4 The Many-Nucleon Problem

4.1 Nuclear Astrophysics

4.1.1 Measurement of the $^{17}$O(p, $\alpha$)$^{14}$N Reaction at Stellar Energies

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When a star evolves from the main sequence and enters the giant branch, its atmosphere rapidly expands and becomes convective. This convective envelope dredges up material processed by nuclear burning in the interior and changes the relative abundances of elements in the star’s atmosphere [Ibe91]. The oxygen-isotopic abundance ratios have been shown to be a sensitive tracer of the dredge-up process and could provide important constraints on mixing theory. However, such a comparison suffers from a large uncertainty in the $^{17}$O(p, $\alpha$)$^{14}$N reaction rate (see e.g. [ElE94a]).

At stellar energies, the $^{17}$O(p, $\alpha$)$^{14}$N rate is believed to be dominated by a resonance at $E_p = 70$ keV, corresponding to $E_x = 5.673$ MeV in $^{18}$F [AS87]. At such low energies, the resonance strength is directly proportional to the proton width. However a direct measurement of this strength has proven to be very difficult because of Coulomb-barrier considerations and because of the low energy of the emitted alpha particle. The stripping reaction $^{17}$O($^{3}$He, d)$^{18}$F was studied by Landre et al. [Lan89], and a proton width of $\Gamma_p = 70^{+40}_{-57}$ neV was deduced from a DWBA analysis of their angular-distribution data. However, this width is in disagreement with an upper limit of $\Gamma_p \leq 3$ neV obtained from a direct $^{17}$O(p, $\alpha$)$^{14}$N measurement in which the resonance was not observed [Ber92].

We have completed our measurements of the $^{17}$O(p, $\alpha$)$^{14}$N cross section at energies of $E_p = 75$ keV, “on resonance,” and $E_p = 65$ keV, “off resonance.” A description of the experimental apparatus may be found in previous progress reports. Briefly, thick Ta$_2$O$_5$ targets were bombarded using an unpolarized beam from the TUNL atomic-beam polarized ion source. Beam currents on target of 400–450 $\mu$A were sustained throughout the experiment. Outgoing alpha particles were detected using six implanted silicon detectors mounted in close geometry, with active areas of 3.1 cm$^2$, and with no metal electrical contacts on their front faces. In order to shield the detectors from the intense flux of elastically scattered protons, high-quality nickel foils of 0.64 $\mu$m thickness were mounted in front of each detector.

Approximately 130 C of charge were collected at $E_p = 75$ keV on targets of enriched

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After gain-matching, the spectra from each detector were summed. The total data are shown in Figure 4.1–1. Because of a damaged Ni foil, only 5 detectors were operational for much of the data collection. Adding the integrated beam on target for each detector yields an equivalent single-detector total of $624^{+19}_{-42}$ C.

The background in this spectrum arises from several sources: cosmic rays, natural radioactivity, elastic protons, and the reactions $^{10}$B($p, \alpha$)$^7$Be, $^7$Li($p, \alpha$)$^4$He and $^6$Li($p, \alpha$)$^3$He. After background subtraction, the spectrum was fit using an $^{17}$O($p, \alpha$) template where the only variable quantity was the number of counts. A peak at the appropriate energy is clearly discernible (Figure 4.1–2).

We also performed a fit in which the location and area of the peak structure was allowed to vary simultaneously with the background. The number of counts in the peak as determined by this fit is $860 \pm 130_{\text{stat}}$. Its location is coincident with the expected location of the $^{17}$O($p, \alpha$) peak.

In order to ensure that this structure was in fact alphas from the $^{17}$O($p, \alpha$) reaction, we made another group of targets with natural oxygen isotopic composition. We then alternated the enriched $^{17}$O targets with the natural oxygen targets after approximately every 5 C of integrated beam. The total data taken on each type of target was fitted as before. The background-subtracted spectra are shown in Figure 4.1–3 along with the best fit $^{17}$O($p, \alpha$) peak. The total number of counts in the data taken with the $^{17}$O target were $465 \pm 65$, whereas the number of counts in the natural-oxygen spectrum were $9 \pm 54$. We repeated this measurement at a beam energy of $E_p = 65$ keV, i.e. below the resonance energy. The data were analyzed as described above and are shown in Figure 4.1–3. The number of counts at the location of the $^{17}$O($p, \alpha$) peak was found to be $44 \pm 55$. Because this is a resonant structure observed only with the enriched $^{17}$O target, and because it is located at the appropriate energy, we identify it as alphas from the 70 keV resonance in $^{17}$O($p, \alpha$)$^{14}$N.

The measured thick-target yield implies a most-probable value for the proton width of $\Gamma_p = 22 \pm 3_{\text{stat}} \pm 2 target + 2 beam$ neV. Since the latter two uncertainties are systematic, we do not combine them. To our knowledge this is the smallest proton-capture width to be measured, but it results in a reaction rate for $^{17}$O($p, \alpha$)$^{14}$N which is as much as a factor of 10 larger than the rate customarily used in model calculations. The error in our measurement of the proton width is small enough to now allow a quantitative comparison between observations of the $^{16}$O/$^{17}$O ratio in the atmospheres of red giants and stellar-model calculations [ElE94b]. With the new observations that are planned, it will be possible to place significant constraints on convection theory. An article describing this work has recently been published [Bla95].

Figure 4.1–1: Total of all data taken at $E_p = 75$ keV with enriched $^{17}$O targets. The smooth curve is the best fit to the background. The region where the resonance in $^{17}$O(p, $\alpha$)$^{14}$N is expected is indicated.

