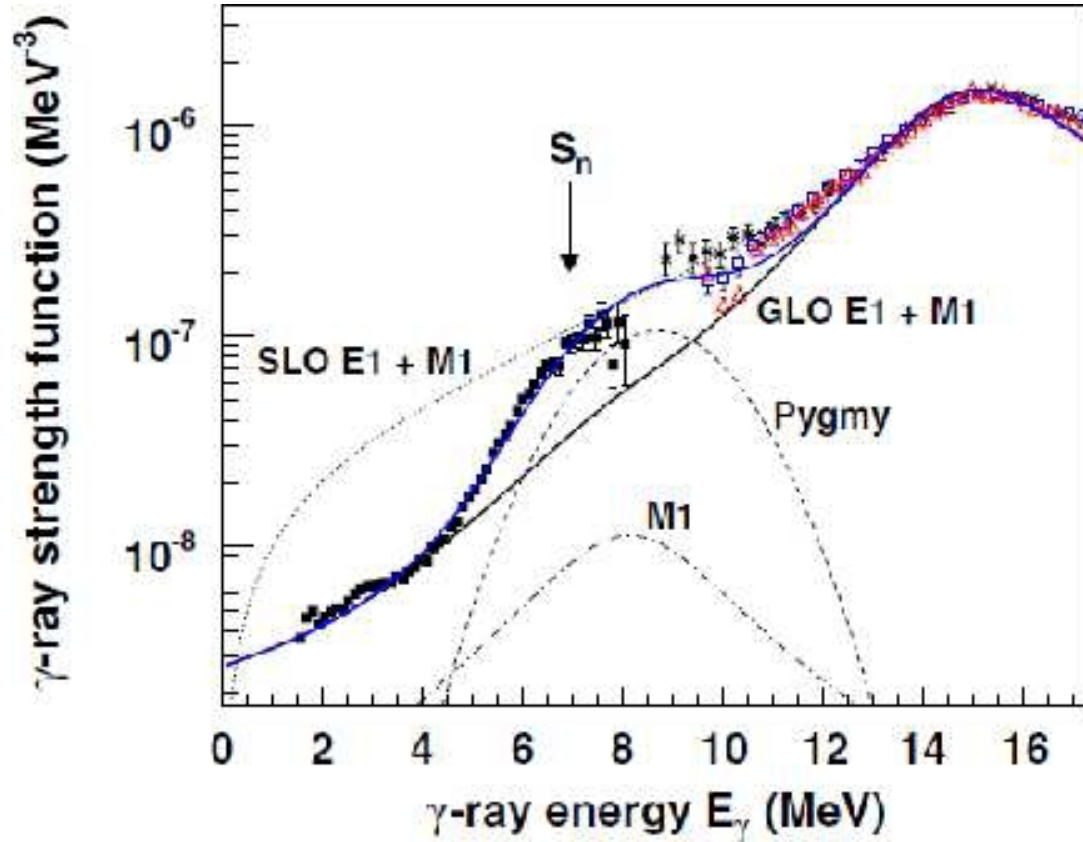


Figure II.1: Radiative strength function of ^{117}Sn from our experiment (black squares), and from (γ, x) photonuclear reactions (red open triangles, stars, and blue open squares). The sum of the Generalized Lorentzian (GLO) E1 strength and the M1 spin-flip resonance is shown as a solid line. The GLO E1 strength, the M1 spin-flip resonance (dashed-dotted line), and a Gaussian parametrization of the pygmy resonance (dashed line) are added to get a best fit (thick, blue solid line) to the data. The sum of the Standard Lorentzian (SLO) E1 strength and the M1 strength is shown for comparison (dotted line). For more detail information see our publication [4].

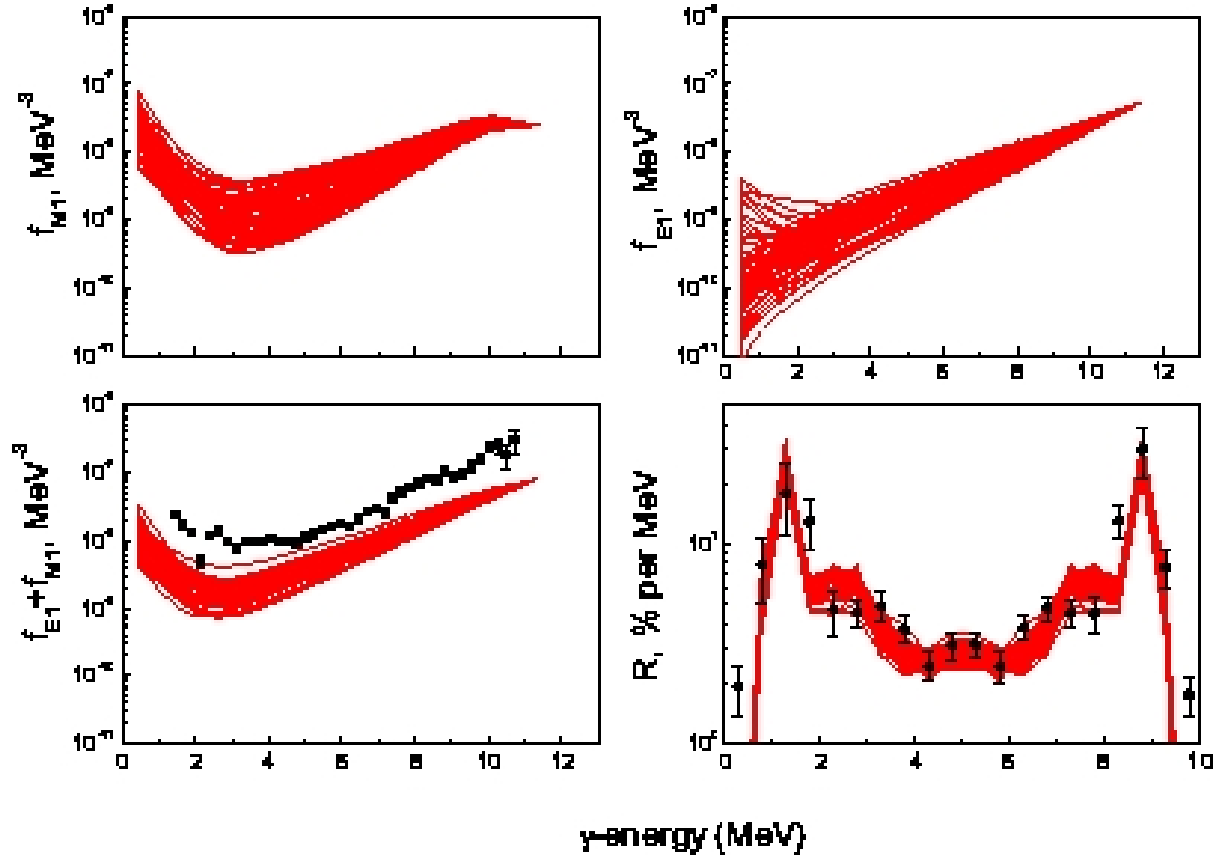


Figure II.2: The result of simulation of the two-step cascade spectrum populating 2^+ level of ^{60}Ni . Lines (red in color) are output functions and corresponding TSC spectra resulted from simulation procedure. R is the ratio of TSC intensity and the intensity of the ground state $2^+ \rightarrow 0^+$ transition in the ^{60}Ni . The absolute normalization of strength functions is arbitrary. Black points on the left bottom panel are data from the Oslo experiment [9].

strength function (II.2). Thus it is shown that the method works and is able to produce new experimental information. We propose to develop this method further to study other nuclei in a wide mass range.

II.B Calculation of Level Densities Off of the Stability Line

Much of the research in the area of nuclear level densities has been based on the Fermi gas model first introduced by Bethe [10]. This model is parametrized in terms of a level density parameter a and an energy shift parameter Δ . It is normally assumed that a is a function of A , the nucleon number, and does not depend separately on Z .

A recent analysis [11] of level densities for $20 \leq A \leq 110$ found tentative evidence for a decrease in a for fixed A as Z was changed to either neutron- or proton-rich nuclei off of the valley of stability. The form

$$a = \alpha A \exp [\gamma(Z - Z_0)^2]$$

was proposed, where α and γ are fitting constants and Z_0 is the Z of the beta stable isobar of that A . γ was found to be negative. This form does decrease a with changes in Z for both $Z < Z_0$ and $Z > Z_0$.

A possible theoretical explanation could be that the level density is lower off the stability line because single-particle levels which have too wide a width should not be counted in applications where the level density is applied in compound nuclear reactions. As an extreme example, when the drip line is reached, the fact that the ground state is particle unbound would probably mean that excited states would have even wider widths. This would make the level density for capture essentially zero. This topic has been examined in some detail for nuclei on the stability line (where it cuts off the compound density at high energies) [12, 13] but has not been examined for nuclei off of the line of stability.

We have made calculations of the size of the effect using this model. Single particle energies were deduced from a program which solved the Schrödinger equation for a Woods Saxon potential well. For each level a width was also inferred (zero in the case of bound

states). A code was then written which allowed the calculation of level densities with a decay width associated with each level. The magnitude of the total level density predicted was in reasonably good agreement with the Fermi gas model for nuclei on the stability line. When a cutoff was imposed to remove levels wider than 200 keV, the effects were negligible for $U < 50$ MeV. The loss of levels became obvious only for $U \gtrsim 150$ MeV and $A \sim 50$. The corresponding point was about 250 MeV for $A \sim 100$. As Z was lowered below Z_0 or increased above Z_0 , the threshold for observing these effects dropped substantially. As the drip line was approached, levels were lost in substantial numbers at energies as low as 5 to 10 MeV. In Figure II.3 the calculation is shown for ^{40}Ti . Note

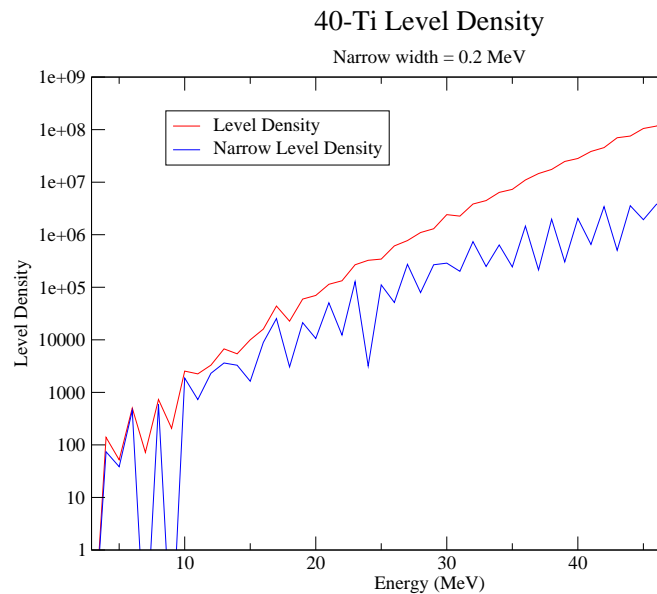


Figure II.3: Calculated level density of ^{40}Ti including all levels (upper curve) and only those with width less than 200 keV (lower curve).

that a lower level density parameter (reduced by 15%) would be appropriate in this case.

At this point calculations have been made for $40 \leq A \leq 100$. A total of 70 nuclei have been studied. A consistent loss of levels is found by imposing a width cutoff if $|Z - Z_0| \geq 2$. Further study of the spin cutoff factor and the parity ratio indicate less profound effects on these parameters.

One further step is contemplated. The present calculations have been made assuming the protons and neutrons are non-interacting. We have available a code which could calculate the level densities using a two-body Hamiltonian. This would include collective effects in the appropriate way. Unfortunately, the present code is written in such a way as to require an isospin conserving interaction. We are planning to modify the code to allow the inclusion of isospin mixing in the Hamiltonian during the coming months.

In summary, calculations of level densities have shown effects similar to those observed experimentally. They appear to justify concerns that level densities used in nucleosynthesis calculations need to be reduced significantly for nuclei near the drip line. The calculations suggest that a may drop by 15% to 20% as $|Z - Z_0|$ reaches 3 and will show larger changes for larger values of $|Z - Z_0|$.

II.C Observation Conditions for the Transition from Deformed to Spherical for Nuclei at High Energy

There is a dramatic difference between level densities for spherical and deformed nuclei. For a spherical nucleus, each level of spin J consists of $2J + 1$ degenerate states and no rotational bands are present. For a deformed nucleus, each level is 2-fold degenerate ($\pm K$) and there are rotational bands build on each level. The net effect of these distinctions is that the level density at a given energy is about a factor of σ^2 larger for a deformed nucleus. Here σ is the spin cutoff factor ($\langle J_z^2 \rangle^{1/2}$) and is about 9 for a nucleus of $A \sim 150$ at 20 MeV. Theoretical predictions suggest that deformed nuclei will undergo a transition to spherical at about 60-70 MeV. Such a drop in level density has not been seen, although some experiments have been set up to look for it.

This has not been understood, since a factor of 70 drop in the level density as the energy increases should be obvious, even if the transition occurs over 4 to 6 MeV.

A careful reexamination of these tests shows they are less definitive than first thought. The Hauser-Feshbach model actually predicts that the evaporation spectra will be proportional not to the level density but to the state density. This distinction is normally not very important, since for a spherical nucleus the level and state density are related by a factor of $\sqrt{2\pi\sigma}$, which varies as $U^{1/4}$ where U is the excitation energy.

The distinction between state and level densities is quite important in examining the transition between deformed and spherical nuclei, however. The ratio between state densities between the two cases is about σ . This is still substantial, but it is nearly an order of magnitude smaller than the σ^2 factor mentioned previously. If this factor changes over a range of 4 to 6 MeV, the effect is more like a plateau than a steep descent. It may also be that even though the transition is to an average deformation that is 0, prolate and oblate deformed states could still be present. These deformed states, even if they represent only 5% to 15% of the states, could remove some of the discrepancy as well. In summary, it appears the lack of an observed drop in level density with increasing energy does *not* contradict models which predict a transition to spherical nuclei at $60 \leq U \leq 80$ MeV. This analysis has been published[14].

II.D Level Density Study via Evaporation from ^{64}Cu

Two reactions that produce the ^{64}Cu compound nucleus have been studied at the Edwards Accelerator Laboratory, Athens, Ohio. They are: ^6Li on ^{58}Fe and ^7Li on ^{57}Fe reactions. In this study, we learned about the optical parameters for the entrance channels, the break up contributions of the projectile beams to the data and the level densities of ^{63}Ni and ^{60}Co . We used a number of level density models to test our data. Two models described the data from the two reactions satisfactorily; they are the Rohr model [15] which is an example of the Fermi gas (FG) model [10] and the Young parameterization of the Gilbert-Cameron (GC) model [16].

Figures II.4 and II.5 show the level densities of ^{63}Ni and ^{60}Co obtained from our experiments, their corresponding level densities obtained from known resolved levels, and how they compare with the Rohr and the Young models. Tables II.1 and II.2 show the level density parameters, energy shifts, and other parameters used in the models.

