4 Nuclear Astrophysics

4.1 Radiative-Capture Reactions

4.1.1 Cross-Section Studies of the $^7\text{Li}(p,\gamma)^8\text{Be}$ Reaction at Low Energies

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Over the last few years, we have been studying the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction at energies $E_p = 80 - 0$ keV. Of particular interest for this experiment is the capture to the ground state and the first excited state of $^8\text{Be}$. Due to the proton's very low incident energy, the beam is stopped within the target and the cross sections previously measured have been for the full energy range from 80 to 0 keV. Evidence for $p$-wave effects in this energy range ([Cha94], [God96] for example) has led us to pursue measurement of the reaction cross section for smaller energy bins.

We performed the present measurements using three 10" × 10" NaI detectors. Although the energy resolution is poor ($\sim 3\%$), the efficiency for 17 MeV gammas is about 25 times higher than that of the available Ge detectors. Two 20 kV power supplies of opposite polarity were connected to the target chamber. The supplies are computer controlled and provide voltages from 0 to $\pm 20$ kV with an accuracy of better than 1 kV. Data have been taken using proton beams with both 80 keV and 60 keV incident energy. The incident proton beam can then be accelerated by the target bias to energies 20 keV above and below the incident energy. Data has been taken from 40 to 80 keV in 10 keV steps and from 60 to 100 keV in 5 keV steps. The times spent at each energy were set so that nearly equal statistical accuracies were obtained in each energy bin. Furthermore, the cycle time over the full voltage range was less than 1 hour for both measurements, allowing the data at different energies to be taken under similar experimental conditions.

The data have been partially analyzed and show a negative slope for capture to both the ground state and the first excited state of $^8\text{Be}$, as well as a large non-zero analyzing power down to 40 keV. Calculations are underway in an attempt to understand the data using a semi-direct capture model that includes the $E1$ and $M1$ direct-capture process and the effects of two higher $M1$ resonances and a subthreshold $E2$ resonance. With the inclusion of the subthreshold $2^+$ state at 16.6 MeV, the negative slope of the capture to the ground state can be reproduced if the capture to this state occurs at $55 \pm 5$ fm. The effect of this surprisingly large radius on the form of the wave function for the 16.6 MeV state is being

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investigated. This state is of particular interest because its $E1$ component is the isobaric analog of the ground state of $^8\text{B}$, which is the residual nucleus of the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, which is of central importance to the solar neutrino problem.


4.1.2 The $^9\text{Be}(p,\gamma)^{10}\text{B}$ Reaction at 100–0 keV


As part of an ongoing effort to understand the dynamics of proton-capture reactions at low energies, we have measured $^9\text{Be}(p,\gamma)^{10}\text{B}$. Studies of other light nuclei at these energies have revealed substantial analyzing powers at $90^\circ$ in some cases, while others have been consistent with zero. A non-zero $A_y(90^\circ)$ implies that two amplitudes of opposite parity are interfering, which means that there is probably $p$-wave as well as $s$-wave strength present in the reaction. For the current reaction, we have shown that the analyzing power can be explained as arising from the tail of a resonance of opposite parity interfering with the low-energy $s$-wave direct capture. This is in contrast to $^7\text{Li}(p,\gamma)^{10}\text{Be}$ which has a measured analyzing power larger than explained with resonant-tail effects [God97].

The thick $^9\text{Be}$ target was biased to -20 kV to increase the count rate because the cross section at 100 keV is approximately 5 times larger than at 80 keV, the maximum energy of the beam out of the polarized ion source. To monitor the beam current and carbon buildup with the target biased, a silicon surface barrier detector viewed the higher count-rate reactions $^9\text{Be}(p,d)^{10}\text{Be}$ and $^9\text{Be}(p,\alpha)^{16}\text{Li}$. The detector was placed behind a thin Ni foil at the end of a long snout coming out of the top of the target chamber at a $55^\circ$ angle to keep 20 keV secondary electrons and scattered protons from striking the detector. The $\gamma$-ray spectra were acquired using two large (130–140%) high-purity germanium (HPGe) detectors. One of the large detectors was kept at $90^\circ$ and the other was moved between $60^\circ$ and $120^\circ$.

The nearest resonance which can decay via $M1$ radiation to the $^{10}\text{B}$ ground state ($3^+$) is a $2^+$ state at $7.56$ MeV ($E_p = 0.99$ MeV) with a width of 100 keV (see Table 4.1–1). The computer code HIKARI was used to do a direct-capture plus $M1$ resonance fit of the $^9\text{Be}(p,\gamma)^{10}\text{B}$ data from Zahnow [Zah95]. The parameters from this fit were then used to calculate the effect of this resonance on the analyzing power at the energies that were measured in the present experiment. The tail from the resonance increased the analyzing

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power substantially and yielded a good fit to the data (see Figure 4.1–1). Even though the tail explained the analyzing power it had less than a 2% effect on the previously calculated S-factor [Cec92].

The first excited state ($1^+$) has two resonances that can decay via $M1$ radiation, but the higher energy one (7.75 MeV) is 22 times stronger. The third excited state ($1^+$) on the other hand, is affected by both $M1$ resonances since their strengths are approximately equal. Using the same method as for the ground state, the resonances for the different states were fitted and their effects calculated. Again the $M1$ resonance tails explain the observed analyzing power for the first excited state with little effect on the $S$ factor. The third excited state on the other hand does not have a good fit at the forward angle. In calculating capture to this state, it was necessary to assume that it was predominantly a $p_{1/2}$ single-particle state in order to obtain a negative analyzing power at backward angles. If, as predicted by the shell-model calculations of Cohen and Kurath [Coh67] we assume a dominant $p_{3/2}$ single-particle state, the predicted analyzing powers shown in Figure 4.1–1(d) change sign, in disagreement with our backward angle data.

Finally, the second excited state has no resonance that can decay via $M1$ radiation. The direct-capture calculation of the analyzing power with $M1$ direct-capture strength turned on was able to explain the small analyzing power measured for this state.