Figure 4.1–2: Difference between the raw data and background fit shown in Figure 4.1–1. Also shown is a fit assuming an $^{17}$O(p, $\alpha$)$^{14}$N peak.
Figure 4.1–3: Differences between collected data and best-fit backgrounds for enriched targets (on and off-resonance) and targets of natural composition (on-resonance). Also shown are the $^{17}\text{O}(p, \alpha)^{14}\text{N}$ peaks fit to the background-subtracted data.
4.1.2 The $^9\text{Be}(\vec{p}, \text{d})^8\text{Be}$ and $^9\text{Be}(\vec{p}, \alpha)^6\text{Li}$ Reactions at Low Energies

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The Be abundance in low-metallicity stars is an important probe of cosmic-ray and Big-Bang nucleosynthesis, as well as stellar evolution models [Boe93]. In particular, significant Be depletion is observed in some stars. This depletion presumably results from the mixing of material from the stellar surface with material from the interior where the temperature is sufficient for the $^9\text{Be}(\vec{p}, \text{d})$ and $^9\text{Be}(\vec{p}, \alpha)$ reactions to be effective. A previous measurement [Sie73] found the low-energy cross section in both reaction channels to be dominated by a broad ($\Gamma_{\text{tot}} \approx 120$ keV) s-wave $1^-$ resonance at $E_p = 330$ keV. At lower energies a significant but very uncertain contribution was attributed to an opposite-parity subthreshold state. This uncertainty is reflected in the estimated $S(0)$ value (summed over both reaction channels) of $35^{+45}_{-15}$ MeV-b. The $S(0)$ value essentially determines the reaction rate, as the effective energy for this reaction at stellar temperatures is $\sim 7$ keV. The existence of a state at 6.57 MeV excitation in $^{10}\text{B}$ (20 keV below the $^9\text{Be} + \text{p}$ threshold) has been established by many experiments, but spin and parity assignments are not definitive. For example, an analysis of $^9\text{Be}(^3\text{He}, \text{d})$ angular distributions [Bla80] favors negative parity for this state.

We have measured $A_{y}(\theta)$ and $\sigma(\theta)$ for both channels at seven energies in the range $80 \leq E_p \leq 330$ keV, using the LEBF facility. The proton beam was incident on targets consisting of $\approx 10$ $\mu$g/cm$^2$ $^9\text{Be}$ evaporated onto thin carbon foils. The reaction products were detected using Si detectors covered with Ni foils which stop elastically scattered protons with energies below $\approx 200$ keV.

The analyzing power data are sensitive to the interference between states of opposite parity, and will help determine the role of the subthreshold state. As a first step in the analysis, we plan to compare our results to predictions calculated from previously reported $R$-matrix parameters [Sie73]. The analyzing power data measured at a mean proton energy of 321 keV are shown in Figure 4.1–4. We find the largest analyzing power in the $(\text{p, d})$ channel to be at this energy, near the peak of the s-wave resonance.

Figure 4.1–4: Analyzing power data measured at a mean proton energy of 321 keV, near the peak of the s-wave resonance.
4.1.3 Measurement of the $^7\text{Li}(n, \gamma)^8\text{Li}$ Cross Section at $E_n = 1$–1000 eV

The flux of high-energy solar neutrinos is directly proportional to the rate of the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction which is the most uncertain rate in the proton-proton chain. It is determined from an extrapolation of existing $^7\text{Be}(p, \gamma)^8\text{B}$ cross section data ($E_p > 100$ keV) to solar energies. This procedure is complicated by the relatively poor agreement amongst the different data sets. However, this uncertainty is not the source of the solar neutrino problem. Although more accurate measurements will not resolve the solar neutrino problem, they will play an important role in its interpretation.

A recent measurement of a substantial p-wave analyzing power in the $^7\text{Li}(p, \gamma)^8\text{Be}$ reaction may have implications for this extrapolation procedure [Cha94]. A similar p-wave contribution to the $^7\text{Be}(p, \gamma)^8\text{B}$ cross section would imply a substantial reduction in the predicted flux of $^8\text{B}$ neutrinos. However, the source of this effect has not been identified conclusively. Unfortunately, a similar analyzing-power measurement using a $^7\text{Be}$ target is not feasible owing to the high flux of gamma radiation produced in the decay of $^7\text{Be}$. Nonetheless, it is possible to measure the analog reaction, $^7\text{Li}(n, \gamma)^8\text{Li}$. In this case, p-wave capture would manifest itself as a deviation from the expected $1/\nu$ behavior of the cross section at low energies. Because incident protons and neutrons sample different parts of the nuclear interior, observation of p-wave strength in $^8\text{Li}$ does not necessarily have implications for $^8\text{B}$. On the other hand, pure s-wave capture in $^8\text{Li}$ would imply s-wave capture in $^8\text{B}$ (neglecting the small d-wave component at low energies). In addition, the $^7\text{Li}(n, \gamma)^8\text{Li}$ reaction involves the same target as was used above and this may help to untangle the source of the p-wave strength in $^8\text{Be}$.

We have begun measurements of the excitation function for the ground-state transition in $^7\text{Li}(n, \gamma)^8\text{Li}$ over the energy range $E_n = 1$–1000 eV. These experiments have been carried out at the Oak Ridge Electron Linear Accelerator (ORELA). Gamma rays were detected using a heavily-shielded Ge detector placed approximately 26.5 cm from a target containing 25 g of $^7\text{Li}$ and 0.39 g of $^{10}\text{B}$. Containers of $^6\text{LiH}$ were placed between the target and the Ge detector in order to attenuate the flux of scattered neutrons at the detector. The 0.478 MeV gamma ray arising from the $^{10}\text{B}(n, \alpha\gamma)^7\text{Li}$ reaction was used to measure the neutron flux. Because the region of interest ($E_\gamma = 2.03$ MeV) is near a gamma ray produced by neutron capture in Ge, spectra were also taken using a Be scatterer in order to measure.