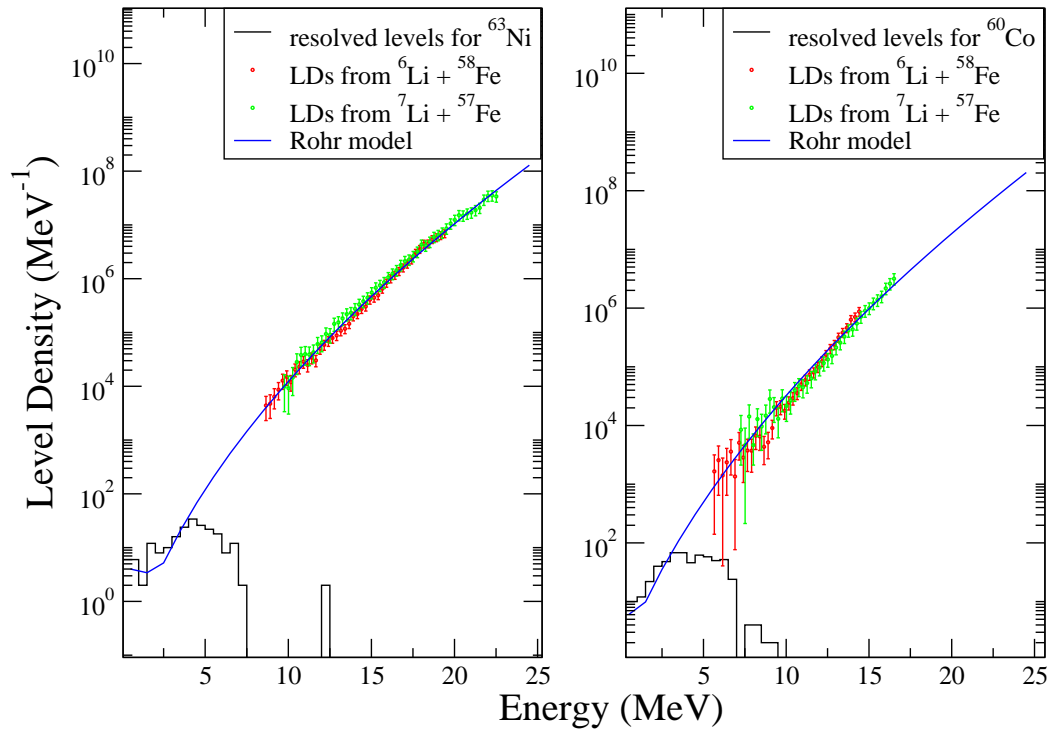


Figure II.4: Level densities of ^{63}Ni (left) and ^{60}Co (right) from proton and alpha-particle evaporation spectra, respectively. The histograms show the level densities from all documented resolved levels as seen in Ref. [17].

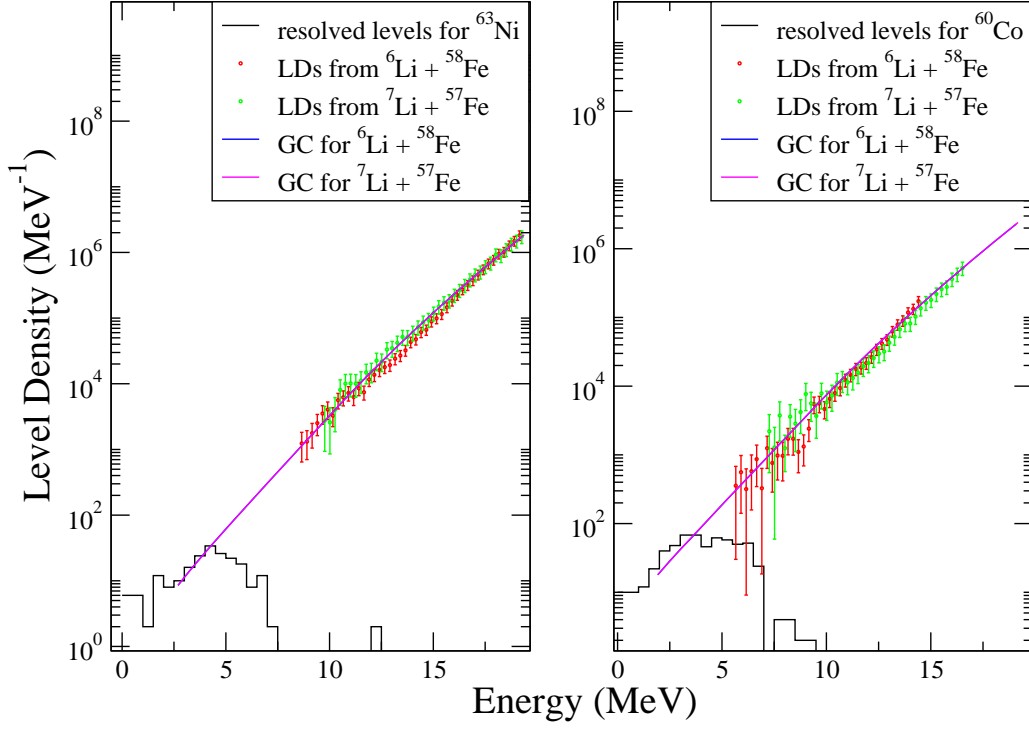


Figure II.5: Same as in Fig. II.4; the calculations are based on GC model.

Table II.1: The level density parameters: a , and energy shifts, δ , predicted by the Rohr formalism.

| Parameters | Rohr | |
|--------------------|------------------|------------------|
| | ^{60}Co | ^{63}Ni |
| a (MeV $^{-1}$) | 8.00 | 8.21 |
| δ (MeV) | 0.00 | 1.51 |

Table II.2: Parameters for the Young parameterization of GC model used in the study. T is the nuclear temperature, Δ is energy shift and U_x is the transition energy from Constant temperature (CT) to FG model.

| GC | | | | | |
|------------------|---------|----------------|-------------|--------------------------|----------------|
| | CT | | U_x (MeV) | FG | |
| | T (MeV) | Δ (MeV) | | a (MeV ⁻¹) | δ (MeV) |
| ⁶³ Ni | 1.2594 | -1.383 | 8.1858 | 7.9562 | 1.5119 |
| ⁶⁰ Co | 1.3501 | -3.411 | 9.1687 | 7.6312 | 0.0 |

II.E Studies of Level Densities Near $A = 80$

In order to better understand the level density of nuclei off of the stability line, three reactions were measured out at the Wright Nuclear Structure Laboratory at Yale University:

- $^{18}\text{O} + ^{64}\text{Ni} \rightarrow ^{82}\text{Kr}$ at 40 MeV and 50 MeV
- $^{24}\text{Mg} + ^{58}\text{Fe} \rightarrow ^{82}\text{Sr}$ at 72 MeV and 80 MeV
- $^{24}\text{Mg} + ^{58}\text{Ni} \rightarrow ^{82}\text{Zr}$ at 70 MeV and 80 MeV

⁸²Kr, ⁸²Sr and ⁸²Zr are 0, 2 and 4 protons away from the nuclear stability line. In the experiments, the gamma rays were measured using eight clover detectors. It is known that the ground states of even-even nuclei have $J^P = 0^+$. The first excited state normally has a spin and parity 2^+ , while higher excited states have higher spins and both parities. The idea of the experiment is most gamma-ray cascades will go through the first excited state. We are therefore most interested in measuring the first-excited state to ground state transitions. We compare the output of our experimental cross sections for $2^+ \rightarrow 0^+$ with the Hauser Feshbach (HF) model calculations. The HF code has transmission coefficients for incoming and outgoing channels and level density parameters of the residual nuclei as input parameters. We input several level density models into the code and compare the output with our experiments.

The level density parameters have been described by a number of systematics, the notable ones are Rohr[15] and Al-Quraishi[18]. Rohr systematics for the level density parameter a is given in equation (II.1) while Al-Quraishi suggested equation (II.2).

$$a = 0.0071A + V \quad (\text{II.1})$$

$$\begin{aligned} \text{where } V &= 1.64 & A \leq 38 \\ V &= 3.74 & 38 < A \leq 69 \\ V &= 6.78 & 69 < A \leq 94 \\ V &= 8.65 & 94 < A < 170 \\ a &= 0.108A + 2.4 & A \geq 170. \end{aligned}$$

$$a = \frac{\alpha A}{\exp[\gamma(Z - Z_0)^2]}. \quad (\text{II.2})$$

$$\begin{aligned} \text{where } \alpha &= 0.1068, \quad \gamma = 0.0389, \\ Z_0 &= \frac{0.5042A}{1 + 0.0073A^{\frac{2}{3}}}. \end{aligned}$$

One of the objectives of the study is to test the Rohr and Al-quraishi formalisms with our results and to obtain the best parameters.

So far, most of the analysis done is on the experiments which have ^{82}Sr and ^{82}Zr as compound nuclei because they are not on the stability line. We have identified some of the gamma ray energies that are of interest in our experiments and we've placed upper limits on the ones we are yet to fully confirm. The identification of the gamma rays is done in two stages:

1. Check the energy of the gamma ray under consideration based on the level scheme from literature to see if it has a peak in the expected position.

2. Place a gate on the peak and check for peaks corresponding to higher excited states. If there are no energy peaks associated with higher excited states, the presence of such residual a nucleus is not indicated; an upper limit will then be evaluated.

The tables below show a summary of the comparison of the calculations and experiments done so far. The analysis is still in progress and all results presented here are still preliminary:

| Decay Channel | $\alpha = 0.11,$ $\gamma = 0.0(\text{I})/\text{mbarns}$ | $\alpha = 0.11,$ $\gamma = 0.04(\text{II})/\text{mbarns}$ | Ratio: I/II | Experiment /mbarns |
|-----------------------------------|------------------------------------------------------------|--------------------------------------------------------------|----------------|-----------------------|
| $\alpha + {}^{78}\text{Kr}$ | 124.9 | 98.3 | 1.27 | 45.7 ± 2.5 |
| $\alpha + 2n + {}^{76}\text{Kr}$ | 85.9 | 17.3 | 4.98 | 15.0 ± 0.83 |
| $\alpha + 2p + {}^{76}\text{Se}$ | 10.9 | 38.7 | 0.282 | 0.114 (UL) |
| $2\alpha + {}^{74}\text{Se}$ | 6.19 | 11.57 | 0.535 | 15.0 ± 1.8 |
| $2p + {}^{80}\text{Kr}$ | 0.46 | 1.55 | 0.302 | 62.4 (UL) |
| $2\alpha + 2n + {}^{72}\text{Se}$ | 0.37 | 0.42 | 0.87 | 0.13 (UL) |
| $4n + {}^{78}\text{Sr}$ | 0.27 | not predicted | | 4.79 ± 0.23 |
| $2n + {}^{80}\text{Sr}$ | 0.22 | 0.02 | 12.8 | 3.09 ± 0.47 |
| $3\alpha + {}^{70}\text{Ge}$ | 0.197 | 0.623 | 0.317 | 0.12 (UL) |
| $4p + {}^{78}\text{Se}$ | 0.0067 | 0.023 | 0.288 | 62.26 (UL) |

Table II.3: Comparison of data and calculations from ${}^{24}\text{Mg} + {}^{58}\text{Fe} \rightarrow {}^{82}\text{Sr}$ at 80 MeV. UL in the Table means “upper limit”.

II.E.1 Level densities of ${}^{60}\text{Ni}$, ${}^{60}\text{Co}$ and ${}^{57}\text{Fe}$

This year we focused on an analysis of experiments with 10 MeV ${}^3\text{He}$ and 7 MeV deuteron beams on ${}^{58}\text{Fe}$ and ${}^{59}\text{Co}$ nuclei, respectively. These reactions form the same compound nucleus ${}^{61}\text{Ni}$. The purpose was to investigate the possibility of getting pure evaporation spectra resulting from compound nuclear reactions. This can be done by comparing particle spectra from both reactions with HF calculations. Because of different reactions,

| Decay Channel | Rohr (I)/mbarns | Al-Quraishi (II)/mbarns | Ratio: I/II | Experiment /mbarns |
|-----------------------------------|-----------------|-------------------------|-------------|--------------------|
| $\alpha + {}^{78}\text{Kr}$ | 138.7 | 79.5 | 1.75 | 45.7 ± 2.5 |
| $\alpha + 2n + {}^{76}\text{Kr}$ | 83.6 | 18.7 | 4.47 | 14.9 ± 0.8 |
| $\alpha + 2p + {}^{76}\text{Se}$ | 7.39 | 33.3 | 0.222 | 0.114 (UL) |
| $2\alpha + {}^{74}\text{Se}$ | 4.91 | 13.7 | 0.358 | 15.0 ± 1.8 |
| $2\alpha + 2n + {}^{72}\text{Se}$ | 1.79 | 0.245 | 7.28 | 0.132 (UL) |
| $2p + {}^{80}\text{Kr}$ | 0.513 | 2.62 | 0.196 | 62.3 (UL) |
| $3\alpha + {}^{70}\text{Ge}$ | 0.039 | 0.498 | 0.783 | 0.120 (UL) |
| $2n + {}^{80}\text{Sr}$ | 0.389 | 0.033 | 11.7 | 3.09 ± 0.47 |
| $4n + {}^{78}\text{Sr}$ | 0.051 | not predicted | | 4.79 ± 0.23 |
| $4p + {}^{78}\text{Se}$ | 0.022 | 0.021 | 1.00 | 62.3 (UL) |

Table II.4: Same as Table II.3.

the contribution of the direct reaction mechanism to the compound nuclear reaction will likely be different. If particle spectra from both reactions can be described with the same set of level density parameters, we can consider the particle spectra to be purely evaporated, from which level density parameters can be determined for corresponding residual nuclei.

The experimental setups included the beam swinger facility with the 30 m tunnel designed to measure angles and energy of neutrons and the charged particle spectrometer designated for measurements of charged particle spectra from nuclear reactions. Both of them are located at Edwards Accelerator Laboratory.

Cross sections of neutron, proton and α -particle evaporation spectra, and level densities of corresponding residual nuclei ${}^{60}\text{Ni}$, ${}^{60}\text{Co}$ and ${}^{57}\text{Fe}$ are presented in Figures II.6 and II.7. Level densities have been compared to the level density systematics widely used in calculations. The conclusion is that none of the systematics fit the experimental level densities simultaneously for all residual nuclei, although some of them fit the level density of one of the nuclei well. New Fermi-gas level density parameters have been obtained by fitting experimental points (see Table II.E.1). The spin cutoff parameters have been extracted from a comparison of the total level density from the measurements with the

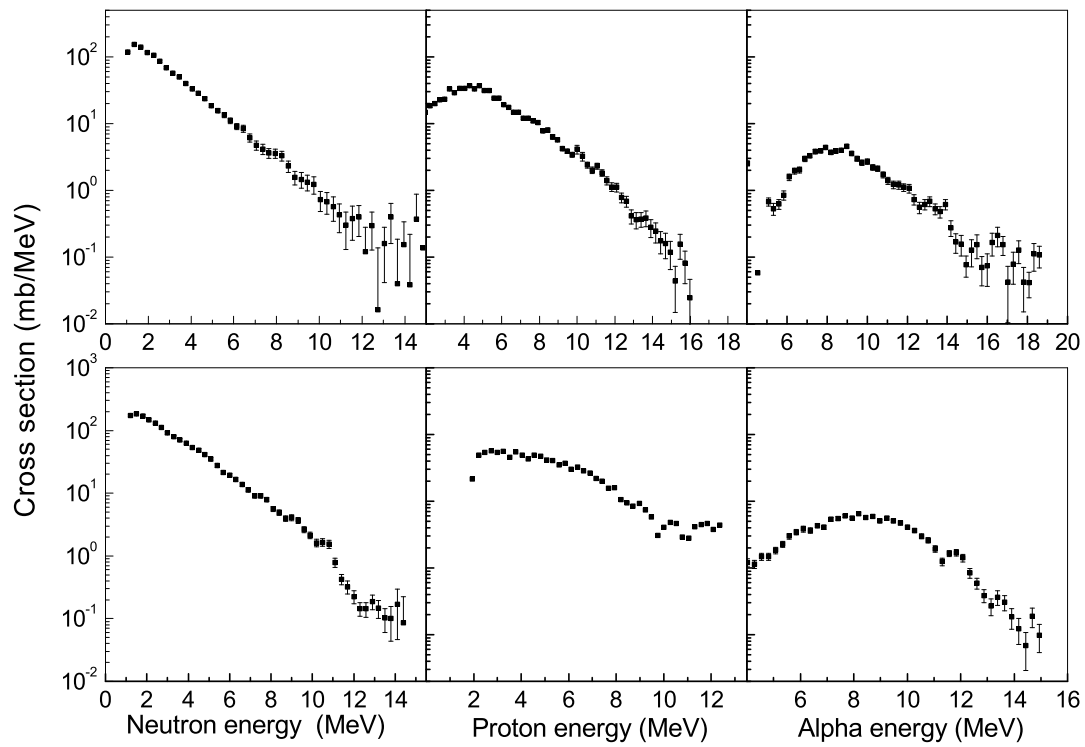


Figure II.6: Cross sections of particles from ${}^3\text{He} + {}^{58}\text{Fe}$ (upper panel) and $\text{d} + {}^{59}\text{Co}$ (lower panel) reactions.

| Decay Channel | $\alpha = 0.11,$ $\gamma = 0.0(\text{I})/\text{mbarns}$ | $\alpha = 0.11,$ $\gamma = 0.04(\text{II})/\text{mbarns}$ | Ratio: I/II | Experiment /mbarns |
|------------------------------------------|------------------------------------------------------------|--------------------------------------------------------------|----------------|-----------------------|
| $\alpha + 2\text{p} + {}^{76}\text{Kr}$ | 160.3 | 187.0 | 0.858 | 40.6 ± 1.8 |
| $4\text{p} + {}^{78}\text{Kr}$ | 10.1 | 19.4 | 0.518 | 10.997 ± 0.571 |
| $2\alpha + {}^{74}\text{Kr}$ | 6.60 | 5.33 | 1.24 | 11.6 (UL) |
| $2\text{p} + {}^{80}\text{Sr}$ | 4.02 | 10.98 | 0.366 | 23.89 ± 4.04 |
| $\alpha + {}^{78}\text{Sr}$ | 3.05 | 0.201 | 15.2 | 1.99 ± 0.25 |
| $\alpha + 2\text{n} + {}^{76}\text{Sr}$ | 0.328 | 0.047 | 7.01 | 0.066 (UL) |
| $3\alpha + {}^{70}\text{Se}$ | 0.213 | 0.063 | 3.37 | 16.9 ± 0.9 |
| $2\alpha + 2\text{p} + {}^{72}\text{Se}$ | 0.209 | 0.169 | 1.24 | 19.9 (UL) |
| $2\text{n} + {}^{80}\text{Zr}$ | 0.023 | 0.013 | 1.74 | 0.071 (UL) |
| $\gamma + {}^{82}\text{Zr}$ | 1.82×10^{-5} | 1.91×10^{-5} | 0.95 | 0.024 (UL) |

Table II.5: Comparison of data and calculation from ${}^{24}\text{Mg} + {}^{58}\text{Ni} \rightarrow {}^{82}\text{Zr}$ at 80 MeV. UL in the Table means “upper limit”

spin projected level density known from neutron resonance data (Table II.8).