The analyzing power values measured for the different states in the $^9$Be($p\gamma)^{10}$B reaction are explained by $p$-wave ($M1$) resonant tails interfering with the direct-capture ($s$-wave) terms. The tails have a negligible effect on the astrophysical $S$ factor. A paper describing this work is being prepared and will be submitted to Phys Rev C.

Table 4.1–1: Radiative transitions in $^9$Be($p\gamma)^{10}$B [AS88]

<table>
<thead>
<tr>
<th>Initial state (MeV)</th>
<th>$J^\pi$</th>
<th>Lowest multipole (relative $M1$ intensity)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ground</td>
<td>0.72</td>
</tr>
<tr>
<td>$E_p = 0.32$</td>
<td>1$^+$</td>
<td>$E2$</td>
</tr>
<tr>
<td>7.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_p = 0.99$</td>
<td>2$^+$</td>
<td>$M1$ (25)</td>
</tr>
<tr>
<td>7.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_p = 1.08$</td>
<td>0$^+$</td>
<td>$M3$</td>
</tr>
<tr>
<td>7.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_p = 1.29$</td>
<td>2$^-$</td>
<td>$E1$</td>
</tr>
</tbody>
</table>

Figure 4.1–1: The analyzing power for direct capture to (a) the ground state, (b) the first excited state, (c) the second excited state, and (d) the third excited state with the calculated fits.


4.1.3 The $^{11}$B(\$p,\gamma\$)$^{12}$C Reaction at Low Energies


We have begun a study of the capture of low-energy polarized protons on $^{11}$B nuclei. A preliminary measurement of the reaction cross sections and vector analyzing powers, as a function of energy and angle, was carried out in order to determine the feasibility and potential problems of a more detailed measurement. This is a continuation of our effort to study the dynamics for low-energy ($p,\gamma$) reactions.

In the past, it has been a general assumption that at low energies pure s-wave amplitudes participate in capture reactions, see for example [Cec92]. However, in studies of low energy $p$ capture on Li [God96] and Be targets we have found that p-wave amplitudes also contribute. The evidence for p-wave amplitudes is found in asymmetric cross sections and in non-zero vector analyzing powers that indicate s-wave and p-wave interference. It is our intention to investigate low energy $p$ capture reactions on light nuclei with the aim of improving the methodology for extracting astrophysical reaction rates.

The first requirement for the measurement of $^{11}$B(\$p,\gamma\$)$^{12}$C was the production of a $^{11}$B target that is thick enough to stop the proton beam, durable enough to withstand the 20-50 $\mu$A of beam current available from the polarized ion source and reasonably pure in $^{11}$B content. Options available were producing the target by compressing a fine powder to make a $^{11}$B pellet, using a colloidal suspension to form a $^{11}$B film on a backing material, or evaporating $^{11}$B onto a metallic backing. The latter approach appeared to best meet our need for purity and durability, so two $\approx 99.0\%$ pure targets were produced by evaporating $\approx 10.5 \times 10^3$ Å of $^{11}$B onto a Ta backing. A very high boiling point, 2550 K, made it necessary to use electron-gun evaporation; even so, an evaporation rate of only 0.1-0.4 Å/sec was achieved.

The reaction is studied by stopping the beam of protons in the target and measuring the emitted $\gamma$ rays. During the runs the beam polarization is changed between the spin-up(+) and spin-down(-) state 280 times per minute to remove systematic uncertainties in the analyzing power measurements. The analyzing power,

$$A_y(\theta) = \frac{\sigma_+(\theta) - \sigma_-(\theta)}{\sigma_+(\theta) + \sigma_-(\theta)},$$

is sensitive to the interference of different capture strength multipolarities, for example s-wave and p-wave, especially at $90^\circ$ and can be used to determine the amplitudes and phases of the interfering terms.

The measurement of reaction cross sections and analyzing powers was performed at three different energies: 80, 90 and 100 keV. A -20 kV power supply was connected to

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the target rod and permitted us to boost the energy of the 80 keV proton beam that had been extracted from the ion source. The measured potential on the target was -19.5 kV when the power supply nominal voltage was 20 kV. In order to collect approximately equal statistics for the number of ground state γ rays detected at the different energies the run time was divided with a ratio of about 15:30:50 for the energies 100/90/80 keV. The target is of stopping thickness, therefore γ-ray production cross sections measured are integrated for all proton energies from the incident energy to 0. Thus, to obtain the energy dependent cross sections it is necessary for us to make several measurements at different energies and use the difference in measured γ-ray flux.

A collection of four detectors surrounded the target to measure the emitted γ rays. Three large NaI detectors were located at laboratory angles of 0°, 90° and 130°, and a 143% HpGe detector was located at 150°. Further details are summarized in table 1.

Table 4.1-2: Summary of detector positions.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Angle (Degrees)</th>
<th>Distance to Target (cm)</th>
<th>Solid Angle (sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI 1</td>
<td>11.1°</td>
<td>14.3</td>
<td>0.60</td>
</tr>
<tr>
<td>NaI 2</td>
<td>-89.3°</td>
<td>12.2</td>
<td>0.69</td>
</tr>
<tr>
<td>NaI 3</td>
<td>131.6°</td>
<td>13.9</td>
<td>0.61</td>
</tr>
<tr>
<td>HpGe 1</td>
<td>58.8°</td>
<td>8.8</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Preliminary analysis of the data indicates that strength, other than s-wave amplitudes, do contribute to the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ capture reactions. Thus far, preliminary analyzing powers have been determined for the 90 – 0 and 100 – 0 keV data. The γ ray from capture to the ground state shows zero analyzing power, while the γ ray from capture to the first excited state at 4.4 MeV has a non-zero analyzing power (see Figure 4.1–2).

When a complete analysis of this data set is completed, which will involve a more careful subtraction of the background, we will attempt to explain the results using a direct-plus-resonance capture-model calculation, HIKARI, which will include the effects of the $2^+$ state at $E_x = 16.1$ MeV.