References:


the background from neutron capture in the detector. A sample spectrum is shown in Figure 4.1–5. We are determining the $^7\text{Li}(n, \gamma)^8\text{Li}$ cross section relative to that for the comparably well-known $^{10}\text{B}(n, \gamma)^{11}\text{B}$ cross section. Analysis of the data is currently in progress.


4.1.4 Sodium and Aluminum in Globular Clusters

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Because the stars in the globular clusters are old and coeval, their evolutionary paths have been used to infer the age of the galaxy. Overall, clusters are chemically homogeneous groups, but within a given cluster there can be a wide range in the abundances of particular

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elements. Some of these abundance variations may be interpreted in terms of stellar burning and evolution. For example, trends in C vs. N could simply indicate operation of the CN cycle during the main sequence. In addition, clusters of roughly the same age can exhibit marked chemical differences, particularly in the strength of CN. Some clusters as a whole can be characterized as “CN strong” while other clusters, which appear to be in the same evolutionary state, are “CN weak” [Nor88]. Although there is no evidence to suggest that these effects have any bearing on galactic age estimates, they do indicate that cluster chemistry is more complicated than what is assumed in deriving an age.

More recent observations show that within a cluster, the abundances of Na and Al are correlated with CN and anti-correlated with O. The interpretation of these observations has been controversial: On one hand, it can be argued that since these stars are not massive enough to produce or destroy Na and Al, these abundances and the overall CN signature reflect variations in the primordial gas from which the cluster formed [Sne92]. The fact that abundance variations exist within a given cluster may imply that the cluster developed rapidly, before homogenization could occur. However, the fact that cluster main sequences are rather narrow implies that the primordial gas was quite homogeneous in composition. In other words, this scenario requires significant fine-tuning of the initial conditions. On the other hand, it has been suggested [Lan93] that all of these observations can be accounted for if the envelopes of these stars are deeply mixed with the interior.

The mixing scenario produces Na and Al within the NeNa and MgAl cycles at low temperature. Our work on the reactions in the MgAl cycle indicates that mixing will not go deep enough to produce the Al signature. The situation regarding Na is not as clear because of large uncertainties (of up to factors of $10^4$) in the rates of several key reactions: $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$, $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$, and $^{23}\text{Na}(p, \alpha)^{20}\text{Ne}$. At the energies of interest, the cross sections for these reactions are too small to permit direct resonance measurements and therefore we have begun to study them via $(^{3}\text{He}, d)$ spectroscopy.

Implanted $^{22}\text{Ne}$ and evaporated $^{23}\text{NaBr}$ targets were bombarded at $E(^{3}\text{He}) = 20$ MeV. Outgoing deuterons were detected using 18 cm-long position-sensitive Si telescopes in the focal plane of the TUNL split-pole spectrometer. Unfortunately, noise in the clean-power system limited the resolution obtained to about 50 keV which was not adequate to cleanly identify the states of interest. However, we have partially analyzed the data obtained with the $^{22}\text{Ne}$ target. A spectrum obtained at $\theta_{\text{lab}} = 10^\circ$ (Figure 4.1–6) shows a number of known states in $^{23}\text{Na}$. The uncertainty in the rate of the $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$ reaction arises from possible states at $E_x \approx 8.862$ and 8.894 MeV which would correspond to resonances at $E_{\text{cm}} = 68$ and 100 keV, respectively. The region near the former state is obscured by the first-excited state of $^{17}\text{F}$. However, our preliminary results indicate that the latter state, if it exists, is quite weak.

We are currently addressing the noise problem in the Si detectors and further measurements are planned.
Figure 4.1–6: Deuteron spectrum from the $^{22}\text{Ne}(^3\text{He}, \, \text{d})$ reaction at $\theta_{\text{lab}} = 10^\circ$. The locations of possible $^{22}\text{Ne} + \text{p}$ resonances are denoted by arrows.


### 4.1.5 Nuclear Astrophysics with Radioactive Beams

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During astrophysical explosions, temperatures and densities reach extreme values. Under these conditions, nuclear reactions will proceed on time scales of fractions of a second.

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Thus any nuclei produced with comparable or longer half lives will become
targets for subsequent nuclear reactions. Some of these reactions are thought to be crucial
to our understanding of the explosive event itself, but direct measurements require the use
of radioactive beams. The HRIBF facility at Oak Ridge is designed to provide beams of
proton-rich radioactive nuclei for both nuclear-structure and nuclear-astrophysics studies.
First beams are scheduled for late 1995 to early 1996.

Since our measurements involve extreme inverse kinematics, we can take advantage of
kinematic focusing to detect recoils with high efficiency. However, because typical beams
and recoils have nearly identical momenta, clean separation of the recoils requires selection
on the basis of velocity. The experimental nuclear-astrophysics effort at the HRIBF is
centered around the Daresbury Recoil Separator (DRS) which was transferred to ORNL
in 1994. The DRS separates reaction products from the incident beam in two long (1.2
m) crossed-field velocity filters. In addition to the velocity filters, there are also 3 sets of
quadrupole triplets for focusing, 2 sextupole magnets to correct for 2nd order abberations,
and a dipole magnet which provides a q/m focus. The total device weighs 90 tons and is
13 meters in length.

