4 Nuclear Astrophysics

4.1 S-Factor Slopes

4.1.1 Slope of the Astrophysical S Factor for the $^6\text{Li}(p,\gamma)^7\text{Be}$ Reaction

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Analysis of spectra from an earlier measurement on the $^6\text{Li}(p\gamma)^7\text{Be}$ reaction [Lay96] suggested that the astrophysical S factor might have a negative slope with energy. The present experiment was undertaken to examine this suggestion. Polarized protons of 80 keV were used to determine the slope of the S factor for the $^6\text{Li}(p\gamma)^7\text{Be}$ reaction. The proton energy was varied in 15 keV steps from 80 to 110 keV by varying the bias voltage applied to the target from 0 kV to $-30$ kV. The target bias was controlled by the data-acquisition computer such that approximately equal counting statistics were obtained for each energy. The gamma rays were detected by two large high-purity Germanium (HPGe) detectors. A spectrum from one detector is shown below.

![Figure 4.1-1: HPGe spectrum. The peak on the right is the full-energy peak for the ground-state transition, and the second peak from the right is the full-energy peak for the transition to the first excited state. The other peaks are the first and second escape peaks for these two gamma rays.](Image)

The S factors for transitions to the ground state and first excited state of $^7\text{Be}$ as a function of energy will be extracted from the spectra at the three beam energies and by

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deconvoluting the detector spectra at each energy. Analyzing powers will also be extracted; preliminary indications are that the analyzing powers are zero at these energies. Assuming a linear dependence on energy the slope of the S factors will be determined.

Analysis of the data will include comparisons to the recently published measurements on the S factor slope for the $^7\text{Li}(p\gamma)^8\text{Be}$ reaction [Spr00].


4.1.2 The $^{11}\text{B}(p\gamma)^{12}\text{C}$ Reaction below 100 keV


The $^{11}\text{B}(p\gamma)^{12}\text{C}$ reaction was studied by measuring the $\gamma$ rays that were produced when 80–100 keV polarized protons were stopped in a thick $^{11}\text{B}$ target. Cross sections and vector analyzing powers at 90° were determined as a function of energy for capture to the ground and first excited states of $^{12}\text{C}$. These analyzing powers are particularly sensitive to the interference between s-wave and p-wave contributions and to the relative phase between direct and resonance amplitudes. The results were used to produce a reliable extrapolation of the astrophysical S factor at 0 keV by means of a direct-capture-plus-resonances model calculation. The value of S(0) that was obtained for $^{11}\text{B}(p\gamma)^{12}\text{C}$ is in agreement with previously determined values, but for $^{11}\text{B}(p\gamma)^{12}\text{C}$ the value of S(0) is $3.5 \pm 0.6$ keV-b and is more than twice as large as previously determined values [Kel00].


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4.2 Hydrostatic Hydrogen Burning

4.2.1 Studies of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ Reaction at Astrophysical Energies


According to calculations using presently published S factors, the reaction $^{14}\text{N}(p,\gamma)^{15}\text{O}$ is the slowest reaction in the hydrogen burning CNO cycle, slower by a factor of 240 than $^{12}\text{C}(p,\gamma)^{13}\text{N}$, the next slowest reaction. As such, it controls the rate of stellar energy generation by this cycle. In the past year we have continued our efforts to take data at beam energies below 200 keV. This data will help the important extrapolation of the S factor to astrophysically important energies. These extrapolations are complicated by the 278 keV resonance in this reaction. One measurement below 200 keV [Lam57] exists. The authors measured the $\beta^+$ activity of the residual nucleus and they used a low-resolution 4" × 4" NaI scintillator for $\gamma$-ray counting, providing no information about the modes of capture. Also, the ability of a nitrated foil target to withstand 25 mA of beam current is called into question by our own experience with such targets. The initial data from this experiment led us to the unsettling conclusion that the S factor for capture to the ground state was more than an order of magnitude higher than previously believed. The more recent data have confirmed our techniques at higher energies where the S factor is relatively well known. These data have also led us to investigate the possibility of a previously unknown resonance at $E_p = 125$ keV ($E_x = 7.415$ MeV in $^{15}\text{O}$) for this reaction.

We have continued to use a thick target of frozen deuterated ammonia (ND\(_3\)) to stop a 260 keV proton beam from the TUNL minitandem. We tested the data from this technique against well-established data in this energy range shown with older data sets and two hand-generated fits in Figure 4.2–1 [Sch86]. The deuterium in the target has a well-known cross section in this energy range, and provides precise stopping-power data with which to accurately determine the S factor for the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction. The thick target yields for capture to the 6179 keV and 6793 keV excited states in $^{15}\text{O}$, the dominant capture processes in the tail (200 keV < $E_p$ < 260 keV) of the $E_p = 278$ keV resonance were calculated using known S factors for the two reactions in this energy range and the stopping power calculated from the $^2\text{H}(p,\gamma)^3\text{He}$ spectrum (Figure 4.2–2). Expected yields of 143 ± 12 counts and 100 ± 10 counts were calculated for the two peaks respectively and the experimental yields were 136 counts and 90 counts. This measurement validates our ability to use the gamma rays from $^2\text{H}(p,\gamma)^3\text{He}$ for a relative cross-section measurement.

As displayed in Figure 4.2–3 the $\gamma$-ray background spectrum makes determining the

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cross section near 140 keV difficult. The left-hand peak in the spectrum is the $^{14}\text{N}(p\gamma)^{15}\text{O}$ capture peak which sits on the Compton edge of a background doublet from thermal neutron capture on $^{56}\text{Fe}$ separated by 14 keV. Figure 4.2–3 shows this background doublet near 7650 keV for 50 hours of background data and 50 hours of beam-on data collection at 140 keV. The thermal neutron capture peaks from a small but steady background of neutrons are the same size. The direct capture peak is very slightly higher in energy and much larger than a small background peak which it overlaps.