Figure 4.1-2: Preliminary results for the analyzing powers \((A_\gamma)\) as a function of the center-of-mass angle for the \(^{11}\text{B}(p\gamma)\) reaction at 100 keV. The circles indicate analyzing powers for capture to the ground state and the diamonds indicate analyzing powers for capture to the 4.4 MeV state of \(^{12}\text{C}\).

4.1.4 Feasibility Study of the \(^{12}\text{C}(\alpha,\gamma)\)\(^{16}\text{O}\) Reaction

J. H. Kelley, B. J. Rice, M. Spraker, and H. R. Weller

The \(^{12}\text{C}(\alpha,\gamma)\)\(^{16}\text{O}\) reaction rate at astrophysical energies is important for understanding the helium burning rate in stars and the production of elements that are heavier than carbon [Zha93]. This reaction rate is not well known at stellar energies. In order to determine the feasibility of a detailed measurement of the reaction dynamics, we have begun a basic study of count rates, available beam currents and background levels. Because the \(^{12}\text{C}(\alpha,\gamma)\) rate at energies less than 1 MeV is so small, we chose to initiate our study using an \(\alpha\) beam energy of \(\sim 3.1\) MeV. At this energy the reaction cross section is still only \(\approx 50\) nb. The modest beam energy permitted the use of a 99.9\% isotopically enriched 100 \(\mu\)g/cm\(^2\) target, without causing large energy losses.

In the TUNL High Resolution Laboratory, the maximum bending limit of \(^4\text{He}^{+1}\) particles is 2.4 MeV when running without a stripper foil. Under the simple conditions of using 2.4 MeV \(^4\text{He}^{+1}\) we were able to deliver a beam current of 13 particle \(\mu\)A to a beam stop that followed our target position; a total beam current of \(\sim 25\) particle \(\mu\)A was extracted from the accelerator. The desired beam energy of 3.1 MeV \(^4\text{He}^{+1}\) is too rigid to bend around the 15\(^\circ\) angle in the dipole selection magnet. Therefore, in order to transport the higher energy \(^4\text{He}^{+2}\) particles through the dipole, a mechanism with a retractable 10 \(\mu\)g/cm\(^2\) \(nat\ C\) foil was substituted in the place of a set of slits that proceed the dipole selection magnet. A beam current of 1-2 particle \(\mu\)A of \(^4\text{He}^{+2}\) particles was transmitted to the reaction target with the stripper foil in place.
The small reaction cross section for producing \( \gamma \) rays in this reaction gave rise to major concerns of background contamination. Backgrounds originated from 3 major areas: cosmic-ray background, reactions of beam particles that scatter along the beamline and beam stop, and reactions of beam particles with contaminants in the target.

In the course of our study it became clear that background was a significant problem in our setup. A serious concern in any \((\alpha, \gamma)\) reaction measurement is with \(^{13}\text{C}\) impurities in the target. The \(^{13}\text{C}(\alpha, \gamma)\) reaction is \(10^6\) times larger than the \(^{12}\text{C}(\alpha, \gamma)\) cross section with 3.1 MeV \(^4\text{He}\); therefore, improvements in the target purity will be necessary for a definitive measurement. It appears, however, that large beam current losses in the beamline preceding our target gave rise to radiation that overwhelmed the detectors. Beam current losses of order 20 particles \(\mu\text{A}\) were lost within 10 meters of the reaction target and detector area. Shielding was not adequate to significantly reduce this background.

In the future, improvements in beam tuning will reduce background contamination and increase the current on the target. Furthermore, better shielding of upstream beamline should reduce the background levels. When a reliable method of beam delivery and background reduction is found we will initiate a systematic measurement of the \(^{12}\text{C}(\alpha, \gamma)\) reaction dynamics to lower beam energies. If it becomes feasible to use HPGe detectors in the setup, we will use the 5-HPGe Compton polarimeter and require a coincidence between an event in the central detector and a 0.511 keV escape event in one of the side crystals. This is expected to significantly reduce the background.

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4.1.5 Measurement of the \(^{16}\text{O}(\gamma,\alpha)^{12}\text{C}\) Cross Section at Astrophysically Significant Energies

P. F. Bertone, A. E. Champagne, and C. Iliadis

In addition to being one of the two key reactions in the helium burning phase of stellar evolution, the \(^{12}\text{C}(\alpha, \gamma)^{16}\text{O}\) reaction has a critical role in determining the structure of a presupernova star, including the iron core mass. As a result, its rate is an important factor in deciding which stars will become black holes rather than neutron stars. Understanding the rate of this reaction in a stellar environment requires knowledge of the cross section at very low energies \((E_{\text{c.m.}} = 300 \text{ keV})\). Due to Coulomb penetrability considerations, direct measurement at this energy is impossible with current experimental techniques. Therefore, extrapolations are made from higher energy data. This procedure is made more reliable by using information on the two subthreshold states of \(^{16}\text{O}\) obtained from indirect methods along with the relative \(E1\) and \(E2\) contributions to the cross section ascertained from \(\gamma\)-ray angular distributions [Rol88].
Excellent progress in reducing the uncertainty in the astrophysical $S$ factor at $E_{c.m.} = 300$ keV has recently been made by other investigators [Oue96, Azu94]. Direct measurement of the $\alpha$-capture cross section presents many formidable challenges, most notably very low $\gamma$-ray yields and high neutron induced $\gamma$-ray background from the $^{13}\text{C}(\alpha,n)$ reaction. It has been suggested that, by employing the principle of time-reversal invariance, the uncertainty in $S$ (300 keV) could be reduced by performing a measurement of the differential cross section of the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction, in reverse kinematics, using a monoenergetic $\gamma$-ray beam from the High-Intensity Gamma-Ray Source (HIGS) at the Duke Free-Electron Laser Laboratory (DFELL) [Cha96]. As with $\alpha$-capture, low yield is a dominant issue with the $\gamma$-ray capture approach. However, based on recently published predictions about the intensity of the $\gamma$-ray beam [Car96], all of the target configurations currently under consideration yield count rates competitive with the $\alpha$-capture experiments. Hence, whether a reverse capture experiment will improve on the present situation depends in large part on the nature of background sources. Of primary consideration is the presence of high-energy bremsstrahlung, produced by electrons interacting with residual gas atoms in the FEL storage ring, in the $\gamma$-ray beam. This unwanted radiation will impinge on secondary or contaminant elements in the target, produce charged particles, and thereby pollute the spectrum of $\alpha$-particles from the $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ reaction. Monte-Carlo calculations of the electron bremsstrahlung, and preliminary measurements suggest that the intensity of this source of background will not be negligible [Sch96]. We have identified several detector/electronics schemes that, in principle, will handle rejection of unwanted particles with sufficient efficiency. We are currently examining the issues involved in determining which approach will provide optimal results with minimal complexity and expense. Current and future plans to achieve this end include performing computer simulations, investigating the details of background yields from prospective targets, and testing methods of background rejection.