The DRS was shipped from Daresbury to Oak Ridge in the fall of 1994, and installation
of the spectrometer began in early 1995. All of the elements arrived from Daresbury in
excellent condition. Presently, all of the magnets have been mounted on their stands and
aligned, and installation of the electrostatic components of the velocity filters is underway.
All of the power supplies have been switched to US power requirements and tested. The
physical layout of the DRS is nearly unchanged from its original configuration, however
we plan to run different optics in order to improve beam rejection. The chief change is
the addition of a new velocity focus between the two filters. The instrumentation at this
location will be built at TUNL as will two target chambers. One chamber is designed to
be used with arrays of BaF$_2$ detectors while the second will accomodate large Si detectors.
Another addition to the DRS is a new time-of-flight leg at the exit to the device. This is
under construction at Yale. Tests of the original focal-plane detector at Yale have indicated
that it will perform to our requirements.

Our initial measurements of the $^1$H($^{17}$F,$^{18}$Ne)$\gamma$ and $^1$H($^{17}$F,$^{14}$O)$^4$He reactions will ex-
amine the transition from the Hot CNO cycle to heavier nuclei. We have also continued to
access the feasibility of a $^1$H($^7$Be,$^8$B)$\gamma$ measurement. The chief problem here appears to be
the risk of activation in the tandem and beam transport owing to the long (53 day) half life
of the beam. However, initial calculations suggest that radiation levels will be tolerable.

4.2 High-Spin Spectroscopy and Superdeformation

As finite condensed-matter systems with strong short-range interactions, nuclei exhibit
a tremendous variety of properties that depend on a number of factors, including nucleon
number, angular momentum, and excitation energy. One manifestation of the dependence on nucleon number is the existence of spherical and deformed gaps in the single-particle energy levels, leading to strong variations in nuclear shape. Our research program focuses on two major areas: (I) Studies of nuclear properties associated with very elongated nuclear shapes (superdeformed shapes), and (II) Investigations of the evolution of nuclear collectivity as a function of particle number and also as a function of angular momentum and excitation energy. Among the collective modes investigated are the rotational excitations of prolate and oblate deformed nuclei, and octupole vibrational states in spherical nuclei. We have recently published the results of a study of dipole bands in the weakly deformed oblate nucleus $^{196}$Pb [Moo95].

With the construction and near completion of the GAMMASPHERE detection system at Lawrence Berkeley Laboratory, the experimental sensitivity for the study of nuclear collectivity has increased by orders of magnitude. We have now performed several experiments at this facility and a paper describing our investigation of superdeformation in $^{191}$Hg has recently been published [Car95].

### 4.2.1 Search for the Two-Phonon Octupole Vibrational State in $^{208}$Pb

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The first excited state of the doubly magic nucleus $^{208}$Pb has $J^{\pi} = 3^{-}$ and is interpreted as a one-phonon vibration of octupole character. The collectivity of this level is inferred from the observed $B(E3)$ value of 34 Weisskopf units. The vibrational nature of this state leads to the expectation of a multiplet of 2-phonon octupole states with $J^{\pi} = 0^+, 2^+, 4^+$, and $6^+$ at roughly twice the energy of the $3^-\text{ state}$ (i.e., around 5.2 MeV). While examples of multi-phonon quadrupole vibrational states are well known (see, for example, Reference [Apr87]), the expected 2-phonon octupole multiplet in magic nuclei has yet to be unambiguously identified.

An experiment to search for members of the 2-phonon octupole multiplet in $^{208}$Pb was recently performed at GSI by bombarding a thin $^{208}$Pb target with $^{208}$Pb beams at an energy of about 10% above the Coulomb barrier. A 2485 keV $\gamma$-ray was observed to be in coincidence with the $5^- \rightarrow 3^-$ and $3^- \rightarrow 0^+$ transitions in $^{208}$Pb and was attributed to the depopulation of one of the members of the 2-phonon multiplet [Wol92]. In a subsequent experiment performed at HMI, targets of $^{208}$Pb were bombarded with $^{64}$Ni and $^{82}$Se beams.

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A 2485-keV γ-ray was also observed in these measurements. However, the 2485-keV line was assigned to $^{207}$Pb [Sch92, Sch93], attributed to the decay of states populated in single-neutron transfer reactions on the basis of coincidence relationships with transitions in $^{65}$Ni and $^{83}$Se.

In order to confirm the placement of the 2485 keV γ-ray and to search for other members of the 2-phonon multiplet, we have performed a series of experiments using the recently upgraded ATLAS facility to provide 1305 MeV beams of $^{208}$Pb to bombard thick (∼50 mg/cm$^2$) targets of $^{208}$Pb and $^{209}$Bi. Gamma rays were measured using the Argonne-Notre Dame BGO Gamma Ray facility, consisting of 12 Compton suppressed Ge detectors surrounding an array of 50 BGO scintillators. A total of approximately $2.2 \times 10^6$ γ − γ coincidence events were recorded for each of the targets. Gamma-ray energies and intensities in $^{208}$Pb and other Pb isotopes were extracted from both the Pb and Bi target data sets. The spectra presented in Figure 4.2–1. were produced from Pb and Bi target γ − γ coincidence matrices by placing gates on the $3^{-} \rightarrow 0^{+}$ (2614 keV) transition in $^{208}$Pb. The identification of known coincident γ-rays is labeled. It is important to note that the 2485 keV line is observed to be only very weakly in coincidence with the gating transition in the Pb target data and not at all in the Bi data set. Furthermore, there are very few unidentified γ-rays seen in coincidence with these gates. A comparison of the spectra obtained from the two targets clearly shows that there is a substantial probability for the simultaneous excitation of both the target and projectile on the $^{208}$Pb target.