More details about these experiments, analysis and results can be found in Ref.[7].

II.E.2 Level density of ${}^{44}\text{Sc}$

In order to develop the method further by understanding and eliminating the possible systematic uncertainties, the level density of ${}^{45}\text{Sc}$ has been obtained from two independent experiments by two independent methods. The first one is ${}^{45}\text{Sc}({}^3\text{He}, \alpha\gamma){}^{44}\text{Sc}$ with a 45 MeV ${}^3\text{He}$ beam from the Oslo University Cyclotron. The level density has been extracted from the α -particle coincidence matrix by the Oslo method. The second experiment consisted of the measurement of the α -particle evaporation spectrum from the ${}^{45}\text{Sc}({}^3\text{He}, \alpha){}^{44}\text{Sc}$ compound nuclear reaction with a beam of 11 MeV ${}^3\text{He}$ produced by the tandem accelerator of the Edwards Laboratory. Energy spectra and angular distributions have been measured with a charged particle spectrometer. The level density has

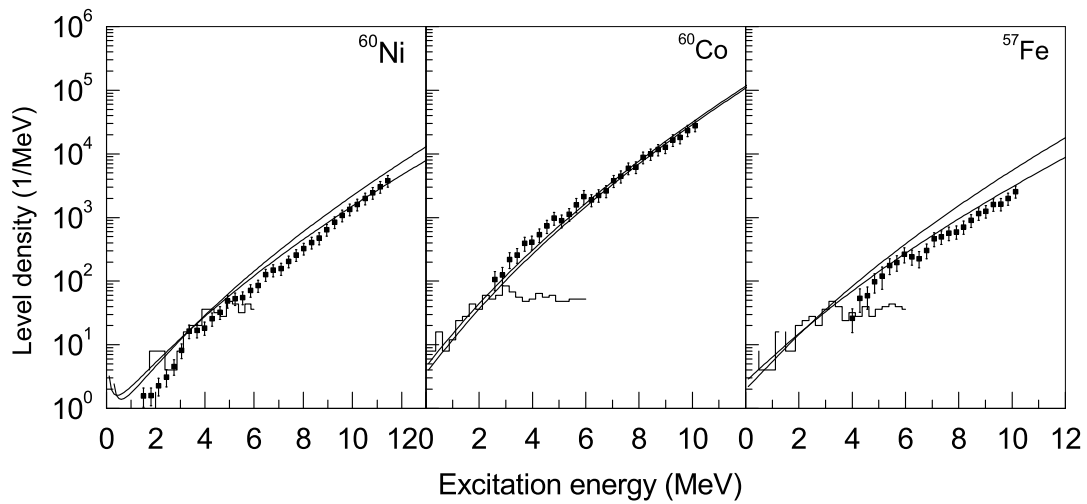


Figure II.7: Level densities of residual nuclei (points). Lines are Fermi-gas level density model calculated with parameters determined from the fitting model to discrete level density and neutron resonance spacing. Upper and lower curves correspond to different spin cutoff factors σ_1 and σ_2 according to that presented in the table II.E.1

| Decay Channel | Rohr (I)/mbarns | Al-Quraishi (II)/mbarns | Ratio: I/II | Experiment /mbarns |
|-----------------------------------|-----------------------|-------------------------|-------------|--------------------|
| $\alpha + 2p + {}^{76}\text{Kr}$ | 116.9 | 179.8 | 0.650 | 40.6 ± 1.8 |
| $4p + {}^{78}\text{Kr}$ | 14.8 | 11.4 | 1.30 | 11.0 ± 0.6 |
| $2p + {}^{80}\text{Sr}$ | 10.6 | 17.4 | 0.606 | 23.9 ± 4.04 |
| $2\alpha + {}^{74}\text{Kr}$ | 2.47 | 7.51 | 0.329 | 11.6 (UL) |
| $\alpha + {}^{78}\text{Sr}$ | 1.99 | 0.288 | 6.92 | 1.99 ± 0.25 |
| $3\alpha + {}^{70}\text{Se}$ | 0.400 | 0.234 | 1.71 | 16.9 ± 0.924 |
| $2\alpha + 2p + {}^{72}\text{Se}$ | 0.347 | 0.0412 | 8.42 | 19.9 (UL) |
| $\alpha + 2n + {}^{76}\text{Sr}$ | 0.007 | 0.026 | 0.270 | 0.066 (UL) |
| $2n + {}^{80}\text{Zr}$ | 0.002 | 0.021 | 0.099 | 0.071 (UL) |
| $\gamma + {}^{82}\text{Zr}$ | 1.52×10^{-5} | 1.85×10^{-5} | 0.821 | 0.024 (UL) |

Table II.6: Comparison of data and calculation from ${}^{24}\text{Mg} + {}^{58}\text{Ni} \rightarrow {}^{82}\text{Zr}$ at 80 MeV.

been extracted by the method described above. The figures II.8 and II.9 show angular distributions of outgoing α -particles and level densities from both experiments. The important result is that the angular distribution allows one to determine the energy range of outgoing α -particles which can be related to a compound nuclear reaction and used for level density determination. In this particular case the experiment shows that the angular distribution is forward peaked for all α -particle energies, indicating the presence of direct reaction contributions. However, at backward angles the angular distributions start to follow calculated curves, indicating the dominance of the compound reaction contribution. The high energy α -particles (from 16-18 MeV energy interval) do not agree with

| Nucleus | ${}^{60}\text{Ni}$ | ${}^{60}\text{Co}$ | ${}^{57}\text{Fe}$ | Spin cutoff formula |
|-------------|--------------------|--------------------|--------------------|-----------------------------------------------------|
| a, δ | 6.16;1.43 | 6.91;-1.89 | 5.92;-0.13 | $\sigma_1^2 = 0.0146A^{5/3}\sqrt{((E - \delta)/a)}$ |
| a, δ | 6.39;0.80 | 7.17;-2.6 | 6.14;-0.78 | $\sigma_2^2 = 0.089A^{2/3}a\sqrt{((E - \delta)/a)}$ |

Table II.7: Fermi-gas parameters obtained from experimental level densities with different spin cutoff parameters

| Nucleus | ^{60}Ni | ^{60}Co | ^{57}Fe |
|-------------------------|------------------|------------------|------------------|
| σ_s^{exp} | 3.3(8) | 3.6(15) | 2.80(30) |
| σ_p^{exp} | | 5.2(12) | 2.88(35) |
| σ_1^{cal} | 4.13 | 3.95 | 3.76 |
| σ_2^{cal} | 3.22 | 3.26 | 3.0 |

Table II.8: Spin cut off parameters obtained from s -wave σ_s^{exp} and p -wave σ_p^{exp} resonances with using the total level density from the experiment. The spin cutoff parameters, σ_1^{cal} and σ_2^{cal} have been calculated according to expressions from the Table II.E.1.

calculations even at backward angles. Therefore these α -particles have been excluded from our analysis.

The level density of ^{44}Sc obtained from both experiments agree very well. This indicates the reliability of both methods of level density determination.

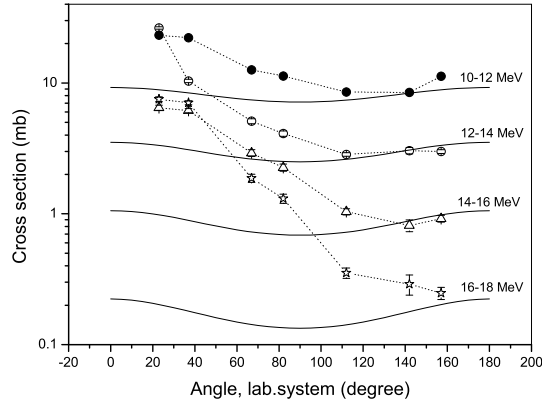


Figure II.8: Experimental and calculated angular distribution of α -particles at different energy intervals.

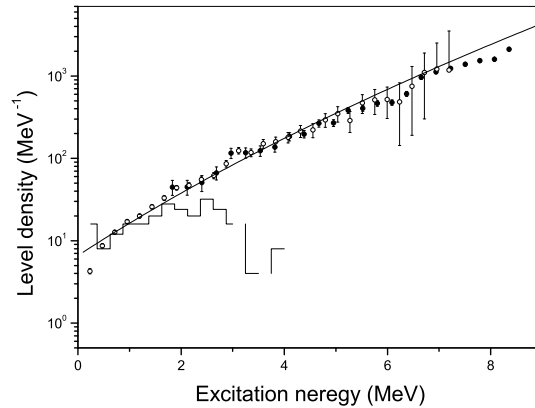


Figure II.9: Level densities of ^{44}Sc . The open points are data from Oslo experiment, black points are data obtained from α -particle evaporation spectra of $^{45}\text{Sc}(^3\text{He},\alpha)^{44}\text{Sc}$ reaction, histogram is the level density of discrete levels

II.F Study of the $^9\text{Be}(\alpha,n)$ Reaction

II.F.1 Nuclear Physics Applications

The $^9\text{Be}(\alpha,n)^{12}\text{C}$ reaction has many important applications in nuclear physics, mainly due to its very large cross section ($\sim \text{mb}$). This reaction can be used as a neutron source using both radioactive α sources and α beams produced by accelerators. The inverse reaction $^{12}\text{C}(n,\alpha)^9\text{Be}$ is important for understanding how fast neutrons interact with carbon such as in reactors or in scintillation-based detectors. Despite the wide range of applications where this reaction is important, there are significant uncertainties, such as in the differential cross section for angles away from 0° . We are currently taking a series of measurements to improve our knowledge of the reaction for $E_\alpha \leq 11$ MeV. These data will also provide information about the level structure of ^{13}C . There are numerous resonances present in the data. We will determine spins and parities of these structures.

II.F.2 Astrophysical Applications

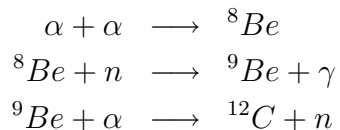
This reaction also plays a significant role in astrophysics. Elements heavier than iron are formed through neutron capture processes, such as the r -process or s -process. However, nuclei with mass number $A = 8$ are unstable. To get the heavier elements, one needs to get over the mass gap at $A = 8$ [19]. The reaction $\alpha(\alpha n, \gamma)^9\text{Be}$ followed by the reaction $^9\text{Be}(\alpha, n)^{12}\text{C}$ is one of the possibilities to bridge this gap.

A “normal” size star (one that is about the size of our sun, $\sim 1M_\odot$) is one that spends its entire life burning hydrogen into helium. Once the hydrogen supply in the core is exhausted, the star becomes a red giant (with temperatures $T \approx 10^8$ K). In these red giant environments, the star undergoes helium burning through the “triple alpha” (3α) process. The 3α -process is a series of reactions that gives out carbon-12, ^{12}C , as its final product. The series is as follows:



As mentioned before, elements with $A = 8$ are unstable and ^8Be is no exception (lifetime $\approx 10^{-17}$ seconds.) It is formed at a rate, though, where enough is present for the 3α process to occur.

Much larger stars ($M \geq 3M_\odot$) end their lives, not as a red giant, but as a Type-II supernova. The environment of a supernova is much different than that of a red giant. It is at a much higher temperature ($T \geq 10^9$ K), and there is a neutrino driven wind that breaks apart elements in the outer ejecta, leaving a lot of free neutrons at a temperature of $T \approx 4 \times 10^9$ K. In this environment, a different form of the 3α -process takes place. The new series of reactions is:



The $^4\text{He}(\alpha n, \gamma)$ reaction can be thought of as a “neutron-catalyzed” [20] version of the 3α -process since the expelled neutron can interact with more ^8Be to form more

${}^9\text{Be}$ and then ${}^9\text{Be}(\alpha, n){}^{12}\text{C}$ occurs with the neutron going off to interact again, and so on. In environments typical of supernovae, the alternate 3α -process occurs at a rate 400 times faster than the 3α -process [20]. But, around 90 percent of the time, the ${}^9\text{Be}$ is converted back to ${}^4\text{He}$ through the reaction ${}^9\text{Be}(\gamma, \alpha n){}^4\text{He}$. Thus, the overall amplification over the 3α -process is around 40 for temperatures $T \approx 4 \times 10^9$ K, and density $\rho \approx 5 \times 10^4 \text{g/cm}^3$ [21]. Therefore, the ${}^9\text{Be}(\alpha, n){}^{12}\text{C}$ reaction is thought to be a more efficient way of producing ${}^{12}\text{C}$. The ${}^{12}\text{C}$ is then a seed nucleus for the production of heavier elements through the fusion with other nucleons.

II.F.3 Experimental Details

Energy conservation tells us that when the ${}^9\text{Be}(\alpha, n){}^{12}\text{C}$ reaction takes place, the ${}^{12}\text{C}$ can be in any state allowed energetically. By measuring the energy of the neutrons released, we can deduce which energy states of ${}^{12}\text{C}$ were produced. In this experiment, the neutrons associated with ${}^{12}\text{C}$ in the ground state, and the first two excited states will need to be considered (see Fig. II.10). The ground state neutrons will be the most energetic, followed by the neutrons in the first excited state, etc. The other states are not energetically allowed for low α energies, and are of no astrophysical interest.