4.1.6 The $\beta$-Delayed Proton Decay of $^{17}$Ne and the $^{12}$C($\alpha,\gamma$)$^{16}$O Reaction Cross Section


The $\beta$-delayed proton decay of $^{17}$Ne to $\alpha$-emitting states in $^{16}$O is being studied with the goal of constraining the $E2$ component of the $^{12}$C($\alpha,\gamma$)$^{16}$O reaction rate. This reaction is dominated by two subthreshold resonances. While knowledge of the contribution from the $E1$ component has been improved considerably from study of the $\beta$-delayed $\alpha$ decay of $^{16}$N, the $E2$ contribution is still poorly known. We first studied the $\beta$-delayed proton decay of $^{17}$Ne to excited states of $^{16}$O by measuring proton-$\beta$ and proton-$\gamma$ coincidences. This decay populates both $1^-$ and $2^+$ states in $^{16}$O. In our previous study of the $\beta$-delayed $\alpha$ decay of $^{16}$N only the $1^-$ states were populated.

A $^{17}$Ne beam of intensity up to $10^5$ ions/s was produced at the TISOL facility at TRIUMF by bombarding a MgO target with 500 MeV protons and extracting a mass 17 beam from an on-line ECR source. We have observed transitions to the $2^+$ state at 6.917 MeV in $^{16}$O from $^{17}$F states at 11.193, 10.0, 9.45, 8.83 and 8.44 MeV. In particular, the transition from the 9.45 MeV state is an order of magnitude stronger than the accompanying transitions to the $1^-$ state at 7.117 MeV and the $3^-$ state at 6.130 MeV, and seems a favorable case for the observation of the breakup into $\alpha + ^{12}$C. Two new proton decay branches have been observed for the isobaric analogue state (IAS) in $^{17}$F at 11.193 MeV. We have also observed, in triple coincidence, the breakup of the IAS into three particles via two channels: decay to the 9.59 MeV state in $^{16}$O which breaks up into an $\alpha$ particle plus $^{12}$C, and $\alpha$ decay to the 2.365 MeV state in $^{13}$N which breaks up into a proton plus $^{12}$C. This is the first reported observation of the decay of the IAS to the $1^-$ state in $^{16}$O at 9.59 MeV. This work has been submitted recently for publication and could provide information on the $E1$ and $E2$ components of the $^{12}$C($\alpha,\gamma$)$^{16}$O reaction cross section.

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4.1.7 Investigation of $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ and $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ Using ($^3\text{He},d$) Spectroscopy

J. C. Blackmon, A. E. Champagne, S. E. Hale, V. Y. Hansper, C. Iliadis, and D. C. Powell

The reactions that produce and destroy sodium in globular cluster red giants depend in part on low-lying ($p,\gamma$) resonances. The reaction rates that change the sodium abundances are important in explaining observed sodium-oxygen abundance anticorrelations [Lan93]. One of the possible explanations for the observations is a theory of deep mixing between the envelope of the star and the upper levels of the hydrogen burning shell [Swe79]. Because the temperature gradient is steep across this region, the rates of proton-induced reactions can vary greatly depending on the depth the mixing reaches. There are resonances in two of the reactions which affect the sodium abundances, $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ and $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$, which currently have sizeable uncertainties. At the stellar energies involved in the appropriate temperature region, $T_9 = 0.03-0.08$, the resonance reactions are dominated by the proton partial width, $\gamma_p$. We are measuring the proton-stripping reactions $^{22}\text{Ne}(^3\text{He},d)^{23}\text{Na}$ and $^{23}\text{Na}(^3\text{He},d)^{24}\text{Mg}$, which will then be compared with DWBA calculations to determine $\gamma_p$.

We have been using the Enge spectrometer to measure the angular distributions of the exiting deuterons from the two reactions. We conducted a week-long run in March, 1997. Using the new multi-angle aperture, we obtained 18 angle settings for the two reactions at $E_{^3\text{He}} = 20$ MeV. The position measurements of the focal-plane detector were calibrated using the known spectra of $^{27}\text{Al}(^3\text{He},d)^{28}\text{Si}$ [Cha86].

The results of the March run showed that the $^{23}\text{Na}$ target, made by evaporating NaI onto a 20 $\mu g/cm^2$ thick carbon foil, was adequate over the range of $5^\circ$ to $19^\circ$. Above $19^\circ$, however, the background from the iodine becomes prohibitive. An initial spectrum for $^{23}\text{Na}(^3\text{He},d)^{24}\text{Mg}$ at $\theta = 15^\circ$ is shown in Figure 4.1–3. The $^{22}\text{Ne}$ target appears to have lost enough of the implanted nuclei to require making another implanted target. During June, 1997, one new target was made using the UNC-Chapel Hill ion implanter. A 40 $\mu g/cm^2$ thick carbon foil was exposed to a total of 12.3 $\mu A\cdot h$ of beam. More implanted targets, both $^{22}\text{Ne}$ and $^{23}\text{Na}$, will be made before the end of the summer to finish the angular distribution studies.


Figure 4.1-3: Deuteron spectrum from $^{23}\text{Na}(^{3}\text{He},d)^{24}\text{Mg}$ at $E_{3\text{He}} = 20$ MeV and $\theta = 15^\circ$. Peaks are labeled by excitation energy in $^{24}\text{Mg}$ or as background final states.