From the coincidence spectra, we have determined the relative intensities of γ-rays in $^{208}$Pb. The partial decay scheme of $^{208}$Pb relevant to our measurement is presented in Figure 4.2–2. The widths of the arrows are proportional to the measured intensities of the transitions. The intensities have been corrected for detector efficiency and internal conversion. States with spin up to 14ℏ were populated in the present reaction. We have observed the majority of the transitions between high-spin states reported in Reference [Sch93]. From the difference in the γ-ray intensity feeding and de-exciting levels in $^{208}$Pb, we have extracted the relative direct feeding strength. The direct feeding strength of the 5$^{-}$ state is roughly 40% of that of the 3$^{-}$ state and the higher-lying states are populated with 10% or less of the intensity of the 3$^{-}$ state. As demonstrated in Figure 4.2–2, our experimental sensitivity is such that we can identify transitions in $^{208}$Pb with intensities of ∼ 0.1%. We find no unidentified discrete transitions in $^{208}$Pb to this intensity level which can be associated with the decay of 2-phonon states.

An examination of Figure 4.2–1 reveals that there are very few unidentified discrete lines in the energy region expected for the decay of the 2-phonon multiplet (i.e., $E_{\gamma} \sim 2.0-2.8$ MeV). In the pure harmonic approximation, assuming $E3$ transitions, one would expect a decay half-life for the 2-phonon states of about $8 \times 10^{-12}$ seconds, nearly a factor of 3 longer than the stopping times of the recoiling Pb nuclei in our target. If, for example, the decay of the 6$^{+}$ and/or 4$^{+}$ members of the multiplet proceeds via $E1$ transitions to the 5$^{-}$ state, the lifetimes could be much shorter and the resulting γ-rays would be strongly...
Figure 4.2.1: Coincidence spectra gated on the $3^- \rightarrow 0^+$ transition in $^{208}$Pb obtained from the $^{208}$Pb target (top) and the $^{209}$Bi target (bottom) data sets. The strongest line (at $E_\gamma = 583$ keV) is the $5^- \rightarrow 3^-$ transition in $^{208}$Pb.
Figure 4.2–2: Decay scheme for $^{208}$Pb obtained from the $^{208}$Pb target data set. The widths of the arrows are proportional to the transition intensities. The level energies and transition energies are indicated in keV. The numbers in parenthesis correspond to the measured intensities and the uncertainties in the intensities, respectively.
Doppler broadened. We have searched our data for broad structures in coincidence with the transitions in $^{208}$Pb. While real quasi-continuum γ-rays are observed to be in coincidence with transitions in $^{208}$Pb, there is little evidence for Doppler-broadened lines in the energy region expected for the decay of two-phonon states. If one assumes the maximum Doppler shift and integrates the quasi-continuum over the corresponding bin size, the intensity in the quasi-continuum amounts to less than 5% of that of the $3^- \rightarrow 0^+$ transition. Therefore, we are able to set limits on the decay of two-phonon states of $\sim 0.1\%$ and 5% for stopped and Doppler shifted transitions, respectively.


4.2.2 Lifetime Measurements in Identical Superdeformed Bands

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The phenomenon of the so-called “identical” superdeformed (SD) bands (i.e., bands with transition energies or moments of inertia identical to those in neighboring nuclei) has been one of the most surprising and inexplicable results in nuclear structure physics to date. A large number of cases are now known to exist in both the $A \sim 150$ and $A \sim 190$ regions of superdeformed nuclei, but a satisfactory understanding of these observations is still lacking. Theoretical suggestions range from the possible presence of a new symmetry to subtle cancellation effects, from the continuous readjustment of the mean field with increasing angular momentum to new terms in the collective Hamiltonian. Our approach to this problem is to perform DSAM lifetime measurements to determine the deformation associated with pairs of identical SD bands. We have carried out experiments using Phase I of GAMMASPHERE, consisting of 55 Compton suppressed Ge detectors, on identical SD bands in $^{151,152}$Dy.

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Figure 4.2–3: Fraction of full Doppler shift, $F(\tau)$, for transitions in the SD bands of $^{151,152}$Dy and the yrast SD band of $^{151}$Dy.
In the Dy measurement, we used the reactions \(^{122}\text{Sn}(^{34}\text{S}, \text{xn})^{156-\text{x}}\text{Dy}\) with 175 MeV beams provided by the 88\(^{9}\) cyclotron at LBL. The target consisted of 1.0 mg/cm\(^2\) \(^{122}\text{Sn}\) on a thick Au backing. Since SD bands in both Dy isotopes are populated at this beam energy and the recoiling nuclei slow down and stop in the same target/backing combination, our experiment amounts to a “differential” lifetime measurement, i.e., it is free from the systematic uncertainties associated with stopping power formulations. Therefore, we are able to make a direct comparison of the deformation in the two nuclei.

Some five SD bands are now known [Nis95] to exist in the nucleus \(^{151}\text{Dy}\). One of these, band 4 in the notation of Reference [Nis95], has transition energies corresponding to the mid-point of the transition energies of the yrast SD band of \(^{152}\text{Dy}\) and is proposed [Nis95] to be the identical band of the \(^{152}\text{Dy}\) yrast band. We have extracted the fraction of the full Doppler shift, \(F(\tau)\), for transitions in the SD bands of \(^{151}\text{Dy}\) and the yrast SD band of \(^{152}\text{Dy}\). Preliminary results are presented in Figure 4.2–3. As can be seen in Figure 4.2–3, within the experimental error bars the fractional Doppler shifts indicate very similar lifetimes for the transitions within the bands. It does appear that band 4 in \(^{151}\text{Dy}\) has slightly larger Doppler shifts than those in the other bands in this nucleus and those in the yrast band in \(^{152}\text{Dy}\). This result suggests that while the differences in deformation between the bands may be small, the “identical” bands may not actually be so identical. We are in the process of performing detailed DSAM simulations in order to extract transition quadrupole moments for these bands, the results of which will allow the comparison to theoretical predictions.