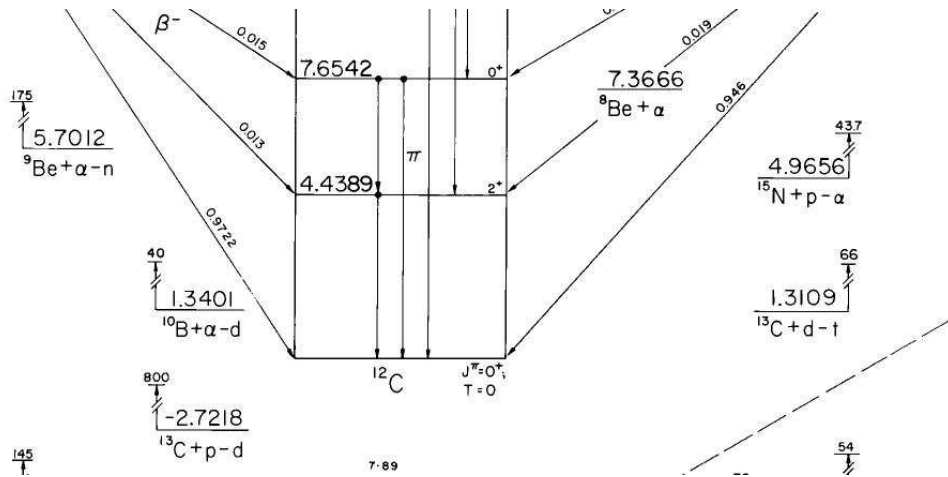


Figure II.10: Energy level diagram for ${}^{12}\text{C}$. The ground state and the first two excited states are the ones being considered.

Our experimental approach was to hit a ${}^9\text{Be}$ target with an α beam of various energies

and detect the neutrons produced with liquid scintillators located 30 m down a tunnel. When the α -particle hits the target, there will be some energy loss. Therefore it is necessary to use targets of different thicknesses. The target thicknesses were determined using the stopping powers of ${}^9\text{Be}$ described in Ref. [22]. We see peaks in the data spectrum corresponding to neutron energies. Theoretically, these peaks should be very narrow, like delta peaks. However, since there is energy loss in the target, the peaks will be spread out. The goal here is to choose a target thickness which has an energy loss which is almost as large as the distance between the peaks, but not so broad that the peaks overlap.

II.F.4 Present Status

Four runs have been performed thus far at the 4.5-MV tandem accelerator at Ohio University: one at $E_\alpha = 2$ MeV using a 50- μm target, one at $E_\alpha = 4.5$ MeV using a 15- μm target, one at $E_\alpha = 7$ MeV using a 25- μm target, and runs at $E_\alpha = 11$ MeV using a 50- μm target. Each run was performed at the following laboratory angles: 0° , 15° , 35° , 40° , 60° , 88° , 110° , 120° , 130° , and 145° . In addition, we have measured a 0° excitation function from 2 up to 11 MeV, in order to check the relative normalization of the angular distribution measurements. The neutron detectors give back a time-of-flight spectrum, e.g. we are able to measure how long it takes for the neutron to reach the detector. Knowing the distance the neutron travels (30 m), we can determine the energy of the neutron. A sample neutron energy spectrum has been included (see Fig. II.11). Detector efficiency was measured using the ${}^{27}\text{Al}(d, n){}^{28}\text{Si}$ reaction which has been carefully measured [23].

Using the kinematics described in Ref. [24], the neutron energy spectra were converted back to alpha particle energy spectra (see Fig. II.12) for each neutron group.

The alpha particle spectra were then converted to differential cross section spectra using various parameters such as the target thickness and the stopping power of ${}^9\text{Be}$ described in Ref. [22]. This project is the thesis project of Zach Heinen. The data taking is complete and the data analysis is nearly completed.

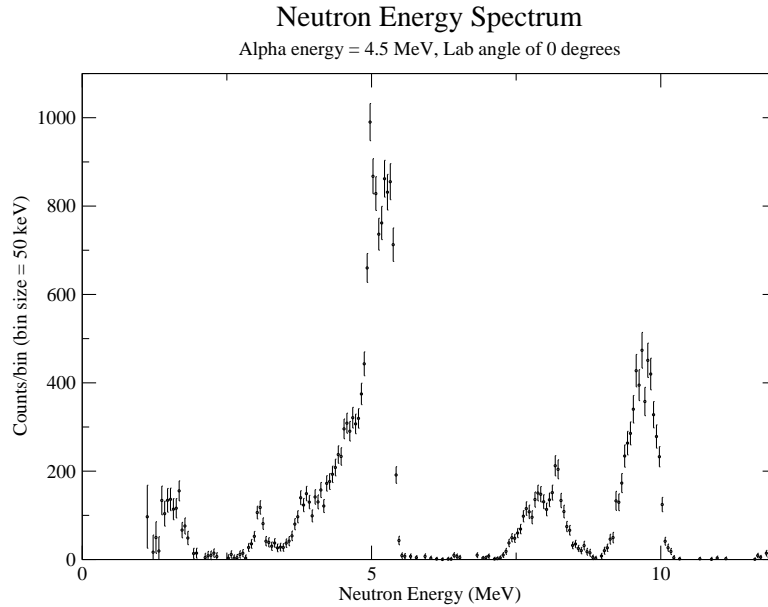


Figure II.11: Efficiency corrected neutron energy spectrum for $E_\alpha = 4.5$ MeV at $\theta = 0^\circ$.

II.G B(d,n) Spectra

II.G.1 Fission Chamber Work

Calibration of neutron detector efficiencies remains an important challenge. Calculation of the efficiency is possible but for good results, detailed information on many cross sections is necessary. Previous studies of the efficiency of hydrogenous scintillators indicate that in addition to the n-p cross sections, elastic and inelastic cross sections as well as the (n, α) cross section on carbon will be necessary. Another technique is to use the D(d,n), T(p,n) or T(d,n) reactions for calibration. If solid targets are used, the determination of the deuterium or tritium concentration is a problem. Gas targets present a challenge in that beam heating can influence the target thickness.

There are substantial advantages to the use of a white source for calibrations. Choice of discrete energies for calibrations with a monoenergetic source could lead to missed structure in the efficiency. A stopping target has the advantage that a precise knowledge of the target thickness is unnecessary. A target which is 10-20% too thick will not produce

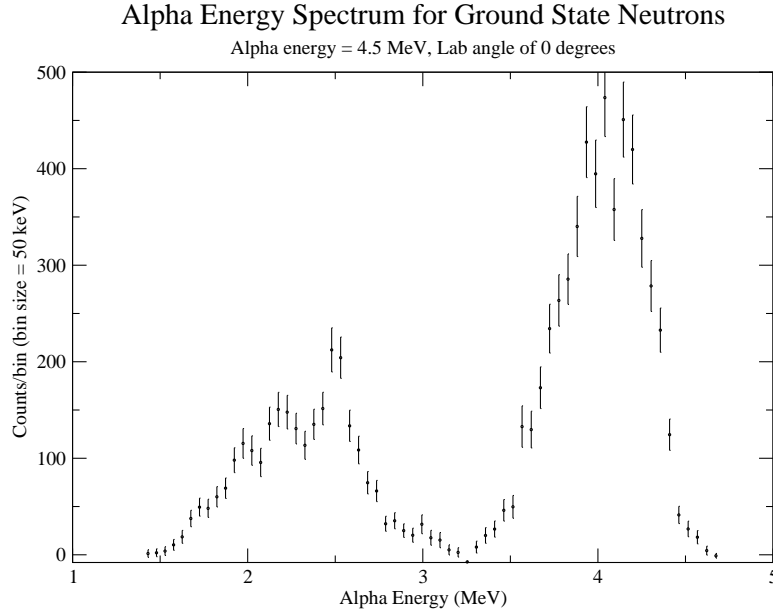


Figure II.12: Alpha particle spectrum corresponding to the ground state neutrons for $E_\alpha = 4.5$ MeV at $\theta = 0^\circ$.

extra neutrons, and one which is slightly too thin will not cut the yield, since the cross section for neutron production is cut off at low energies by the Coulomb barrier. Finally, stopping target spectra have less structure, making it possible to use the spectrum to calibrate detectors with different energy resolutions.

Some time ago, cross sections for the $^{27}\text{Al}(d,n)^{28}\text{Si}$ reaction were published[23]. These results were obtained with a stopping target at a bombarding energy of 7.44 MeV. In principle, the neutron spectrum covers the energy range from 250 keV to 14.9 MeV, but the statistical accuracy was poor for energies below 0.6 MeV or above 12.5 MeV. The measurements were made with a ^{235}U fission chamber. Such a chamber has low efficiency but has an efficiency which can be accurately calculated.

We have now completed a similar measurement for the $\text{B}(d,n)$ reaction at 7.5 MeV. This measurement was done for a stopping target of natural boron. The dominant isotope is ^{11}B and the Q value for the (d,n) reaction allows neutrons with energies as large as 20 MeV to be produced from 7.5 MeV deuterons. A further advantage over Al is that the total neutron production is about eight times larger. The sole disadvantage to B is that there is more structure in the spectrum than for Al. This is not ideal in that the

fission chamber measurements were made at a 3.7 m flight path, but calibrations will be done for detectors at various flight paths. If the energy resolution of the detector being calibrated does not match that of the calibration measurement, a smooth spectrum is obviously preferable.

The availability of “white source” calibration reactions allows much more reliable efficiency determination than was previously possible. Detailed variation of efficiency on energy scales as fine as 10 keV or less can be observed. We can also verify that the efficiency of ${}^6\text{Li}$ glass scintillators above $E_n = 2$ MeV is largely due to reactions other than ${}^6\text{Li}(n, \alpha)$.

We have completed a series of measurements on beryllium, boron and aluminum targets to allow more flexibility in neutron calibration. The measurements were all done using a deuteron beam from 5.0 to 7.5 MeV. Eight lithium glass detectors were refurbished by our summer students Andrew Di Lullo and Yuri Marmorstein. Six of the lithium glass detectors and a single NE213 detector were used in this measurement. The energy and angles used for each target is shown in Table II.9.

| Target | Deuteron Energies | Angle(s) |
|--------|-------------------|----------------|
| Al | 7.44,7.0,5.0 | 120 |
| Be | 7.50,7.0,5.0 | 60 |
| B | 7.50,7.0,5.0 | 60, 50, 40 ,30 |

Table II.9: Measurement energies and angles for standard thick targets.

These spectra were accumulated for high statistics to allow them to be related to the well measured B(d,n) 7.5 MeV 60 degree neutron production spectrum. We also used the Mesyttec neutron gamma discrimination module for the first time during this experiment. We found nearly as good separation between the neutrons and gamma with this method as with our older method which needed 11 modules for the same result. These data are being analyzed.

We have extended our analysis of the neutron data to include two- dimensional gating. This was accomplished using the replay programs SCANOR and display program DAMM[25] which we had used previously in the analysis of data from Oak Ridge National Laboratory. Examples of two dimensional gates are shown in Figure II.13.

We have received a large well characterized fission chamber from NIST. This chamber

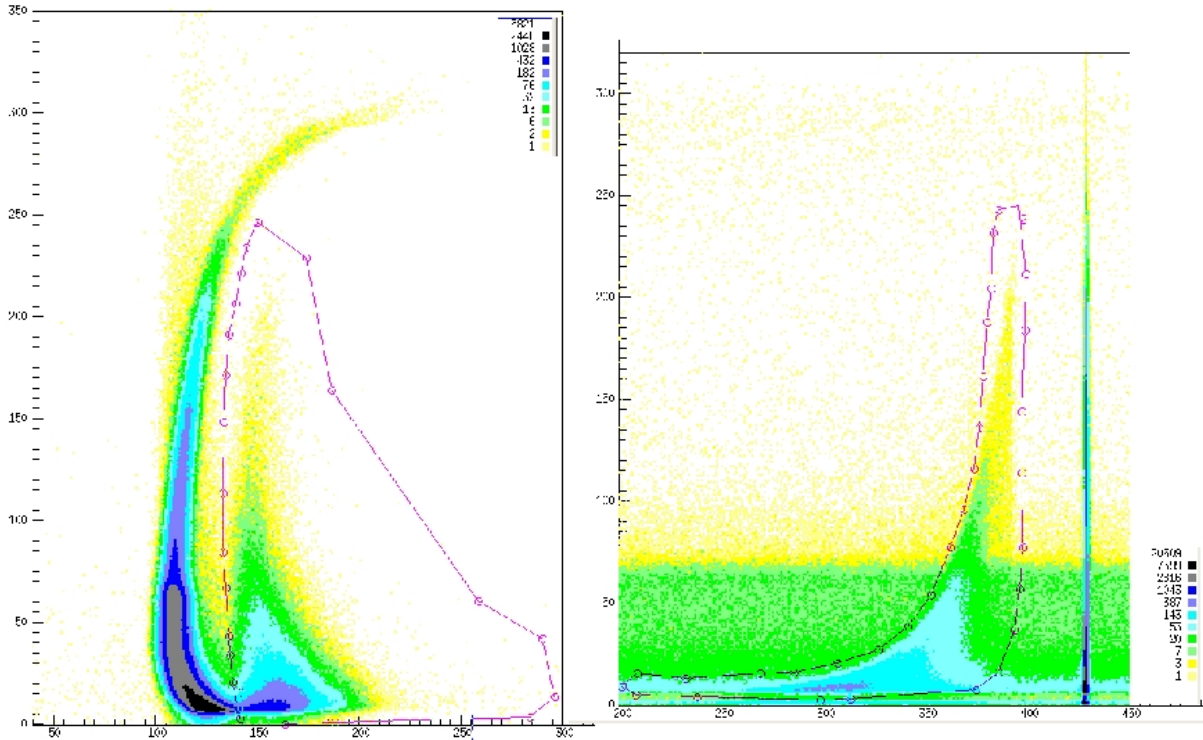


Figure II.13: The plot on the right shows a gate for neutrons in a Pulse Height(Y) versus PSD(X) plot. The plot on the left shows a dynamical gate for neutrons in a Pulse Height(Y) versus Time of Flight(X). The neutron energy increases from right to left and the gamma flash is the largest pulse height peak at channel 425. These gates result in a very clean spectrum with little background.

has been characterized to better than 1.8% in absolute uncertainty. It is hoped that measurements with this chamber will allow the absolute error on the B(d,n) standard at 7.5 MeV and 60 degrees to be reduced to $\sim 2\%$.

II.G.2 Reanalysis of the B(d,n) data

We have re-investigated the B(d,n) neutron spectrum at an incident deuteron energy of 7.5 MeV and an angle 60 degrees as a candidate white source for neutron detector calibration. Results of a measurement of this neutron spectrum with a fission chamber have been published[26]. We have attempted to use this neutron spectrum for efficiency calibration for some recent experiments. The efficiencies determined using the B(d,n) reaction showed discrepancies from those determined by the Al(d,n) reaction.

The time-of-flight spectra for the B(d,n) reaction with a fission chamber and a NE213 liquid scintillator detector were compared after correcting for distance. This comparison is shown in Figure II.14. The alignment of the two spectra was made based on features in the B(d,n) spectrum and the endpoint neutron energy. When this was done the position of the gamma ray in the liquid scintillator spectra was different than that assumed from the fission chamber spectra. There is a small peak in the fission chamber spectra (at channel 691) where the gammas from the liquid scintillator spectra are located.

The B(d,n) spectrum has been recalculated using this determination of the position of the gamma ray for the fission chamber spectra. We think the larger peak to the left of the true gamma ray peak may be due to beam hitting the collimator. The resulting spectrum is shown in Figure II.15.

In an effort to reduce the systematic error in the B(d,n) neutron spectra, we have borrowed a well-characterized fission chamber from NIST. This chamber has systematic uncertainties of 1.8% in the mass and a total mass of 0.2 g of ^{235}U . We anticipate measuring neutron spectra for calibration purposes with this chamber, which is shown in Figure II.16, in the near future.

We are also working with a ^{252}Cf source for detector calibration. The current evaluation of the prompt ^{252}Cf (spontaneous fission) spectrum is thought to be known to at least 2%, below 12 MeV. This will help in checking the low energy portion of the B(d,n) spectra and the absolute normalization.