### 4.1.8 Determination of the Rate for the $^{24}\text{Mg}(p,\gamma)^{25}\text{Al}$ Reaction at Low Stellar Temperatures

**A. E. Champagne, C. A. Grossmann, S. E. Hale, V. Y. Hansper, C. Iliadis, L. K. McLean, E. F. Moore, and D. C. Powell**

Isotopic anomalies (C, O, N, Na, Al, and Mg) observed on the surface of globular cluster red giant branch stars are thought to be the result of mixing of material from the envelope into regions of hydrogen burning [Swe79]. Recent observations made by Shetrone show an anticorrelation between the isotopic abundances of Al and $^{24}\text{Mg}$ on the surfaces of M13 red giant stars [She97]. The rates of production of Al and destruction of $^{24}\text{Mg}$ depend on the $^{24}\text{Mg}(p,\gamma)^{25}\text{Al}$ reaction rate at stellar temperatures $T_0 \sim 0.04 - 0.07$ [Cav], which is influenced by the total width, $\gamma$, of the $E_p = 223$ keV resonance [Zai97].

The total width of the $E_p = 223$ keV resonance can be determined experimentally using two methods. The first method requires measuring the resonance strength $\omega_\gamma$ and the ratio, $\gamma/\gamma$, of the $\gamma$-ray partial width to the total width of the state of interest. The total width, $\gamma$, can be determined from these two measurements. Measurement of the ratio, $\gamma/\gamma$, at the High Resolution Laboratory was made by exciting the $E_p = 1616$ keV resonance.
and detecting the $\gamma$-ray cascades feeding and decaying from the $E_x = 2485$ keV compound nuclear state (see Figure 4.1-4). The target was fabricated by reducing $^{24}$MgO with Zr and evaporating $^{24}$Mg onto a 0.25 mm thick Ta backing. A 10 $\mu$A proton beam was incident on the target which was water cooled to prevent target deterioration. A 145% high purity germanium detector was placed at an angle of 55° with respect to the incident beam and located at a distance of 6 cm from the target center to the front face of the detector. Photopeak efficiencies were determined from a calibrated $^{56}$Co source placed at the target location. Due to the close proximity of the target and detector, summing corrections to all $\gamma$-ray data are required. A preliminary analysis yields a value of $\lambda/\gamma = 0.922 \pm 0.032$.

![Gamma-ray spectrum](image)

Figure 4.1-4: $\gamma$-ray spectrum for the $^{24}$Mg$(p,\gamma)^{25}$Al reaction at $E_p = 1616$ keV. The efficiency corrected intensities of the labeled peaks determine the ratio $\Gamma_\gamma/\Gamma$.

The strength $\omega_\gamma$ of the $E_p = 223$ keV resonance was measured utilizing the polarized ion source and the minitandem. The value for $\omega_\gamma$ is determined by simultaneously measuring the resonant $\gamma$-ray yield and the intensity of elastically scattered protons [Tra75]:

$$\omega_\gamma = \frac{8\pi\Delta_{res}}{\lambda^2} \frac{Q_R Y_\gamma}{Y_R \text{Eff}(E_\gamma)} \frac{d\Omega_p}{d\Omega} \frac{d\sigma_R}{d\Omega}(\theta_{c.m., E_p c.m.,}),$$

with $\lambda$ the de Broglie wavelength of the incident protons, $\Delta_{res}$ the target thickness, $Q_R$ ($Q_\gamma$) the total charge accumulated for the proton ($\gamma$-ray) spectrum, $Y_R$ ($Y_\gamma$) the observed proton ($\gamma$-ray) yield, $d\Omega_p$ ($d\Omega_\gamma$) the efficiency of the proton ($\gamma$-ray) detector, $\text{Eff}(E_\gamma)$ the
photop eak e/#0Eciency of the \( \gamma \)-ray detector, and \( (d\sigma_R/d\Omega) \) the Rutherford scattering cross section. A proton beam with an intensity of 200 - 500 nA was incident on a \( ^{24}\text{Mg} \) target evaporated onto a 20 \( \mu \text{g/cm}^2 \) carbon backing. The charged particle detector was positioned at an angle of 155° with respect to the beam direction and at a distance of 11 cm from the target. A 128% high purity germanium detector was located at an angle of 135° and a distance of 6 cm. Efficiency data were taken with a \(^{56}\text{Co} \) source. The data is presently being analyzed.

The second method for determining the total width \( \gamma \) will be a measurement of the mean lifetime \( \tau \) of the \( E_x = 2485 \text{ keV} \) state using the Doppler Shift Attenuation Method (DSAM). The width of the state is then determined through the relation \( \gamma = \hbar/\tau \). The state of interest will be populated by \( \gamma \)-ray decay of the \( E_p = 1616 \text{ keV} \) resonance. Implanted \(^{24}\text{Mg} \) targets have been prepared utilizing the ion implantor at UNC. The targets were fabricated with 100 keV \(^{24}\text{Mg}^+ \) ions incident on a 0.5 mm thick Ta backing. The accumulated dose was 450 \( \mu \text{A-h} \). The DSAM experiment will take place at the High-Resolution Laboratory.

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4.1.9 Measurement of \(^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti} \) at \( E_\alpha \leq 6.0 \text{ MeV} \)

\( A. E. \) Champagne, S. E. Hale, V. Y. Hansper, and D. C. Powell

The \(^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti} \) reaction is part of the sequence of alpha-capture reactions which occur during silicon burning. It plays an important role in the production of \(^{44}\text{Ti} \) and its daughter, \(^{44}\text{Ca} \), where the former leaves signature gamma radiation that can be readily observed by orbiting telescopes like GRO. The latter decay product, \(^{44}\text{Ca} \), can also be observed in presolar meteorite grains [Nit96].