### 4.2.3 Lifetime Measurements in \(^{184}\text{Pt}\)

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This study is one of a series of Doppler Shift Attenuation Method (DSAM) lifetime measurements in light platinum isotopes to investigate shape-coexistence and shape transitions in these nuclei. Previous measurements of lifetimes in the yrast band of \(^{184}\text{Pt}\) [Gar86] have established that there is a sharp increase in the transition quadrupole moment, \(Q_t\), at low spin followed by a rapid and significant decrease in the backbending region.

The present measurements were undertaken with the goal of determining the behavior of \(Q_t\) above the backbending region, and in the excited bands based on intruder configura-

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Figure 4.2–4: Lineshape fits to the 644 keV transition in $^{184}$Pt. The panels in the left (middle) column present fits (heavier line) to the spectra measured in the backward (forward) rings of GAMMASPHERE, while the rightmost panel shows the fit to the 90° spectrum. The arrows indicate the unshifted $\gamma$-ray energy.
The reaction $^{124}\text{Sn}(^{64}\text{Ni}, 4\text{n})^{184}\text{Pt}$ at 275 MeV was used to populate high-spin states in $^{184}\text{Pt}$. The target consisted of 1.0 mg/cm$^2$ $^{124}\text{Sn}$ on a thick Pb backing. The early implementation of GAMMASPHERE, consisting of 36 Compton suppressed Ge detectors, was used to measure the $\gamma$-rays. The data were sorted into $\gamma - \gamma$ coincidence matrices in which the $\gamma$-ray energies measured in an individual “ring” of GAMMASPHERE (i.e., those detectors located at constant polar angle with respect to the beam direction) were histogrammed against the $\gamma$-ray energies measured in any other detector. Coincidence gates were then set on those transitions in the bands of interest which were emitted after the recoiling $^{184}\text{Pt}$ nuclei had come to rest in the backing. A total of 7 spectra were obtained (corresponding to the 7 rings in the GAMMASPHERE’s early implementation) for both the yrast and excited bands in $^{184}\text{Pt}$.

The measured Doppler broadened $\gamma$-ray lineshapes are compared to lineshapes calculated using the analysis code LILIFI [Eml89, Eml87]. This code uses the TRIM85 [Zie85] electronic and nuclear stopping powers and allows the fitting of both the state lifetime and side-feeding lifetimes as free parameters. Examples of lineshape fits to the 644 keV transition in the excited band of $^{184}\text{Pt}$ are presented in Figure 4.2–4. Preliminary results indicate that the $Q_t$ values in the excited band are somewhat larger than those in the yrast band and that the $Q_t$ values in the yrast band increase again following the first backbend. The analysis of these data is continuing and the results will be compared to detailed cranked shell-model calculations in order to determine the deformation driving properties of the single-particle orbitals involved in these bands.


### 4.3 Phenomenology of Preequilibrium Nuclear Reactions

The exciton model of preequilibrium nuclear reactions provides a simple way to describe the continuum energy and angular distributions of particles emitted during energy equilibration in light particle induced reactions at incident energies of about 14 to 200 MeV. Over the years the model has proven to be quite adaptable to the inclusion of additional physics as well as remarkably successful at describing experimental results. Because of its
simplicity, its physical transparency, its utility, and its adaptability, the exciton model continues to be used in spite of the development of more microscopic and quantum mechanical models.

Work on the exciton model and the code PRECO-E has progressed by using relatively simple physical concepts and appealing to available data to direct choices between alternative formulations and to provide values for key model parameters that cannot be obtained from independent sources. Current work is concentrated on (nucleon, nucleon) or (N, N) reactions, which are the most straightforward to address.

4.3.1 Multiple Preequilibrium Emission

C. Kalbach Walker

It was originally expected that the main region of applicability of the exciton model would extend up to incident energies of about 60 MeV. In recent years, however, there has been increasing interest in energies up to around 200 MeV. Thus the exciton model, like other preequilibrium models, needs to be modified to allow more than one particle to be emitted during the nuclear equilibration process. Fortunately, in the exciton model this is a relatively straightforward process. All of the necessary equations and parameters are carried over directly from primary emission. On the other hand, a significant reprogramming effort is required to modify the code PRECO-E because of all of the extra physics that has been added to the model. This reprogramming has been completed and is in the last stages of study.

For the statistical geometry dependent hybrid (GDH) model [Bla83] and the quantum mechanical Feshbach-Kerman-Koonin (FKK) model [Cha94], the approximation has been made to consider only secondary preequilibrium emission that follows directly on primary preequilibrium emission. This so called “simultaneous” emission was thought (and later demonstrated [Cha94]) to be dominant, and inclusion of secondary emission after one or more two-body internal interactions substantially increased the calculational effort. In the exciton model and particularly in the code PRECO-E [Kal91] it is virtually no extra work to consider all secondary emission. This is what has been done.

Currently multiple preequilibrium emission is considered only after primary emission of either a proton or a neutron, even though primary emission of particles up through mass 4 is calculated. Likewise only secondary emission of nucleons is considered. From a physical standpoint, the nucleon channels should be the main ones involved in multiple preequilibrium emission, and neglecting the complex particle channels greatly reduces calculation time.

For the primary residual nuclei which can undergo secondary preequilibrium emission, PRECO-E is programmed to recalculate the mean square matrix element for the internal interactions using the excitation energy of the emitting nucleus. This is the more physical
result and gives better agreement with experiment than using the energy of the original composite nucleus.

Secondary preequilibrium emission accounts for about 35–50% of the reaction cross section for 90 MeV projectiles (with the amount decreasing with increasing $A$) and about 60% for $^{90}$Zr at 160 MeV. Primary emission is almost totally preequilibrium. Comparisons with the $^{58}$Ni + p data at 90 MeV [Kal83, Wu79] are given in Figure 4.3-1. All of the PRECO-E calculations were run with shell structure and collective pairing effects included using standard default parameter values. Isospin was assumed to be mixed.