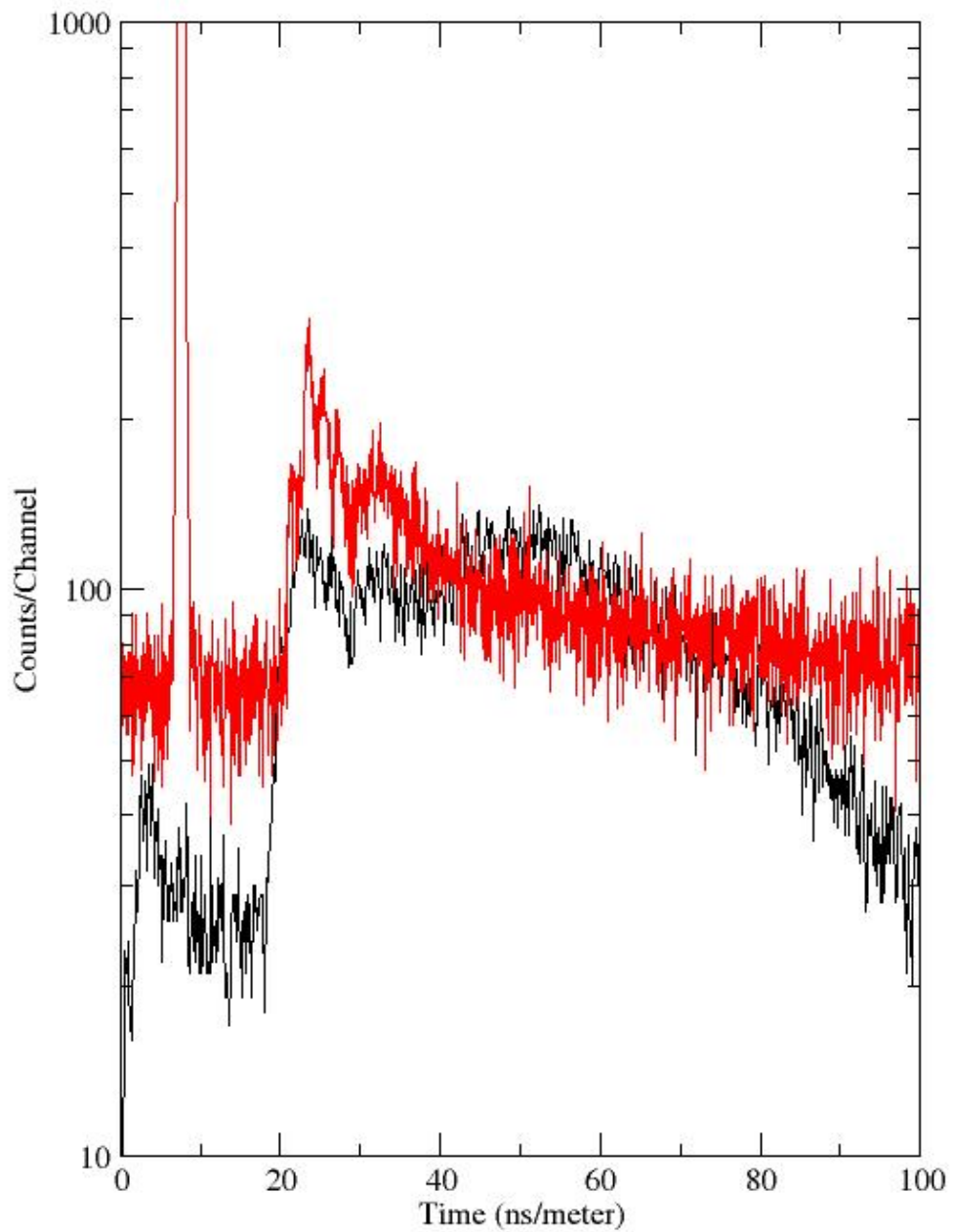


Figure II.14: The spectra for B(d,n) from a fission chamber measurement and from the liquid scintillating detectors at 15 meters.

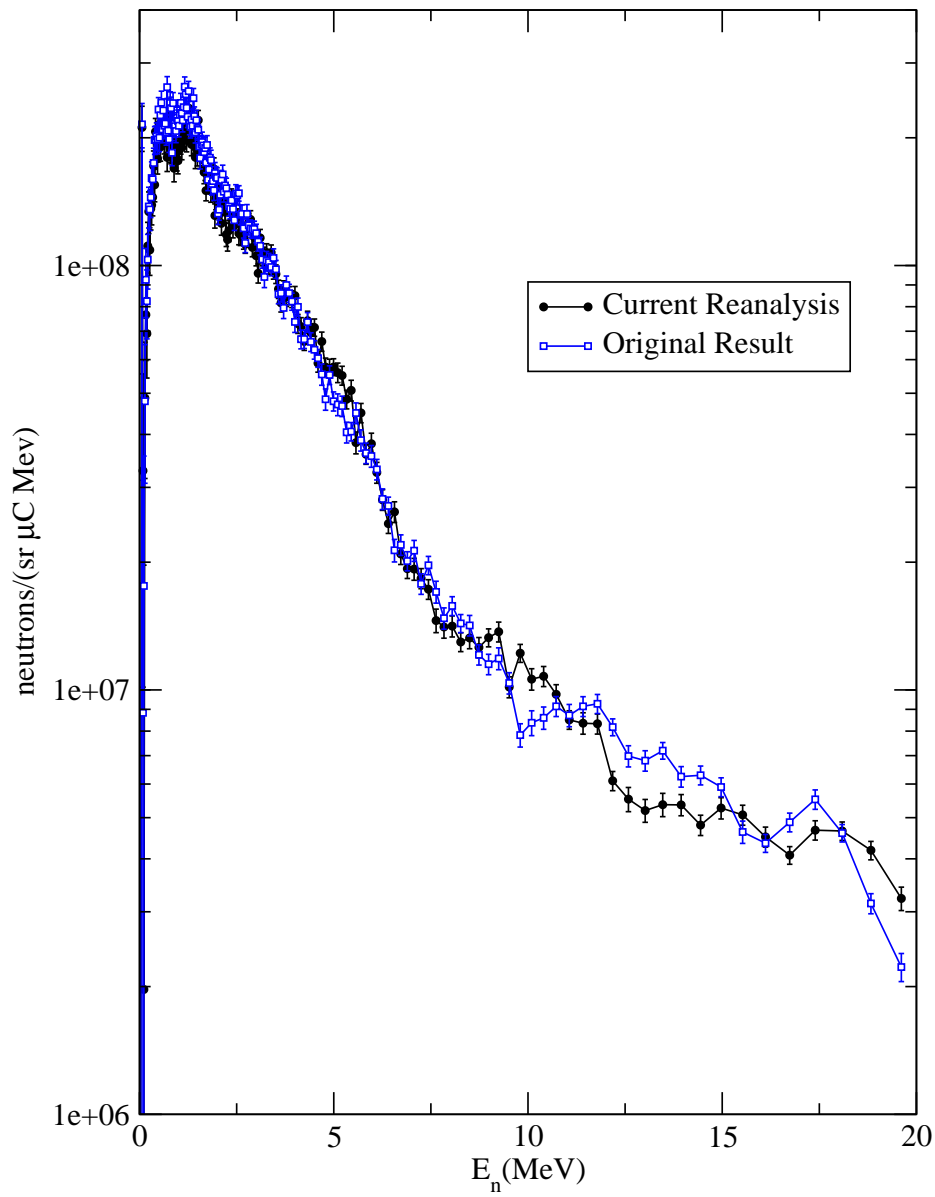


Figure II.15: A comparison of the reanalyzed data with the initial analysis.
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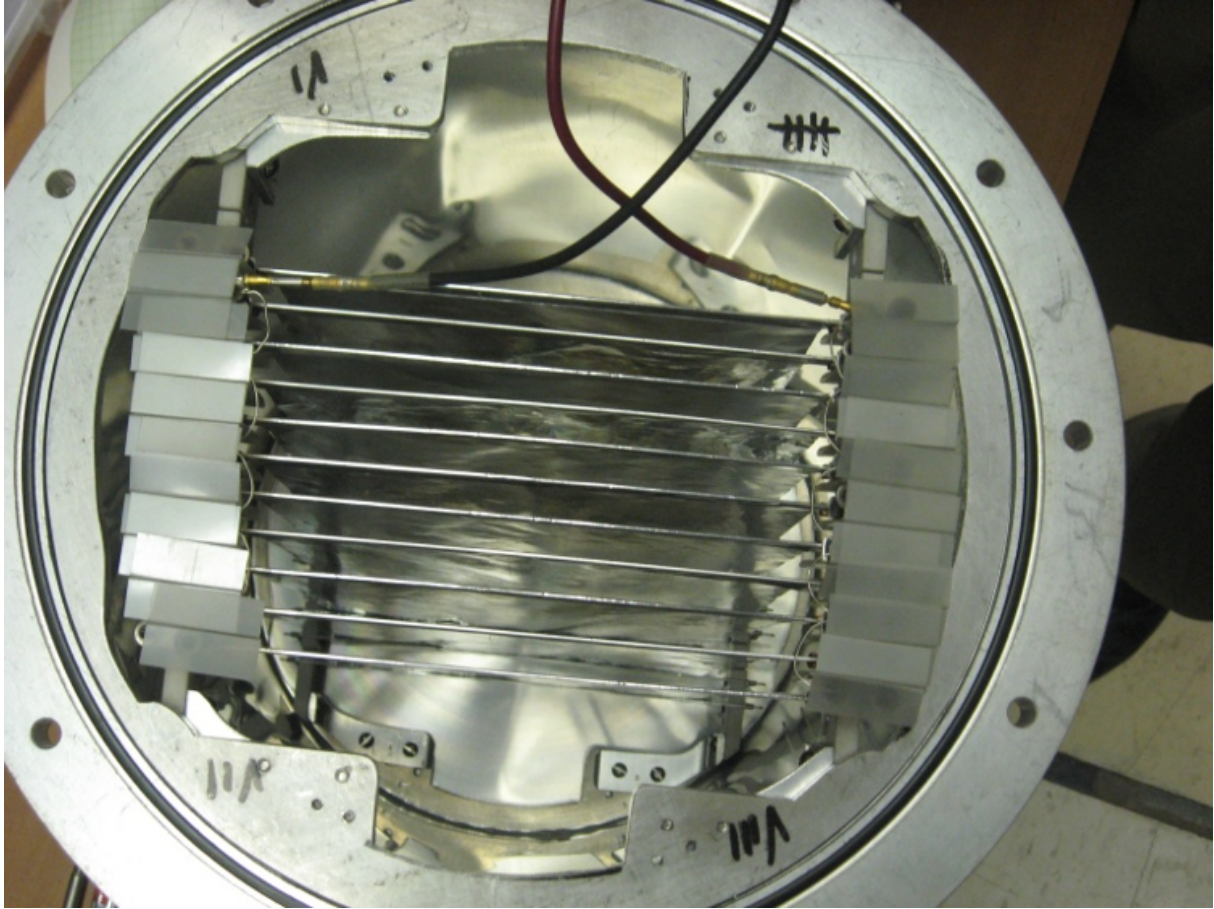


Figure II.16: NIST fission chamber with each plane alternating between aluminum and ^{235}U

II.H (n, Z) Experiments at LANSCE

The ^{11}B nucleus is one for which the threshold for particle emission occurs first for the alpha particle. Thus, when low energy neutrons bombard ^{10}B , the $^{10}\text{B}(\text{n}, \alpha)^7\text{Li}$ reactions occurs with a large cross section. At an energy close to the neutron threshold, the third channel, $^{10}\text{Be} + \text{p}$, also opens. For neutrons of a few MeV, the neutron, proton, and alpha channel all compete in compound nuclear decay.

We have measured the (n,z) cross sections of ^{10}B between 500 keV and 15 MeV. This will allow an R-Matrix fit to the excitation functions for (n, α) and (n,p), yielding information about these reactions and for the various resonances observed. In approximately the same region of excitation, we propose to measure the $^{10}\text{Be}(\text{p}, \text{n})$ excitation function as a complimentary part of the project. This will give information about and widths of resonances seen in the region, as well as further constraints on the total width and resonance energies. It will also be useful to investigate the total neutron cross section from the R-Matrix fit. Accurate values of this quantity are already available.

This project will give additional information on the nuclear structure of ^{11}B . It will also expand the data base for $\text{n} + ^{10}\text{B}$ reactions. There is very little currently known about the $^{10}\text{Be} + \text{p}$ channel. Our (n, α) cross section can be compared with those measured from thermal to 1 MeV for this reaction. Finally, the proton cross section measurements on ^{10}Be will give values useful for calculating the destruction of this stable nuclide in astrophysical nucleosynthesis calculations. Initial measurements have already been performed. We have recently performed experiments at LANSCE WNR facility on charged particle production on an boron target. We are looking at the emission of protons with a gas ΔE detector and a thick silicon surface barrier detector. We are interested in $^{10}\text{B}(\text{n}, \text{p})$ from 0.1 to 20 MeV.

This study was motivated in part to complete measurements of the outgoing channels from the ^{11}B compound nucleus. When all outgoing channels have been measured the total cross section can be used to constrain the cross section of the outgoing channels. As the total cross section is the sum of all of the outgoing channels, the cross section of each outgoing channel is constrained. The cross section for the $^{10}\text{B}(\text{n}, \text{p})$ reaction was estimated in ENDF/B-VII.0 as shown in Figure II.17. The cross section for $^{10}\text{B}(\text{n}, \text{p})$ is estimated to be two orders of magnitude lower than the $^{10}\text{B}(\text{n}, \alpha)$.

The target used in the experiment was $0.25 \mu\text{m}$ of ^{10}B deposited on a 0.05 mm

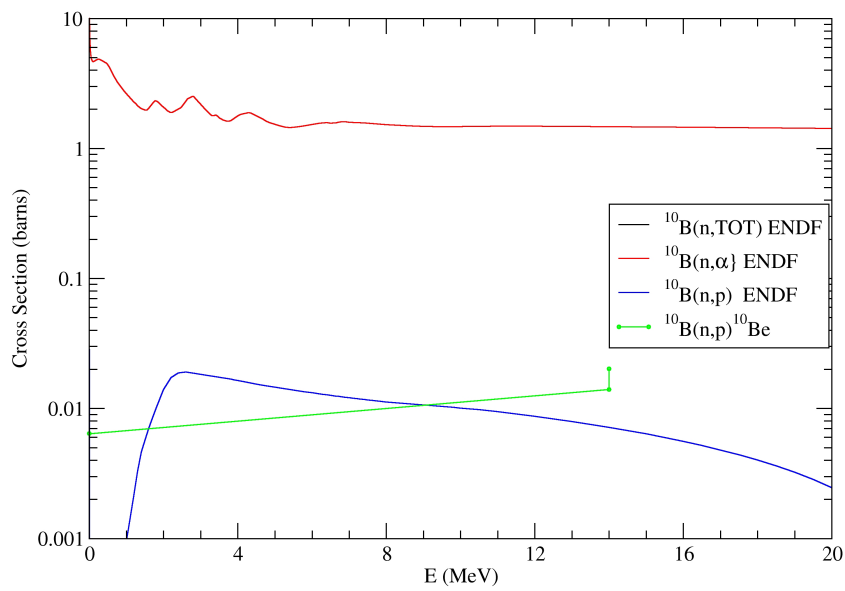


Figure II.17: ENDF/B-VII evaluation for the open reaction channels for ^{11}B compound nucleus.