The importance of this reaction is emphasized in that \(^{44}\text{Ti} \), and thereby also \(^{44}\text{Ca} \), is uniquely produced by alpha-rich freeze out in Type II supernovae [Arm96]. There is currently only one previous measurement of this cross section, \([\text{Coo77}]\), made in the alpha-bombarding energy range of 2.75 to 4.00 MeV. Their results gave data which was more than a factor of two less than that predicted by theory. Typical cross sections at these energies would be of the order of tens of nanobarns, with many of the gamma rays of interest sitting
on a large Compton background. Even with the difficulty that such a measurement presents, the importance of this reaction makes a second such measurement highly desirable.

Initial tests of targets, including Rutherford backscattering measurements were made earlier this year. These also allowed beam current integration tests of a recently made target chamber. The design of this chamber is such that it permits both a Germanium detector to be positioned at either 35 and/or 55 degrees, and a surface barrier detector (or CPD) to be placed at backward angles of 125 and/or 145 degrees. Further, they enabled assessment of the detection configuration to be made. The results emphasized the need for shielding of background gamma rays as much as possible, and that a high beam intensity was desirable.

In preparation for a more recent measurement, the disused -15 degree leg in target room 4 of TUNL was completely disassembled, cleaned, realigned and reconfigured. This included repairs to a backing pump and tests of a refurbished turbo pump. The new configuration included a cold trap situated above the pump stand. The above mentioned chamber was also included in the beam line. This measurement looked for a strong resonance in the reaction, so that extra target information could be obtained. Unfortunately, problems with the alpha source of the TUNL tandem system hindered a significant part of this experiment, and further testing will be required.


4.2 Nucleon Induced Reactions

4.2.1 The $^9$Be($\bar{p},d$)$^8$Be and $^9$Be($\bar{p},\alpha$)$^6$Li Reactions at Low Energies

C. R. Brune, H. J. Karowski, and E. J. Ludwig

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 $^9$Be($p,d$)$^8$Be and $^9$Be($p,\alpha$)$^6$Li reactions to be significant. A previous measurement [Sie73] found the low-energy cross section in both reaction channels to be dominated by a broad ($\sim 120$ keV) s-wave $1^-$ resonance at $E_p = 330$ keV. At lower energies an important contribution was attributed to an opposite-parity subthreshold state at $E = 6.57$ MeV in $^{10}$B. This assumption causes the $S$-factor to have a significant but uncertain energy dependence as $E \to 0$. This uncertainty is reflected in the estimated $S(0)$ value (summed over both reaction channels) of $35_{-15}^{+45}$ MeV-b.

We have measured angular distributions of cross section and analyzing power for seven energies with $77 \leq E_p \leq 321$ keV. We find the analyzing power at low energies to be very small, which is inconsistent with the properties of the 6.57-MeV state assumed in [Sie73]. We have however confirmed the finding of [Sie73] that the $^9$Be($p,d$)$^8$Be differential cross section is highly anisotropic about $\theta_{c.m.} = 90^\circ$. In Figure 4.2-1 we show the energy dependence of the dominant Legendre coefficient in the cross-section expansion, $a_1$. The highly negative value of this coefficient at very low energies is unusual – in fact it was this finding which led previous workers to assume that the tail of the subthreshold state was making a substantial $p$-wave contribution to the cross section.

Our analysis indicates that the cross section and analyzing power data cannot be described by interference between the positive-parity subthreshold state and other known states above the threshold. Calculations in the direct reaction framework have been more successful. The weak binding of the valence neutron in $^9$Be and the near-zero $Q$-value of the $^9$Be($p,d$)$^8$Be reaction are especially favorable for direct reactions at energies below the Coulomb barrier. We have carried out distorted-wave born approximation (DWBA) calculations utilizing optical potentials determined at higher energies, and a previously-determined neutron spectroscopic factor. The calculated total cross section is in agreement with that determined in [Sie73]. The calculated $a_1$ coefficient is in good agreement with the data, as shown in Figure 4.2-1. The calculated analyzing powers are very small, in general agreement with our measurements. We thus conclude that the anisotropy in the low-energy $^9$Be($p,d$)$^8$Be angular distribution can be satisfactorily understood using the direct reaction mechanism, without contribution from the subthreshold resonance. The energy dependence of the $S$ factor from the DWBA calculation varies smoothly as $E \to 0$, implying that
a smooth extrapolation of the lowest cross-section measurements should provide a reliable $S(0)$ value.

![Angular distribution coefficient $a_1$ for $^6\text{Be}(p,d)^7\text{Be}$ as a function of energy.](image)

Figure 4.2–1: The experimental (squares) and calculated (solid line) angular distribution coefficient $a_1$ for $^6\text{Be}(p,d)^7\text{Be}$ as a function of energy.


### 4.2.2 The Reaction $^{35}\text{Cl}(p,\alpha)^{32}\text{S}$ in Explosive Hydrogen Burning


In a new class of novae, so-called neon novae, the energy production and nucleosynthesis is believed to derive from the accretion of hydrogen-rich material onto the surface of a ONeMg white dwarf. A thermonuclear runaway occurs converting $^{20}\text{Ne}$ and $^{24}\text{Mg}$ into heavier nuclei via sequences of proton-capture reactions and $\beta$-decays. For certain target nuclei, ($p,\gamma$) reactions must compete with energetically favorable ($p,\alpha$) reactions. If the ($p,\alpha$) reaction is dominant, the target nuclei are converted into lighter nuclei and the material is stored in a reaction cycle (similar to the CNO cycle). Reliable predictions for the reaction flows and final abundances in neon novae requires the experimental determination of the ($p,\alpha$)/($p,\gamma$) reaction branching ratios.

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The stellar rates for the $^{35}\text{Cl}(p,\gamma)^{36}\text{Ar}$ reaction have been determined for temperatures in the region of interest for explosive hydrogen burning. However, the direct measurement of the competing reaction $^{35}\text{Cl}(p,\alpha)$ at low bombarding proton energies is difficult due to background contributions from the $^{11}\text{B}(p,3\alpha)$ reaction and from elastically scattered protons. Recently, a new $\alpha$-particle emitting state in $^{36}\text{Ar}$ has been observed [Ill96] in $\beta$-delayed $\alpha$-decay studies of $^{36}\text{K}$. The measured excitation energy corresponds to a resonance energy of $E_R = 351 \pm 4$ keV. It has been shown that this resonance could influence appreciably the nucleosynthesis in explosive hydrogen burning events.