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4.3.2 Exciton Model Input and Assumptions

C. Kalbach Walker

With the inclusion of secondary preequilibrium emission, the research effort is becoming more focussed on elucidating various physics questions related to the exciton model input and assumptions. Several issues in this category have been addressed.

Most of the general input needed for exciton model calculations for (N, N) reactions, including the initial particle-hole configuration and the pairing and shell gaps, is well specified [Kal95]. Recent work [Kal94, Kal95] also indicated preliminary values for model-specific parameters for systems at incident energies of 18 to 25 MeV, and confirmed that isospin is conserved in the preequilibrium phase of the reaction, though it appears to be substantially mixed at equilibrium. At 90 MeV, isospin appears to be mixed, but other model input is unchanged.

Symmetry energies for calculations where isospin is conserved are sometimes derived from the Q-values of (p, n) reactions. These, however, should not be appropriate for exciton model calculations since they contain the effects of shell structure and the pairing interaction which are included separately in the calculations. Thus PRECO-E has been coded to use the volume and surface (V+S) symmetry energy terms from the semi-empirical mass formula. Since the Q-value derived energies generally fall in the range between the V and V+S results, the sensitivity of exciton model calculations to the choice between these options was studied. Results for 18 MeV (p, p') spectra show that using only the volume term yields too much cross section for the neutron rich targets and destroys the systematic agreement previously obtained with experiment.

Another question studied was the assumed functional dependence of the mean square residual matrix elements causing nuclear equilibration. Because the interactions are both residual and effective they cannot be derived a priori. In 1973 [KC73] I determined empirically that for initial \( n = 3 \) states in nucleon induced reactions the values of \( M^2 \) varied as \( E^{-1} A^{-3} \), and they were assumed to be independent of the exciton number. Later, theoretical work by Gadioli et al. [Gad73] based on nuclear matter calculations suggested that \( E/n \) rather than \( E \) was the pertinent parameter, and this was eventually adopted. The effect was to reduce the amount of preequilibrium emission from the more complex (higher \( n \)) states populated later in the equilibration process. When comparisons with data [Kal95] indicated that more late-stage preequilibrium emission would be helpful in PRECO-E, calculations were run replacing \( n \) with its initial value of 3. In all cases slightly improved agreement is obtained. Thus it can now be concluded that the theoretical exciton number dependence does not carry over to the residual \( M^2 \) in the exciton model.

In extending this work to higher incident energies, new physical effects may need to be
considered. For instance, it was observed [Kal88] that the physical parameter determining the degree of forward peaking of continuum angular distributions changes dramatically at bombarding energies between 100 and 160 MeV. There is a substantial body of both \((p, p')\) and \((p, n)\) data in this energy region which can be interrogated to look for such effects in the energy spectra. A preliminary look suggests that the surface peaking of the initial target-projectile interaction which is evident at incident energies of 40 to 100 MeV [Kal85] has disappeared by 160 MeV, perhaps indicating an effectively longer range of the interaction due to pion exchange. There is also an indication from one pair of spectra that using the standard value of \(M_{pn}^2/M_{pp}^2 = 0.6\) underestimates the experimental \((p, n)\) to \((p, p')\) yield ratio suggesting that a higher value is needed. This work is in an early stage.

Work is continuing on developing a full set of global input parameters for the exciton model, particularly with regard to the residual two-body matrix elements, the systematics of isospin conservation with target mass and incident energy, and the transitions in behavior at bombarding energies around the pion rest mass.

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4.4 High Resolution Studies at Münster and Bochum

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Significant improvements have been made to the energy resolution characteristics of the 400-keV Münster accelerator [Sch92]. The HV terminal ripple is usually less than 12 V, and under favorable circumstances less than 4 V. For many of these experiments windowless gas targets were used. The target thickness could be varied from less than a monolayer of target material to relatively thick targets. The stability and reproducibility of the ion beam energy

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were less than 3 eV. The German group now has moved to Ruhr Universität Bochum, where there is a Tandem Dynamitron accelerator. Recent results include significant improvements in high resolution depth profiling utilizing heavy ions from the Dynamitron and observation of replica resonances which reflect atomic excitation processes.

4.4.1 Energy Loss Phenomena

The quantized energy loss of charged particles in matter is manifested in the yield curves of narrow nuclear resonances. There is a peak in the thick target yield curve near the resonance energy, followed by a plateau; this phenomenon is called the Lewis effect. The physical basis for this effect is that particles lose energy in discrete steps—some particles with an energy above the resonance will “jump over” the resonance and not contribute to the yield. The Lewis effect is only observed with very good energy resolution and very clean targets. To analyze such data the energy loss process must be well understood. Since for gas targets the Doppler effect is greatly reduced, we have studied the Lewis effect and related energy loss phenomena in windowless gas targets. Energy loss spectra were obtained for gas targets ranging from ultra-thin targets to thick targets. Data for very thin targets provide information on the atomic excitation mechanism at impact parameter $b = 0$, while thick target studies provide information on the energy loss spectra integrated over all impact parameters. For $^{21}\text{Ne}$ we observed a very pronounced Lewis peak—the first observation of the Lewis effect in a gas target.

For very good energy resolution and thin targets, atomic excitation effects must be included. These excitations result in echoes or replicas of the resonance at projectile energies above the resonance energy. For the 272 keV resonance in $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ a very clear replica resonance is observed. The energy of this replica resonance corresponds well to the L-shell excitation energy for the compound atom Na, not to the L-shell energy of the Ne target. Similar results were observed for a resonance in $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$. With the measured collision spectra, the thick-target yield curve was correctly simulated. These results were published recently [Sch94].