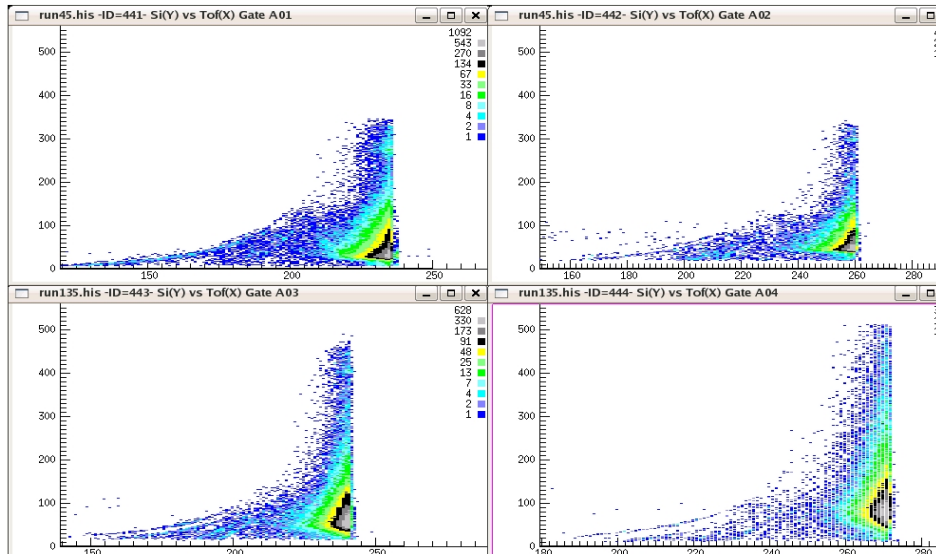


Figure II.18: Two dimensional spectra gated on protons for forward (top) and backward (bottom) angle detectors. The axes are silicon pulse height in the y direction and time of flight in the x direction. The decay to different states in ^{10}Be can be seen as lines in this display.

tantalum blank. Initial runs with an argon methane gas in the (n, Z) chamber showed protons present at backwards angles. At forward angles scattering from the hydrogen in methane was observed. To improve the signal to noise for detecting protons the gas in the chamber was changed to xenon. At that time a CH_2 foil was put into the beam line to harden the spectrum.

We have begun the analysis of the data. A plot of the silicon pulse height versus time of flight is shown in Figure II.18.

Further work will be done to complete the conversion of the data taken into cross section information, including for the forward angles the separation or subtraction of the contribution of hydrogen in the gas and water in the target. The alpha channel will also be determined to check against previous measurements.

We are carrying out the evaluation of data taken using an ^{58}Fe target. The goal was to measure charged particle production cross sections, emitted charged-particle spectra and angular distributions for neutron-induced reactions on ^{58}Fe from threshold to over

50 MeV. These reactions are termed "(n,xz)", where "z" denotes protons, deuterons, tritons, ^3He or alpha particles and "x" denotes that the reactions are inclusive.

A measurement of the charged-particle emission spectra from neutron reactions on aluminum would permit a further investigation of two effects that can influence Hauser-Feshbach calculations. A recent paper by Bateman et al. [27] has presented (n,xz) spectra from silicon in the range of neutron energies up to 40 MeV. The data were reasonably described by multi-step Hauser-Feshbach calculations. Some evidence was found that partial conservation of isospin influenced the calculations. The effect was to steal flux from the neutron and proton channels and enhance the alpha decay. At about the same time as this paper was published, another paper by S. I. Al Quraishi et al. [18] suggested another effect which has similar consequences. This would come about if the level density parameter a were dependent on Z and A rather than simply on A . This change would have somewhat similar effects to the partial conservation of isospin. Separating the two will be possible only if data on more than one nucleus in a given mass region are available. The spectrometer used for the previous measurements would be appropriate for accumulating data on ^{56}Fe and ^{58}Fe .

We carried out this work at LANSCE using the WNR (n,z) chamber in collaboration with Robert C. Haight. This work done with the largest and thickest available target of ^{58}Fe available. However, the thickness of this target was at least a factor of 4 thinner than optimal.

We have begun to analyze the data collected over the course of two summers. The raw data was converted to columnar format using a program written by Terry Tadeuchi. We have used the SCANNOR and DAMM packages to form histograms and two dimensional plots. Much of the analysis was carried out by James Ralston (a current undergraduate student). The identification plots were used to separate the proton and the alphas. Gating on the proton and alpha results in the spectra shown in Figure II.19, II.20. The plots on the right hand side show the background (sample out for the foil holder) for this measurement.

The analysis of these data will be concluded by using the neutron flux inferred from the neutron fission chamber. The fission chamber has a well known ^{235}U foil as a standard.

Two additional targets have been investigated recently. Neutron induced charged particle emission experiments were performed on targets of ^{13}C and ^{14}N . It was planned that the data from these targets would be part of a graduate students thesis. However,

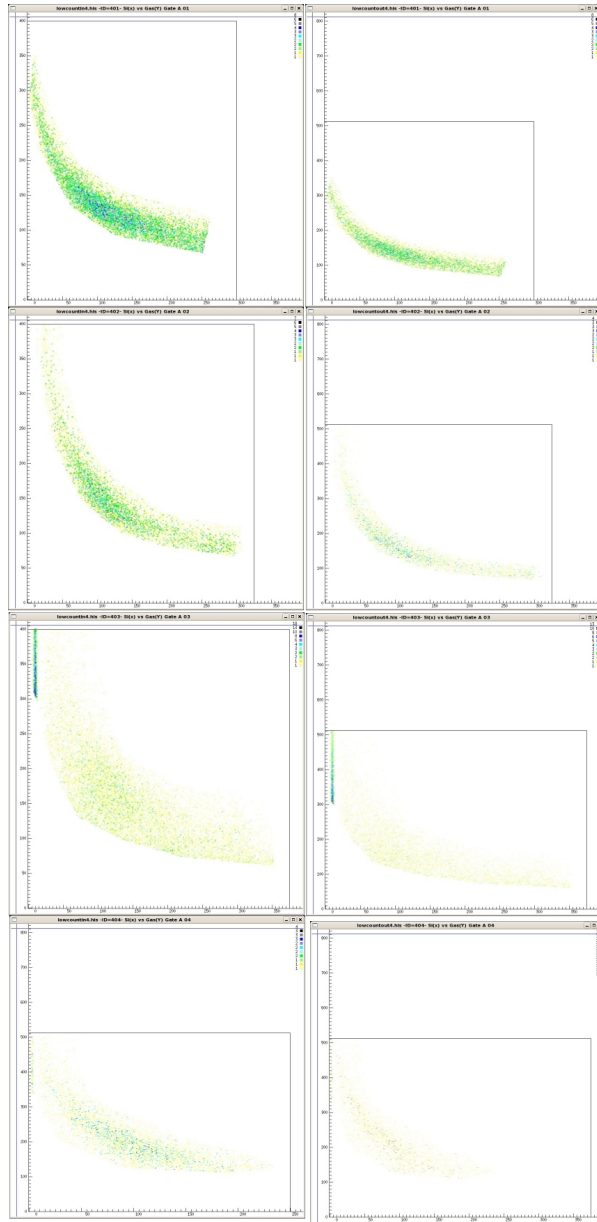


Figure II.19: Alphas seen in a silicon versus gas proportional counter identification plot. The angles in the experiments are shown from the most forward angle at top and the more backward angle at the bottom. The sample out spectra are shown at the right of each sample in spectrum.

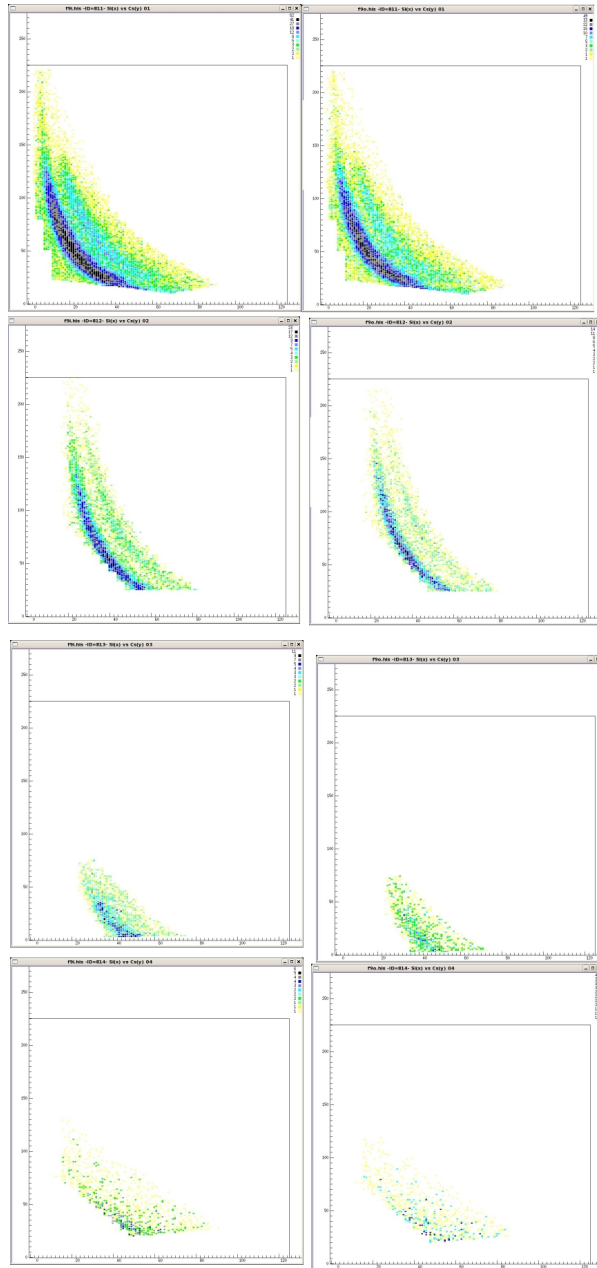


Figure II.20: Protons seen in a silicon versus CsI identification plot. The angles in the experiment are shown from the most forward angle at the top and the most backward angle at the bottom. The sample out spectra are shown at the right of each sample in spectrum.

the student working on this project left before the analysis was completed. We are now planning to perform the data analysis in the next year. The target of ^{14}N was composed of TaN_x where x was between 2 and 3 on a thin tantalum backing. These data should be good enough to determine the cross section for each of the outgoing channels. This is important as almost all previous information on this system was based on proton bombardment of ^{14}C . We hope the much smaller data set from the ^{13}C target will be usable. The ^{13}C target thickness was limited to the amount of carbon which could be deposited uniformly on a tantalum backing.

II.I Empirical Formula for (n,p) and (n, α) Cross Sections

It has long been known[28, 29] that cross sections for (n,p) and (n, α) reactions measured at 14 MeV can be fit with the formula $\exp[\alpha + \beta S]$, where S is $\frac{(N-Z)}{A}$ and α and β are fitting constants. N , Z and A are the neutron number, proton number and nucleon number, respectively, of the nucleus. By (n,p) and (n, α) cross sections in this section, we denote exclusive reactions, i.e., reactions such as (n,np) and (n,2p) are excluded from (n,p), and (n,n α) and (n,p α), for example, are excluded from (n, α). The (n,p) and (n, α) cross sections so defined are the ones which would be measured in a radio-chemical determination of the cross section. We have examined the reasons why such a form might work, with a view to finding possible improvements. The present form, though useful, does often miss measured values by 20-30%. Since many cross sections of this type have not been measured, it would be useful to reduce these discrepancies so that the predictive power of the formula is improved.

We make the assumption that the reaction mechanism is compound nuclear. The Weisskopf model for compound nuclear reactions predicts that the cross section for emission of a particle X at an energy E will be proportional to

$$\sigma_x(E) \propto E \sigma_{inv}(E) \rho(E_m - E)$$

where E is the energy with which particle X is emitted, E_m is the maximum (endpoint) energy for the particle X , $\rho(E_m - E)$ is the level density of the residual nucleus and $\sigma_{inv}(E)$ is the inverse cross section for forming the compound nucleus by bombarding the residual nucleus with a particle X of energy E . We assume that the level density has the

form

$$\rho(E) = \alpha \exp \frac{E}{\theta}.$$

In general, the neutron channel dominates the decay. In this case,

$$\sigma_x = \frac{\int_{E_1}^{E_2} \sigma_{inv}(X)(E)E \exp [(E_m + \theta_{n,x} - E)/\theta]de}{\int_0^{E_m} \sigma_{inv(n)}(E)E \exp [(E_m - E)/\theta]de} \sigma_{react}$$

We further assume that the neutron inverse cross section is independent of energy, that the proton and alpha inverse cross sections are independent of energy above the Coulomb cut off and are zero below this point and that they are equal to the neutron inverse cross section above this point.

Under these assumptions

$$\sigma_{n,p} = \left(\left(\frac{E_1}{\theta} + 1 \right) \exp \left[\frac{+Q_{n,p} - E_1}{\theta} \right] - \left(\frac{E_2}{\theta} + 1 \right) \exp \left[\frac{(Q_{n,p} - E_2)}{\theta} \right] \right) \sigma_{react}$$

where E_1 is the Coulomb cutoff or $E + Q_{n,p} - B_{n_1}$, whichever is larger. B_{n_1} is the binding energy of the last neutron in the (n,p) residual nucleus. E_2 will be $E + Q_{n,p}$, which makes the second exponential $e^{-E/\theta}$. This makes the second term negligible in comparison with the first. Thus,

$$\sigma_{n,p} \approx \left(\frac{E_1}{\theta} \exp \left[\frac{(Q_{n,p} - E_1)}{\theta} \right] \right) \sigma_{react}.$$

Similarly,

$$\sigma_{n,\alpha} \approx \left(\frac{E_3}{\theta} \exp \left[\frac{(Q_{n,\alpha} - E_3)}{\theta} \right] \right) \sigma_{react}.$$

where E_3 is the alpha Coulomb cutoff or $E + Q_{n,\alpha} - B_{n_2}$, where B_{n_2} is the binding energy of the last neutron in the (n, α) residual nucleus.

If E_1 or E_3 is given by the Coulomb cutoff, it should vary as $a_c(Z/A^{1/3})$ (protons) or $2a_c(Z/A^{1/3})$ (alphas). On the other hand, if the second choice is higher, it would be a function of $E + Q_{n,p} - B_{n_1}$ or $E + Q_{n,\alpha} - B_{n_2}$. Use of the semi-empirical mass formula gives terms of the form a_v , $a_s(Z/A^{2/3})$, $a_c(Z/A^{1/3})$, $a_c(Z^2/A^{1/3})$, $a_z((N - Z)/A)$ and

$a_a((N - Z)^2/A^2)$ for $Q_{n,p}$, $Q_{n,\alpha}$, B_{n_1} and B_{n_2} where the semi-empirical mass formula is

$$BE(n, Z) = -a_v A + a_s A^{2/3} + a_c \frac{Z^2}{A^{1/3}} + a_a \frac{(N - Z)^2}{A}.$$

This result suggests a more complicated form in the exponential. The situation is complicated by the fact that for targets which are stable the beta stability criterion gives

$$0 = 1.3 + \frac{2Z}{A^{1/3}} - \frac{4(N - Z)}{A}.$$

Thus, a correlation exists between $(N - Z)/A$ and $Z/A^{1/3}$.

To cover the possibility that these extra terms could influence the cross section, two alternative forms were fitted to a total of 89 (n,p) and (n, α) cross sections. The (n,p) and (n, α) cross sections were separately fit with:

- (A) the $(N - Z)/A$ term in the exponential;
- (B) the $(N - Z)/A$ term in the exponential but a separate fit was done for proton-rich and neutron-rich targets;
- (C) a constant (a_0), a constant divided by $A^{1/3}$, $a_2(Z/A^{1/3})$, $a_3(Z^2/A^{1/3})$, $a_4(N - Z/A)$ and $a_5(N - Z/A)^2$ in the exponential.

Both (B) and (C) fits improved the fits substantially. Fits of type C were better in χ^2 by a factor of nearly two in fitting the entire (n,p) or (n, α) data set than those of type A. Using the type B procedure gave a comparable improvement and small changes between (C) and (B) were seen when the fit was done separately for proton-rich and neutron-rich nuclei.

It appears that either approach (fitting in two groups or using more terms) substantially improves the fit to (n,p) and (n, α) cross sections at 14 MeV.

III Facilities

III.A Accelerator

The 4.5-MV tandem accelerator at the Ohio University Edwards Accelerator Laboratory has delivered beams reliably over the time period 1 March 2008 – 28 February 2009. Ohio University has committed \$100,000 for refurbishment of the Laboratory. The first phase of this process consisted of the rebuilding of the compressor for transferring sulfur hexafluoride gas into and out of the accelerator tank and took place in Spring 2005. The second phase involves implementing a computer-control system for the accelerator, ion sources, and beam-handing systems and is nearly completed. This system includes a fiber optic link for monitoring and controlling power supplies on the high-voltage platform of the ion source. All magnets are now computer controlled except one small power supply for the swinger. We are searching now for a replacement power supply which can be computer controlled. We are also testing a new design for a computer-controllable electrostatic steerer supply power which allows the polarity to be reversed. In addition, new vertical shelving and a small forklift have been purchased to facilitate storage and increase the floorspace available for experiments. The final phase of the upgrade is a replacement of the cryopumps on the low-energy end of the machine, took place in summer 2009.