We have begun preparations for a direct search of the $E_R = 351$ keV resonance in $^{35}\text{Cl}(p,\alpha)$ using an unpolarized proton beam from the atomic beam polarized ion source at TUNL. Targets were made by evaporating NaCl onto thin 20 $\mu$g/cm$^2$ carbon foils. A 450 mm$^2$ silicon surface barrier (SSB) detector positioned at 55 degrees with respect to the beam was used to detect the $\alpha$ particles. In order to minimize the number of elastically scattered protons that reach the detector, a 2.2 $\mu$m HAVAR foil was placed in front of the SSB detector. Figure 4.2-2 shows a preliminary $\alpha$-particle spectrum and the position of the expected $\alpha$-particle peak from the $E_R = 351$ keV resonance. Furthermore, tests were performed in order to determine whether time-of-flight information could be utilized to improve the signal-to-noise ratio.

For the next experimental runs a new scattering chamber permitting close detector geometries has been developed.

![Figure 4.2-2](image.png)

Figure 4.2-2: Alpha-particle spectrum from the proton bombardment of a NaCl target. The position of the expected $\alpha$-particle peak from the $E_R = 351$ keV resonance in $^{35}\text{Cl}(p,\alpha)^{32}\text{S}$ is indicated.
4.2.3 Proton Single-Particle Reduced Widths for Unbound States

C. Iliadis

The partial width of a nuclear level can be estimated experimentally and theoretically using a variety of different techniques. The comparison of measured and calculated values allows quantitative predictions regarding the nuclear structure of the levels involved in the transition and also the validity of the nuclear model applied. In some instances the width of a certain nuclear level is not accessible experimentally. This situation occurs frequently, for example, in nuclear astrophysics. In such cases estimates of stellar reaction rates rely on theoretical predictions for the partial widths of the astrophysically important levels.

The present work is concerned with theoretical estimates of partial widths and more specifically, of dimensionless single-particle reduced widths $\theta_{sp}^2$ for proton decay. The proton partial width $\Gamma_p$ can be written in the framework of R-matrix theory as

$$\Gamma_p = 2\frac{\hbar^2}{M_c a_c^2} P_c C^2 S \theta_{sp}^2,$$

with $M_c$ the reduced mass, $a_c$ the interaction radius, $P_c$ the penetrability, $C^2$ the isospin Clebsch-Gordan coefficient, and $S$ the spectroscopic factor.

The dimensionless single-particle reduced width $\theta_{sp}^2$ depends on the interaction radius $a_c$, the orbital angular momentum $\ell$ and the number of nodes $n$ in the single-particle radial wave function. The quantity $\theta_{sp}^2$ was estimated previously for a square-well and harmonic oscillator potential with the result $\theta_{sp}^2 \approx 0.6$. In the literature $\theta_{sp}^2$ is often set equal to unity in calculations of proton partial widths. In such cases, a significant error is introduced in the calculation of $\Gamma_p$. This error gives rise to an overestimate of the stellar reaction rates if these are influenced by the partial width of the compound-nucleus state in question.

In the present work $\theta_{sp}^2$ was estimated by using wave functions generated with (more realistic) optical-model potentials. Figures 4.2–3a and b show the resulting values of $\theta_{sp}^2$ versus target mass $A$ (full circles) at fixed energies of $E = 100$ and 1000 keV, respectively. The solid curves, which represent least-square fits to the calculated $\theta_{sp}^2$ values, indicate a smooth mass dependence of $\theta_{sp}^2$ for different combinations of radial and orbital angular momentum quantum numbers $n\ell$. At $E = 100$ keV the average values over the whole mass range considered are $\theta_{sp}^2 \approx 0.55, 0.70, 0.36$ and 0.35 for $2s$, $2p$, $1d$ and $1f$ single-particle orbits, respectively. These averages change little for different bombarding energies, although the shape of the obtained curves is modified.

The values of $\theta_{sp}^2$ presented here depend on the choice for the interaction radius $a_c = a_0(A^{1/3} + 1)$. Figure 4.2–4 shows values of $\theta_{sp}^2$ versus target mass $A$, calculated at $E = 100$ keV.
keV by using different radius parameters of \( a_0 = 1.12, 1.25 \text{ and } 1.45 \text{ fm} \). It can be seen that the values for \( \theta_{sp}^2 \) are very sensitive to variations in \( a_0 \) for each single-particle orbit \( n\ell \). It is clear from Figure 4.2–4 that uncertainties of up to a factor of 10 are introduced in the calculation of proton widths \( \Gamma_p \) if \( \theta_{sp}^2 = 1 \) is used in the above equation and if the Coulomb penetrabilities \( P_c \) are calculated for \( a_0 = 1.45 \text{ fm} \) as has been done frequently in the literature. This work has been published recently [Ili97].

![Graphs showing values of \( \theta_{sp}^2 \) versus target mass \( A \) for bombarding proton energies of a) 100 keV and b) 1000 keV.](image)

Figure 4.2–3: Values of \( \theta_{sp}^2 \) versus target mass \( A \) for bombarding proton energies of a) 100 keV and b) 1000 keV.

4.2.4 Stellar Reaction Rates for Explosive Hydrogen Burning

P.M. Endt, C. Iliadis, and W.J. Thompson

Thermonuclear explosions induced by reactions involving hydrogen are expected to occur in classical novae, type I X-ray bursts, type II supernovae, Thorne-Zytkow objects, accreting black holes and supermassive star explosions. At elevated stellar temperatures typical for these objects, most nuclear reactions involve short-lived target nuclei. An experimental determination of the stellar reaction rates requires the use of a radioactive ion beam. A few reactions important for hydrogen burning scenarios were measured recently using this technique. However, for the majority of reactions the stellar rates are based on theoretical estimates. In the present work we have reanalysed several nuclear reactions of importance to explosive hydrogen burning scenarios. Nuclear structure information (e.g., single-particle spectroscopic factors, lifetimes etc.) needed for the theoretical estimate are adopted from the mirror states. The analog state assignments are taken from [End97]. Proton partial widths are estimated according to the method described in Section 4.2.3.