4.4.2 High Resolution Depth Profiling

The very high stopping power at projectile energies of a few hundred keV makes low energy resonances attractive for depth profiling measurements. To achieve the full potential, excellent beam energy resolution is required, and the target should be free of surface contaminants and cooled to reduce the Doppler spread. In our initial experiments [Sch93] we studied depth profiling with narrow resonances in the $^{18}\text{O}(p, \gamma)^{19}\text{F}$, $^{18}\text{O}(p, \alpha)^{15}\text{N}$, $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$ and $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reactions.

In recent measurements [Bec95] we determined precisely the resonance parameters of a low energy resonance ($E_p = 151 \text{ keV}$) in the $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction. We then studied
this resonance in inverted kinematics. This resonance occurs at $E_{\text{oxygen}} = 2.70$ MeV in the $^1\text{H}(^{18}\text{O}, \alpha)^{15}\text{N}$ reaction and thus is accessible to single-ended 3-MV accelerators. With the relatively good energy resolution of the Bochum Dynamitron, and the favorable characteristics of this resonance, our first results are comparable to those obtained using this approach at higher energy resonances. This resonance may be suitable as a new standard for depth profiling measurements with solid targets. Our studies with gas targets suggest that analysis of Doppler broadening in these reactions is sufficiently sensitive to reflect vibrational and rotational motion in the hydrogen molecules. Such investigations might be applied to the determination of bond strengths of hydrogen on the surface of solids.

### 4.4.3 Vibrations of Solid Neon

A cryogenic target UHV system has been built to study narrow nuclear resonances [Ber95a]. The crucial part of the system is a liquid helium cooled sample holder mounted on a goniometer. With this target system we have studied the 272 keV resonance in $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ at temperature of $\sim 8$ K. An extremely large Lewis effect is observed (peak to plateau of $\sim 2.5$ to $1$). The shape of the Lewis peak is affected by both electronic stopping and motion of the target atoms. Since the Doppler contribution is strongly reduced for a gas target, we studied this same resonance with a gas target under similar low temperature conditions. We used the information from these energy loss spectra in fitting the observed Lewis peak. The resulting experimental value for the Doppler width [Ber95b] agrees with estimates using an effective temperature calculated from the standard Debye temperature for bulk solid neon.

[Berheide95b] M. Berheide et al., 1995, to be published in the proceedings of the Twelfth International Conference on Ion Beam Analysis.

### 4.5 Nuclear Data Evaluation for $A = 3$–$20$

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TUNL efforts in nuclear data evaluation and dissemination are summarized as follows:
4.5.1 Data Evaluation Activities


The review of $A = 18–19$ is complete. Preliminary versions were issued ($A = 18$ in January 1994 and $A = 19$ in July 1994), and copies were mailed out to solicit corrections and suggestions. The final manuscript, entitled “Energy Levels of Light Nuclei, $A = 18–19$”, was submitted to *Nuclear Physics A* in July 1995. In addition, TUNL has completed entry into the NNDC Evaluated Nuclear Structure Data Files (ENSDF) of adopted levels, decay data, and (for the first time in this mass region) reaction data for $A = 18–19$.

Work has begun on the $A = 20$ evaluation. A preliminary version, written in collaboration with S. Raman of Oak Ridge National Laboratory, is expected in the fall of 1995.

4.5.2 World Wide Web Services

In the fall of 1994, the TUNL Nuclear Data Evaluation Group began developing its informational services on the World Wide Web (http://www.tunl.duke.edu/NuclData). This is part of an effort by the entire Nuclear Data Network to make its work more easily accessible to a larger community of basic and applied research workers. The capabilities of this new method of providing evaluated nuclear data were demonstrated at the NSAC/DNP Long Range Planning Town Meeting held in Durham, North Carolina in January 1995. The TUNL group has been encouraged by the response to this demonstration and by similar indications of interest from the applied scientific community. For example, the group was asked for and submitted (in collaboration with B. Doyle of Sandia National Laboratory) an abstract for a paper at the Ion Beam Analysis Conference (IBA-12) which took place in Tempe, Arizona in May 1995.

Currently, the following items are available:

- Energy Level Diagrams for $A = 4–20$ nuclei in the style of Fay Ajzenberg-Selove.
These diagrams provide a good overview of the major features of a nucleus.

- Abridged versions of the $A = 16, 17, 18$, and 19 evaluations. Full text, tables, and references are available, with search capabilities and hypertext links for navigating through the document. Adobe Acrobat technology allows these platform-independent documents to appear on the screen just as they would on the printed page.

- Adopted levels and decay data in ENSDAT style for $A = 3–20$ nuclei as well as reaction data for $A = 18$ and 19. This format is very similar to the Nuclear Data Sheets for higher-mass nuclei and is based on the information found in the NNDC Evaluated Nuclear Structure Data Files.

- Information on the status of the evaluations, lists of all published $A = 3–20$ compilations, instructions for obtaining reprints and preprints, and links to other Nuclear Data centers.

The TUNL group plans to release all future preprints and publications on WWW in the form described above, in addition to continuing publication in Nuclear Physics A. The WWW release will allow the reviews to be updated more frequently and made available to more researchers. In addition we have received permission from the publishers of Nuclear Physics A to provide abridged versions of Fay Ajzenberg-Selove’s earlier “Energy Levels of Light Nuclei” for $A = 5–20$, giving the user quick electronic access to nuclear information from several back issues of the Ajzenberg-Selove reviews. Our goal is to provide, in one convenient location, all available forms of evaluated data for the light-mass nuclei.