III.B Detection Equipment

III.B.1 Neutron Detection

We have now purchased two Mesytex pulse-shape discrimination modules which are ideal for instrumenting neutron time-of-flight experiments with liquid scintillators. We have recently purchased six neutron detectors from Eljen Technology which have NE213 equivalent scintillators. We have also purchased three 2.54 by 2.54 cm cells which can be viewed

with two photo tubes. These cells are filled with NE213, benzene and deuterated benzene. These are intended to be used in the H(n,n)H experiment. A cylindrical stilbene detector of size 2.54 cm diameter by 2.54 cm thick is also available. This detector proved to have excellent PSD.

To improve our ability to determine neutron detector efficiencies, we have also acquired a ^{252}Cf foil and are installing it in a fission chamber. This isotope decays (in part) by spontaneous fission. A pulse from the fission chamber signifies that a fission event has occurred; the well known ν and neutron source shape allow us to infer neutron detector efficiencies as a function of energy. We will be undertaking a comparison of values deduced from this technique with those obtained from other techniques in the coming years.

III.B.2 Gamma-Ray Spectroscopy

We purchased an annular plastic scintillator to be used with our 10.2-cm \times 10.2-cm BGO detector. In addition, we have purchased a 5.1-cm \times 5.1-cm Lanthanum Bromide scintillator for gamma-ray detection.

III.B.3 Charged-Particle Time-of-Flight Spectrometer

We have completed the instrumentation of 10 arms of the spectrometer, which allows the simultaneous measurement of 10 angles. Silicon surface-barrier detectors are located at the ends of each tube which can stop protons with energies of up to 13 MeV. The flight path for each tube can be chosen to be 0.3, 1.0, or 1.8 m. The measurement of total energy and time of flight is a powerful tool for particle identification. After tracking down several noise sources, we have now achieved resolutions of 30 keV or better for every detector, for 5-MeV α particles. In addition we have designed mounts for four NE213 scintillators and Ge detectors in order to measure neutrons and γ rays, respectively. We have recently ordered two CsI scintillators and one 5-mm-thick lithium-drifted Si detector. These detectors will allow us to measure protons with energies greater than 10 MeV.

We have also now implemented the distributed data acquisition system described

below. The six additional data acquisition computers can be used for supplemental detectors. A test experiment has recently been completed with both gamma and neutron detectors. The time coincidence unit has been tested with the mixed detector set. The time difference between any two events can be determined to 0.5 ns in a several day period. Software for rapid analysis of the data has been written and tested. A point-and-click user interface for the distributed data acquisition system has been developed which greatly enhances the efficiency for the user.

Experiments have been completed with different configurations. Experiments to measure just the charged particle angular distribution have used the ten charged particle legs only. Several recent measurements to look at compound reactions have used five computers to measure neutrons, gammas and charged particles simultaneously. When more angles for the charged particles are needed the cables were simply switched to other time-of-flight legs. We have also begun to use the shorter path lengths to increase the solid angle when only protons and alphas are expected.

III.C Computers

We have used reliably for several years the “Distributed DAQ,” data acquisition system, which is made up of 16 single-PC nodes connected to a central computer. Each node consists of an independent computer and DAQ hardware and is dedicated to a single detector or detector-telescope system. This system is running the Linux version of the Ohio University DAQ software for each detector or detector-telescope. This new method eliminates detector-detector interferences (pileup, deadtime, etc. . .) and eliminates detector multiplex/demultiplex hardware. It also greatly improves our long flight time time-of-flight resolution. Both of these capabilities were crucial for the work we undertook in this project. A 16-channel coincidence unit has also been constructed to allow processing detector-detector coincidences.

We have acquired a new 24-CPU computer farm system, utilizing equipment that the university was discarding as excess property. Each system includes a 2.4-GHz Intel Pentium 4 processor and at least 512 Mb of core memory (some systems have 768 Mb and one has 1 Gb of core). We also acquired several terminal displays and printers. The total cost of these 24 systems was less than \$3,000. The systems are currently running the Debian variation of Linux and using Knoppix distributed computation software, although

other options are also available, including MPI and PVM. The systems are all connected to a high speed switch and can share disk space with our existing 15 CPU farm system. We believe this presents a substantial increase in available computation ability for a low cost, and is an excellent value for money. These resources are primarily used for Monte Carlo simulations and data fitting.

IV Publications

IV.A Publications in Professional Journals

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IV.B Publications in Conference Proceedings

- “The $^{25}\text{Al}(p, \gamma)^{26}\text{Si}$ Reaction Rate in Novae”, D. W. Bardayan, J. C. Blackmon, W. R. Hix, J. F. Liang, M. S. Smith, J. A. Howard, R. L. Kozub, C. R. Brune, K. Y. Chae, E. J. Lingerfelt, J. P. Scott, M. S. Johnson, K. L. Jones, S. D. Pain, J. S. Thomas, R. J. Livesay and D. W. Visser, in *Proceedings of the International Symposium on Nuclear Astrophysics - Nuclei in the Cosmos - IX, Geneva, Switzerland, 25-30 June 2006*, page 217.
- “Level Structure of ^{19}Ne from studies of the $^{17}\text{O}(^3\text{He}, n)^{19}\text{Ne}$ Reaction,” M. J. Hornish, C. R. Brune, S. M. Grimes, M. H. Hadizadeh, T. N. Massey, A. V. Voinov, J. E. O'Donnell, A. Adekola, C. Matei and Z. Heinen, in *Proceedings of the International Symposium on Nuclear Astrophysics - Nuclei in the Cosmos - IX, Geneva, Switzerland, 25-30 June 2006*, page 119.
- “Level densities of iron isotopes and low-energy enhancement of gamma-strength function,” A.V. Voinov, S.M. Grimes, U. Agvaanluvsan, E. Algin, T. Belgya, C.R. Brune, M. Guttormsen, M.J. Hornish, T.N. Massey, G.E. Mitchell, J. Rekstad, S. Siem, and A. Schiller, in *Proceedings of CGS12, the Twelfth International Conference on Capture Gamma-Ray Spectroscopy and Related Topics, Notre Dame, IN, 4-9 September 2005*, Eds. A. Woehr and A. Aprahamian, AIP Conference Proceedings Vol. 819 (AIP, New York, 2006), pp. 545-549.
- “A new measurement of the $\text{H}(n,n)\text{H}$ elastic scattering angular distribution at 15 MeV,” N. Boukharouba, T. N. Massey, R. C. Haight, S. M. Grimes, D. E. Carter, A. D. Carlson, C. E. Brient and F. B. Bateman, in *Proceedings of the International Conference on Nuclear Data for Science and Technology 2007*.
- “Nuclear Level Densities Off of the Stability Line,” S. M. Grimes, T. N. Massey, B. M. Oginni, S. Shukla and A. Voinov, in *Proceedings of the 2007 International Workshop in Compound Nuclear Reactions and Related Topics (CNR*2007)*, Yosemite National Park, California, 22-26 October 2007, American Institute of Physics, Melville, NY, pg. 57.

- “Experimental Level Densities and γ -Strength Functions in Rare Earth Nuclei,” S. Siem, M. Guttormsen, A. C. Larsen, H. T. Nyhus, R. Chankova, F. Ingebretsen, S. Messelt, J. Rekstad, N. U. H. Syed, A. Schiller, A. Voinov, and S. W. Ødegård, in *Proceedings of the 2007 International Workshop in Compound Nuclear Reactions and Related Topics (CNR*2007)*, Yosemite National Park, California, 22-26 October 2007, American Institute of Physics, Melville, NY, pg. 65.
- “Experimental Study of Level Density and γ -strength Functions from Compound Nuclear Reactions,” A. V. Voinov, S. M. Grimes, C. R. Brune, M. Guttormsen, T. N. Massey, A. Schiller and S. Siem”, in *Proceedings of the 2007 International Workshop in Compound Nuclear Reactions and Related Topics (CNR*2007)*, Yosemite National Park, California, 22-26 October 2007, American Institute of Physics, Melville, NY, pg. 61.
- “Nuclear Astrophysics at TRIUMF,” L. Buchmann, P. Amaudruz, J.D’Auria, D. Hutcheon, C. Matei, J. Pearson, C. Ruiz, G. Ruprecht, M. Trinczek, C. Vockenhuber, and P. Walden, *Nucl. Phys* **A805**, 462c-469c (2008).
- ”Band structures in light neutron-rich nuclei”, H.G. Bohlen, W. von Oertzen, R. Kalpakchieva, T.N. Massey, T. Dorsch, M. Milin, Ch. Schulz, Tz. Kokalova, and C. Wheldon *J. Phys. Conf. Series* **111** 012021 (2008)
- ”Core x (sd)³ structures in ¹⁷C, ¹⁶C and ¹⁵C up to high excitation energies”, H.G. Bohlen, W. von Oertzen, Ch. Schulz, Tz. Kokalova, C. Wheldon, R. Kalpakchieva, T.N. Massey, M. Milin *Proceedings of the Int. Symp. on Physics of Unstable Nuclei (ISPUN07)*, July 3-7, 2007, Hoi An, Vietnam, editors P. Egelhof, S. Gales, N.V. Giai, D.T. Khoa, and T. Motobayashi, World Scientific Publ. Comp. (2008) (in press).
- “Astrophysically important ¹⁹Ne states studied with the ²H(¹⁸F, α + ¹⁵O)*n* reaction,” A. S. Adekola, D. W. Bardayan, J. C. Blackmon, C. R. Brune, K. Y. Chae, A. E. Champagne, C. P. Domizioli, U. Greife, Z. Heinen, M. J. Hornish, M. Johnson, K. L. Jones, R. L. Kozub, R. J. Livesay, Z. Ma, T. N. Massey, B. Moazen, C. D. Nesaraja, S. D. Pain, J. F. Shriner, Jr., J. S. Thomas, N. D. Smith, M. S. Smith, D. W. Visser, A. V. Voinov, in *Proceedings of the International Symposium on Nuclear Astrophysics - Nuclei in the Cosmos - X*, Mackinac Island, Michigan, USA, July 27 - August 1 2008, PoS(NIC X)151.
- “AZURE, An R-Matrix Computer Code,” R. deBoer, R. Azuma, C. R. Brune, H. Costantini, J. Görres, P. J. LeBlanc, E. Uberseder, M. Wiescher, E. C. Simpson,

and C. Ugalde, in Proceedings of the International Symposium on Nuclear Astrophysics - Nuclei in the Cosmos - X, Mackinac Island, Michigan, USA, July 27 - August 1 2008, PoS(NIC X)204.

- “Nuclear Level Densities,” S. M. Grimes and A. Voinov, in *Capture Gamma-Ray Spectroscopy and Related Topics, 13th International Symposium*, p. 79, Cologne, Germany, 25-29 August 2009.
- “Level densities and radiative strength functions,” S. Siem, A. Agvaanluvsan, A. Bürger, M. Guttormsen, A. C. Larsen, G. Mitchell, H. T. Nyhus, R. Chankova, J. Rekstad, A. Schiller, N. U. H. Syed, H. K. Toft, G. M. Tveten and A. Voinov, in *Capture Gamma-Ray Spectroscopy and Related Topics, 13th International Symposium*, p. 79, Cologne, Germany, 25-29 August 2009.
- “R-matrix Methods with an application to $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$,” Carl R. Brune, proceedings of the 5th European Summer School on Experimental Nuclear Astrophysics, Santa Tecla, Sicily, 2009, AIP Conference Proceedings (in press).

IV.C Conference Talks and Posters

- *Measurement of the cascade cross section to the 6.049-MeV state in ^{16}O in $^{12}\text{C}(\alpha, \gamma)$* , C. Matei, L. Buchmann, W. R. Hannes, D. A. Hutcheon, C. Ruiz, C. R. Brune, J. Caggiano, A. A. Chen, J. D’Auria, A. Laird, M. Lamey, Z. H. Li, W. P. Liu, A. Olin, D. Ottewell, J. Pearson, G. Ruprecht, M. Trinczek, C. Vockenhuber and C. Wrede, invited talk presented at *Nuclei in the Cosmos - IX*, CERN, Geneva, Switzerland, June 25-30, 2006.
- *The $^{25}\text{Al}(p, \gamma)$ reaction rate in novae* (poster), D.W. Bardayan, C.R. Brune, and others, poster presented at *Nuclei in the Cosmos - IX*, CERN, Geneva, Switzerland, June 25-30, 2006.
- *Level Structure of ^{19}Ne from studies of the $^{17}\text{O}(^3\text{He}, n)^{19}\text{Ne}$ reaction* (poster), M.J. Hornish, C.R. Brune, and others, presented at *Nuclei in the Cosmos - IX*, CERN, Geneva, Switzerland, June 25-30, 2006.
- *Study of unbound ^{19}Ne states via the proton transfer reaction $^2\text{H}(^{18}\text{F}, \alpha + ^{15}\text{O})n$* (poster), A. Adekola, C.R. Brune, and others, presented at *Nuclei in the Cosmos - IX*, CERN, Geneva, Switzerland, June 25-30, 2006.

- *Study of unbound ^{19}Ne states via the proton transfer reaction $^2\text{H}(^{18}\text{F}, \alpha + ^{15}\text{O})\text{n}$* , C.R. Brune, invited talk presented at the *Nuclear Measurements for Astrophysics* workshop at the Holifield Radioactive Ion Beam Facility, Oak Ridge, TN, October 23, 2006.
- *Level density and γ -strength function for $A=56-60$ nuclei*, A.V. Voinov, C.R. Brune, S.M. Grimes, M.J. Hornish, T.N. Massey, presented at The American Physical Society, Division of Nuclear Physics Annual Meeting, October 25-28, 2006.
- *Cross section measurements of $^9\text{Be}(\alpha, \text{n})^{12}\text{C}$* , Z. Heinen, A. Adekola, C.R. Brune, S.M. Grimes, H. Hadizadeh, M.J. Hornish, T.N. Massey, C. Matei, A. Voinov, presented at The American Physical Society, Division of Nuclear Physics Annual Meeting, October 25-28, 2006.
- *Prospects for Improved Measurements of the S-Process Neutron Source Reactions*, Carl R. Brune, presented at The American Physical Society, Division of Nuclear Physics Annual Meeting, October 25-28, 2006.
- *A New Measurement of the E1 Component of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ Reaction*, X.D. Tang, M. Notani, K.E. Rehm, I. Ahmad, J. Greene, A.A. Hecht, D. Henderson, R.V.F. Janssens, C.L. Jiang, E.F. Moore, N. Patel, R.C. Pardo, G. Savard, J.P. Schiffer, S. Sinha, M. Paul, L. Jisonna, R.E. Segel, C. Brune, A. Champagne, and A. Wuosmaa, presented at The American Physical Society, Division of Nuclear Physics Annual Meeting, October 25-28, 2006.
- *R-Matrix Analysis and Data Needs for $^{12}\text{C}(\alpha, \gamma)$* , invited talk presented at the *Workshop in Honor of the 85th Birthday of Charlie Barnes*, C. R. Brune, California Institute of Technology, December 15, 2006.
- *Neutron Time-of-Flight Spectroscopy*, C. R. Brune, Astrophysics, Study of Nuclei, Neutrinos, Neutrons, Fundamental Symmetries Long-Range Plan Town Meeting, Chicago, Illinois, January 19-21, 2007.
- *Applied Nuclear Physics at Ohio University*, C. R. Brune, Astrophysics, Study of Nuclei, Neutrinos, Neutrons, Fundamental Symmetries Long-Range Plan Town Meeting, Chicago, Illinois, January 19-21, 2007.
- *Studies in Low Energy Nuclear Science*, S. M. Grimes, Stockpile Stewardship Annual Review, Washington, D.C., February 6, 2007.