Several tests are performed in order to deduce stellar reaction-rate uncertainties. We
assume that single-particle (proton or neutron) spectroscopic factors for all components of the same isospin multiplet are the same. Consequently, we have compared spectroscopic factors from \((d,p)\) and \((^3\text{He},d)\) reactions, populating states of the same isospin multiplet. We have found altogether 33 pairs of spectroscopic factors for which the required experimental information is available in the literature and the resulting ratios of neutron to proton spectroscopic factors \(S_n/S_p\) are shown in Figure 4.2–5a. The average systematic deviation amounts to a factor 0.94. The average (logarithmic) scatter around this mean corresponds to a factor 1.48. Therefore, we conclude that \(S_n\) values measured in the \((d,p)\) reaction can indeed be used instead of the unknown \(S_p\) values, with an error of about a factor 1.5. However, the above considerations do not provide an estimate for the reliability of our method to calculate proton partial widths (Section 4.2.3). For example, uncertainties might exist for the optical-model parameters used in the calculation of the dimensionless single-particle reduced width. Therefore, another test was performed. We have used Eq. 4.1 in Section 4.2.3 together with \(S_n\) values measured in \((d,p)\) reactions in order to calculate proton partial widths \(\lambda_p\). The estimated values are then compared to experimental \(\lambda_p\) values measured in proton elastic scattering experiments. We have found altogether 21 pairs of transitions for which the required information is available. The resulting ratios \(\lambda_p^{exp}/\lambda_p^{calc}\) are displayed in Figure 4.2–5b. The average systematic deviation amounts to a factor of 1.03. The average (logarithmic) scatter around this mean corresponds to a factor 1.73. Therefore, we conclude that our method of calculating proton widths by using Eq. 4.1 in Section 4.2.3 together with experimental \(S_n\) values provides accurate results within a factor of about 1.7.

We are planning to perform stellar network calculations in order to investigate the astrophysical implications of our new reaction rates.

Figure 4.2-5: Ratios $S_n/S_p$ and $\Gamma_p^{\text{exp}}/\Gamma_p^{\text{calc}}$ versus neutron spectroscopic factor $S_n$. 
4.3 Radioactive Beams

4.3.1 Nuclear Astrophysics at HRIBF

*J. C. Blackmon and A. E. Champagne for the astrophysics collaboration at HRIBF*

Reactions involving radioactive nuclei play a critical role in explosive stellar events, such as novae and supernovae. The work of the astrophysics collaboration at the Holifield Radioactive Ion Beam Facility (HRIBF) is centered on absolute cross-section measurements of these reactions in inverse kinematics using radioactive ion beams. Beams of $^{17}\text{F}$ and $^{18}\text{F}$, important nuclei in explosive hydrogen burning, and $^7\text{Be}$, important to the solar neutrino problem, are under development. A versatile experimental station for conducting these measurements has been built around the Daresbury Recoil Separator (DRS). The separator is currently undergoing stable beam commissioning, and experiments with radioactive beams will begin in 1998.

The DRS separates reaction products from the incident beam in two crossed-field velocity filters and a 50° dipole bending magnet. There are 14 total elements, and the magnetic fields are continuously measured using hall probes with a resolution better than 1 Gauss. A computer control system has been developed to monitor the field measurements and adjust the magnet currents to maintain constant fields. The magnet fields were calibrated using a $^{244}\text{Cm}$ source and a $^{12}\text{C}$ beam with different rigidities.

Particles are detected at the focal plane of the DRS with a carbon-foil microchannel plate detector and a $\Delta E-E$ gas ionization counter. The performance of the separator and the focal plane detectors was tested using a $^{244}\text{Cm}$ source and by measuring $^{27}\text{Al}(^{12}\text{C},^{27}\text{Al})^{12}\text{C}$ elastic scattering. The acceptance of the separator was measured to be approximately 4 msr. However, the resolution (both position and energy) in these initial tests was poor. Changes in the electronics, shielding, and grounding have since improved detector performance. Capture reactions using stable beams will be measured in the near future, and the separator is expected to be ready for experiments with radioactive beams by the end of 1997.

Radioactive nuclei are produced at HRIBF by transfer reactions in a high temperature target. Atoms must diffuse out of the target and travel through a transfer tube to an ion source where they can be extracted into a beam. Target material with a large surface area is desired to reduce the diffusion time for short-lived isotopes. Online testing of target materials for the production of radioactive fluorine beams has been carried out at HRIBF using the UNISOR separator, a plasma-discharge ion source, and low intensity beams from the Holifield tandem accelerator. The most efficient production of fluorine beams has been achieved using a fibrous $\text{Al}_2\text{O}_3$ target material. The target material was irradiated with protons to produce $^{18}\text{F}$ by the $^{18}\text{O}(p,\alpha)^{18}\text{F}$ reaction. A deuteron beam was also used to produce $^{17}\text{F}$ by the $^{16}\text{O}(d,\alpha)^{17}\text{F}$ reaction.

Because of the extreme reactivity of fluorine, fluorine atoms which are released from the
target and transported to the ion source must do so in molecular form. A mass analysis (using the UNISOR separator) of molecules extracted from the ion source found that 88% of the fluorine observed was in the form of AlF. The total hold-up time for release and transport of the fluorine atoms was determined by measuring the decrease in the Al$^{18}$F current after the proton driver beam was turned off. The total hold-up time in the source at this temperature was determined to be 16.4±0.8 minutes. Somewhat shorter hold-up times, and consequently better release of $^{17}$F have been achieved at higher target temperatures. The best efficiency achieved with the plasma-discharge source has been $6 \times 10^6$ $^{17}$Fs per microampere of deuterons. A negative surface ionization source is currently being developed which will both dissociate the fluorine molecules and produce a negatively charged, F$^-$, beam without a charge-exchange cell. Online testing of this source at the UNISOR separator will begin in the Fall of 1997.