- *Calculations of Level Densities Off the Stability Line* (poster), S. Shukla, Stockpile Stewardship Annual Review, Washington, D.C., February 6, 2007.
- *Cross Section Measurements of ${}^9\text{Be}(\alpha, n){}^{12}\text{C}$* (poster), Z. Heinen, A. Adekola, C. R. Brune, S. Grimes, T. N. Massey, A. Voinov, and H. Hadizadeh Stockpile Stewardship Annual Review, Washington, D.C., February 6, 2007.
- *Experimental studies of nuclear level density* (poster), A. V. Voinov, S. M. Grimes, A. Adekola, C. R. Brune, H. Hadizadeh, Z. Heinen, T. N. Massey, B. Oginni and S. Shukla Stockpile Stewardship Annual Review, Washington, D.C., February 6, 2007.
- *The level structure of ${}^{19}\text{Ne}$ via measurement of the ${}^2\text{H}({}^{18}\text{F}, \alpha + {}^{15}\text{O})n$ reaction*, A. S. Adekola, C. R. Brune, Z. Heinen, M. J. Hornish, T. N. Massey, A. V. Voinov, D. W. Bardayan, J. C. Blackmon, C. D. Nesaraja, M. S. Smith, A. Chae, C. Domizioli, Z. Ma, B. Moazen, A. E. Champagne, D. W. Visser, U. Greife, R. Livesay, M. Porter-Peden, M. Johnson, K. L. Jones, S. D. Pain, J. S. Thomas, R. L. Kozub, J. F. Shriner, N.D. Smith, presented at American Physical Society, APS April Meeting, April 14-17, 2007.
- *New measurement of the $H(n, n)H$ elastic scattering angular distribution at 15 MeV*, N. Boukharouba, T. N. Massey, R. C. Haight, S. M. Grimes, D. E. Carter, A. D. Carlson, C. E. Brient and F. B. Bateman, 2007 International Conference on Nuclear Data for Science and Technology, Nice, France, April 22-27, 2007.
- *Nuclear Level Densities*, S. M. Grimes, Conference on Nuclear Level Densities and Gamma-strength Functions, Oslo, Norway, May 21-24, 2007.
- *Calculations of Level Densities Off the Stability Line* (poster), S. Shukla, Conference on Nuclear Level Densities and Gamma-strength Functions, Oslo, Norway, May 21-24, 2007.
- *Core $x(sd)^3$ structures in ${}^{17}\text{C}$, ${}^{16}\text{C}$ and ${}^{15}\text{C}$ up to high excitation energies*, H.G. Bohlen, R. Kalpakchieva, T.N. Massey, W. von Oertzen, M. Milin, Ch. Schulz, Tz. Kokalova, and C. Wheldon Talk at the Int. Symp. on Physics of Unstable Nuclei (ISPUN07), July 3-7, 2007, Hoi An, Vietnam
- *Band structures in light neutron-rich nuclei* H.G. Bohlen, W. von Oertzen, R. Kalpakchieva, T.N. Massey, T. Dorsch, M. Milin, Ch. Schulz, Tz. Kokalova, and C. Wheldon Talk at The Cluster Conference 2007, Stratford upon Avon, UK, Sept. 3-7, 2007.

- *Studies in Low-Energy Nuclear Science*, C. R. Brune, invited talk presented at the 2008 Stewardship Sciences Academic Alliances (SSAA) Symposium, February 28, 2008, Washington, DC.
- *The Excitation Function of ${}^9\text{Be}(\alpha, n)$ below $E_\alpha = 11 \text{ MeV}$* , Z. Heinen, poster presented at the 2008 Stewardship Sciences Academic Alliances (SSAA) Symposium, February 28, 2008, Washington, DC.
- *Studies of the Structure of Light Nuclei*, T. N. Massey, poster presented at the 2008 Stewardship Sciences Academic Alliances (SSAA) Symposium, February 28, 2008, Washington, DC.
- *Level Densities from Neutron and Charged Particle Spectra*, A. Voinov, poster presented at the 2008 Stewardship Sciences Academic Alliances (SSAA) Symposium, February 28, 2008, Washington, DC.
- *Level Densities of Nuclei Off of the Nuclear Stability Line*, Babatunde Oginni, poster presented at the 2008 Stewardship Sciences Academic Alliances (SSAA) Symposium, February 28, 2008, Washington, DC.
- *A Theoretical Study of Level Density for Nuclei off the Stability Line*, Shaleen Shukla, poster presented at the 2008 Stewardship Sciences Academic Alliances (SSAA) Symposium, February 28, 2008, Washington, DC.
- *Bandenstrukturen in ${}^{12}\text{Be}$* H.G. Bohlen, W. von Oertzen, R. Kalpakchieva, T.N. Massey, S.M. Grimes, Tz. Kokalova, M. Milin, und Ch. Schulz Talk at the Spring Meeting of the German Physical Society, Darmstadt, March 10-14, 2008.
- *Level densities of residual nuclei from the reactions ${}^6\text{Li}$ on ${}^{58}\text{Fe}$ and ${}^7\text{Li}$ on ${}^{57}\text{Fe}$* , B. Oginni, S. M. Grimes, A. Voinov, A. Adekola, C. R. Brune, Z. Heinen, M. Hornish, T. N. Massey, C. Matei, D. E. Carter, J. E. O'Donnell, presented at the Meeting of the American Physical Society, 12-15 April 2008, St. Louis, Missouri.
- *Calculation of Level Densities for Nuclei Far from the Line of Stability*, S. Shukla and S. M. Grimes, presented at the Meeting of the American Physical Society, 12-15 April 2008, St. Louis, Missouri.
- *Recent Developments in R-Matrix Analysis*, C. R. Brune, invited talk presented at the Joint Institute for Nuclear Astrophysics R-matrix Workshop, Sante Fe, NM, 21 April 2008.

- *Band structures in ^{12}Be : experimental results*, H.G. Bohlen, W. von Oertzen, R. Kalpakchieva, T.N. Massey, S.M. Grimes, Tz. Kokalova, M. Milin, and Ch. Schulz
Talk at the First Workshop on State of the Art in Nuclear Cluster Physics, Strasbourg, May 13-16, 2008
- *Towards a Precision $^{235}\text{U}/\text{H}(n,n)\text{H}$ Measurement*, T. N. Massey, S. M. Grimes and T. S. Hill, presented at the Annual Meeting of the American Nuclear Society, June 8-12, 2008, Anaheim, California.
- *Experimental Study of Level Density and Gamma-Strength Functions at Edwards Accelerator Laboratory*, Alexander Voinov, presented at the Workshop on Statistical Nuclear Physics and Applications in Astrophysics and Technology, Athens, Ohio, July 8-11, 2008.
- *Nuclear Level Densities of Residual Nuclei from Evaporation from ^{64}Cu* , B. Moses Oginni, presented at the Workshop on Statistical Nuclear Physics and Applications in Astrophysics and Technology, Athens, Ohio, July 8-11, 2008.
- *Calculation of Nuclear Level Densities Near the Drip Line*, Shaleen Shukla, presented at the Workshop on Statistical Nuclear Physics and Applications in Astrophysics and Technology, Athens, Ohio, July 8-11, 2008.
- *Interference Effects Associated with the $E_{\text{c.m.}}=2.68\text{-MeV}$ Resonance in $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$* , D.S. Sayre and C.R. Brune, poster presented at the 10th Symposium on Nuclei in the Cosmos, Mackinac Island, MI, July 27 - August 1, 2008.
- *Excitation Function Measurements of $^9\text{Be}(\alpha, n)^{12}\text{C}$* , Z. Heinen, C.R. Brune, A. Adekola, S.M. Grimes, H. Hadizadeh, M.J. Hornish, T.N. Massey, C. Matei, B. Sayre, and A. Voinov, poster presented at the 10th Symposium on Nuclei in the Cosmos, Mackinac Island, MI, July 27 - August 1, 2008.
- *Astrophysically important ^{19}Ne states studied with the $^2\text{H}(^{18}\text{F}, \alpha + ^{15}\text{O})n$ reaction*, A.S. Adekola, D.W. Bardayan, J.C. Blackmon, C.R. Brune, K.Y. Chae, A.E. Champagne, C.P. Domizioli, U. Greife, Z. Heinen, M.J. Hornish, M. Johnson, K.L. Jones, R.L. Kozub, R.J. Livesay, Z. Ma, T.N. Massey, B. Moazen, C.D. Nesaraja, S.D. Pain, J.F. Shriner, Jr., J.S. Thomas, N.D. Smith, M.S. Smith, D.W. Visser, and A.V. Voinov, poster presented at the 10th Symposium on Nuclei in the Cosmos, Mackinac Island, MI, July 27 - August 1, 2008.
- *AZURE, An R-Matrix Computer Code*, R. deBoer, R.E. Azuma, C.R. Brune, H. Constantini, J. Görres, P.J. LeBlanc, E. Simpson, E. Uberseder, C. Ugalde, and

M. Wiescher, poster presented at the 10th Symposium on Nuclei in the Cosmos, Mackinac Island, MI, July 27 - August 1, 2008.

- *Transfer Reactions with Radioactive Ion Beams*, Carl R. Brune, invited talk presented at the Workshop on Experiments with Reaccelerated Beams at NSCL, Michigan State University, East Lansing, MI, August 2, 2008.
- *Nuclear Science Possibilities at the National Ignition Facility*
Carl R. Brune, Presented at the NIF and Photon Science Directorate Review, April 1, 2009.
- *Nuclear Level Densities*, S. M. Grimes, T. N. Massey, B. M. Oginni, S. Shukla and A. Voinov, presented at the Workshop on Gamma Strength Functions and Nuclear Level Densities, Oslo, Norway, May 11-15, 2009
- *Testing big bang nucleosynthesis at NIF*, Carl R. Brune, presented at the American Chemical Society Fall Meeting, Washington, DC, August 16-20, 2009.
- *R-Matrix Methods and an Application to $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$* , Carl R. Brune, lecture presented at the 5th European Summer School on Experimental Nuclear Astrophysics, Santa Tecla, Sicily, September 24, 2009.

IV.D Colloquia and Seminars

- C. R. Brune *Nuclear Astrophysics*, invited lecture series (3 one-hour lectures) presented at the School-cum-Workshop on Low Energy Nuclear Astrophysics, Saha Institute of Nuclear Physics, Calcutta, India, January 16-20 2006.
- C. Matei, *New measurements of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction*, Triangle Universities Nuclear Laboratory, Durham NC, March 2006.
- S. M. Grimes, *Nuclear Level Densities*, Michigan State University, April 13, 2006.
- S. M. Grimes, *The Role of Nuclear Level Densities in Nucleosynthesis*, Ohio University, May 19, 2006.
- S. M. Grimes, *The Nuclear Ramsauer Effect*, Seminar at Ohio University, October 9, 2007.

- C.R. Brune, *Nuclear Processes in Novae*, colloquium presented to the University of West Virginia Physics Department, November 1, 2007.
- C.R. Brune, *Some Recent Nuclear Physics Results Relevant to Understanding Novae*, seminar presented at LANSCE (Los Alamos National Laboratory), December 12, 2007.
- Aderemi Adekola made 4 one-hour seminar presentations on our ${}^2\text{H}({}^{18}\text{F}, \alpha + {}^{15}\text{O})n$ experiment at Ohio University, Southwest Baptist University, the University of Tennessee – Knoxville, and the University of North Carolina – Chapel Hill, Fall 2008.
- Babatunde Moses Oginni, *Test of Level Density Models from Nuclear Reactions*, seminar presented at Edwards Accelerator Laboratory, Ohio University, January 13, 2009.
- Carl R. Brune, *Proton-transfer study of unbound ${}^{19}\text{Ne}$ states via ${}^2\text{H}({}^{18}\text{F}, \alpha + {}^{15}\text{O})n$* , seminar presented at TRIUMF, Vancouver, Canada, January 15, 2009.
- Carl R. Brune, *Study of Astrophysically-Important ${}^{19}\text{Ne}$ States via ${}^2\text{H}({}^{18}\text{F}, \alpha + {}^{15}\text{O})n$* , seminar presented at Lawrence Berkeley National Laboratory, Berkeley, CA, July 30, 2009.
- S. M. Grimes, *Towards a more precise (${}^{235}\text{U}(f)/n$ -p elastic) ratio*, seminar presented at Lawrence Livermore National Laboratory, September 22, 2009.

V Personnel

V.A Personnel

- Carl R. Brune, Associate Professor, Co-Principal Investigator
- Steven M. Grimes, Distinguished Professor, Co-Principal Investigator
- David C. Ingram, Professor, Edwards Accelerator Laboratory Director
- Thomas N. Massey, Research Assistant Professor
- Andreas Schiller, Assistant Professor (September 2007 – present)

- Alexander Voinov, Visiting Assistant Professor (February 2004 – present)
- Nikolai Kournilov, Postdoctoral Fellow (December 2008 – present)

- Donald E. Carter, Nuclear Instrumentation Engineer
- Devon K. Jacobs, Accelerator Engineer
- John E. O'Donnell, Software Specialist
- Cindy White, Administrative Assistant (retired December 2008)

- Aderemi Adekola, Graduate Student (June 2004 – December 2008)
- Andrew Di Lullo, Graduate Student (September 2007 – June 2008)
- Zachary Heinen, Graduate Student (June 2004 – present)
- Daniel Sayre, Graduate Student (June 2006 – present)
- Shaleen Shukla, Graduate Student (June 2004 – June 2008)

- Babatunde Moses Oginni, Graduate Student (June 2005 – present)
- Harsha Attanayke, Graduate Student (September 2009 – present)
- Dilupama Divaratne, Graduate Student (September 2009 – present)

V.B Personnel Effort Breakdown

Table V.1 shows the personnel effort breakdown by year from 2007 to 2009.

V.C Degrees Granted

- Shaleen Shukla, M.S.
- Catalin Matei, Ph.D.
- Shaleen Shukla, Ph.D.
- Aderemi Adekola, Ph.D.
- Babatunde Moses Oginni, Ph.D.

| Person | Position | % Effort | Total Effort |
|------------------------|------------------------------|----------|---------------------|
| 2007 | | | |
| Carl R. Brune | Associate Professor | 9 % | 12 months |
| Steven M. Grimes | Professor | 9 % | 12 months |
| Thomas N. Massey | Research Assistant Professor | 50 % | 12 months |
| Alexander Voinov | Postdoctoral Fellow | 80 % | 12 months |
| John E. O'Donnell | Software Specialist | 100 % | 12 months, 3/4 time |
| Zachary Heinen | Graduate Student | 100 % | 6 months |
| Babatunde Moses Oginni | Graduate Student | 100 % | 6 months |
| Shaleen Shukla | Graduate Student | 100 % | 6 months |
| 2008 | | | |
| Carl R. Brune | Associate Professor | 9 % | 12 months |
| Steven M. Grimes | Professor | 9 % | 12 months |
| Thomas N. Massey | Research Associate Professor | 50 % | 12 months |
| Alexander Voinov | Postdoctoral Fellow | 80 % | 12 months |
| John E. O'Donnell | Software Specialist | 50 % | 12 months, 3/4 time |
| Zachary Heinen | Graduate Student | 100 % | 6 months |
| Babatunde Moses Oginni | Graduate Student | 100 % | 6 months |
| Shaleen Shukla | Graduate Student | 100 % | 6 months |
| 2009 | | | |
| Carl R. Brune | Associated Professor | 9 % | 12 months |
| Steven M. Grimes | Professor | 9 % | 12 months |
| Thomas N. Massey | Research Associate Professor | 50 % | 12 months |
| Alexander Voinov | Postdoctoral Fellow | 80 % | 12 months |
| John E. O'Donnell | Software Specialist | 50 % | 12 months, 3/4 time |
| Zachary Heinen | Graduate Student | 100 % | 6 months |
| Babatunde Moses Oginni | Graduate Student | 100 % | 6 months |

Table V.1: Breakdown of the personnel effort by year according to the fraction of time supported by this grant. The last column give the number of months the individual was supported by this grant during the indicated year. Personnel not listed here were supported completely by other means.

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