To connect an S factor responsible for counts from the $^{14}\text{N}(p\gamma)^{15}\text{O}$ reaction at $E_p = 140$ keV to measured S factors at $E_p = 200$ keV (Figure 4.2–1) requires an S factor with a very large negative slope. By raising the energy of the beam to $E_p = 160$ keV we were able to observe that the $^{14}\text{N}(p\gamma)^{15}\text{O}$ peak shown in Figure 4.2–3 did not increase in width indicating that the S factor in this 20 keV energy range possesses such a large negative slope. Background indicates that the size of the peak is definitely related to the amount of beam incident on the target. The relatively narrow width of the peak indicates that the cross section drops again after peaking close to 125 keV suggesting that 140 keV protons slowing in the thick target pass through the energy range of a resonance. After careful literature searches for alternative reactions and neutron capture peaks which might be responsible for this peak we have concluded that a new resonance is a definite possibility. We are further certain that thermal neutron capture is not responsible because we know
Figure 4.2-2: Raw γ-ray spectrum and convolution fit for $^2H(p,γ)^3He$.

Figure 4.2-3: Raw γ-ray spectrum for $^{14}N(p,γ)^{15}O$ and a scaled background run.
that scattered deuterons in the target create measurable levels of neutrons through the $^2\text{H}(d\bar{\text{n}})^3\text{He}$ reaction at $E_p = 160$ keV. These begin to increase the size of the $^{56}\text{Fe}$ neutron capture doublet over background when the beam energy is raised to 160 keV and the scattered deuterons have more energy. The size of the $^{14}\text{N}(p\gamma)^{15}\text{O}$ peak however remains proportional to the number of coulombs of protons incident on the target. A series of experiments with water, heavy water ($\text{D}_2\text{O}$) and normal ammonia ($\text{NH}_3$) targets as well as beam energies of 120–130 keV are planned in order to confirm the existence of and to characterize any low-energy resonance in order to be able to perform a more accurate extrapolation of the $S$ factor to astrophysically important energies.

\[\text{[Lam57]} \quad \text{W. Lamb and R. Hester, Phys. Rev. 108 (1957).}\]

\[\text{[Sch86]} \quad \text{U. Schröder et al., Nucl. Phys. A467 (1986).}\]

### 4.2.2 The Reaction Rate of $^{26}\text{Mg}(p,\gamma)^{27}\text{Al}$

**A.E. Champagne, C. Iliadis, and C. Rowland**

Globular clusters have been used as a test of stellar evolution theories because the stars are believed to be coeval and initially chemically homogeneous. However recent observations have shown a large scatter in the abundances of C, N, O, Na and Al among globular cluster red giant stars. Of particular interest is the observed anticorrelation between Mg and Al. Using isotopic analysis of MgH bands of six stars in the globular cluster M13, Shetrone [She96] observed that it is the isotope of $^{24}\text{Mg}$ that is depleted in Al-rich giants. Further the abundance sum of $^{25}\text{Mg} + ^{26}\text{Mg}$ is constant over a wide range of Al anomalies. These observations are in dispute with what theory predicts. Particularly the expectation is that $^{25}\text{Mg}$ and $^{26}\text{Mg}$ would be anticorrelated with Al. The accepted reaction rates for $^{25}\text{Mg} + p$ and $^{26}\text{Mg} + p$ are large compared to the $^{24}\text{Mg} + p$ rate at $T_9 \approx 0.055$ making Shetrone’s observation difficult to understand. Further hydrogen burning at $T_9 = 0.055$ cannot account for the observed Mg-Al anticorrelation. To reproduce the observations the $^{24}\text{Mg}(p\gamma)^{25}\text{Al}$ reaction rate would need to be increased by a factor of 35 which has been shown by [Pow99] not to be the case. The question is then whether these anomalies are a product of primordial abundance variations or if some new physics (such as mixing) is necessary to explain the observations.

Tests of any alternative scenario require the proton-capture rates on all three magnesium isotopes. Of the three $^{26}\text{Mg}(p\gamma)^{27}\text{Al}$ is the least well known. It is uncertain by a factor of 200 at temperatures of astrophysical interest.

In addition to the abundance anomaly problem the $^{26}\text{Mg} + p$ reaction rate has bearing on the “second parameter” effect observed in globular clusters. Age has long been regarded as a prime candidate for the second parameter though helium abundance also will affect
horizontal branch (HB) morphology since a higher helium fraction (and therefore lower hydrogen fraction) contributes fewer electrons per unit mass to the stellar envelope. The lower ensuing opacity leads to a smaller stellar radius and thus a bluer color. The $^{26}\text{Mg} + p$ reaction rate is important here in the context of where the Al is being produced within the hydrogen shell. If the rate is high, $\text{Al}$ is made above the hydrogen shell. If the rate is low, $\text{Al}$ is produced deeper within the shell, which requires penetrating the hydrogen shell to get out Al. Mixing into the hydrogen shell means mixing out helium forcing the star to evolve onto the blue HB. Further, mixing out helium makes for brighter HB stars which are often used as standard candles and age calibration of clusters. A brighter HB can lower cluster ages to less than the accepted age of the universe.

In last year’s progress report [Row99], we described a reanalysis of $^{26}\text{Mg}(^{3}\text{He},t)^{27}\text{Al}$ data. The hope was that we would be able to better determine the quantum numbers for several states and therefore calculate a more accurate reaction rate. Although the reanalysis was useful, it still left for some uncertainty in the quantum numbers for the 8362 keV state in $^{27}\text{Al}$. To ameliorate this uncertainty, we chose to measure direct capture into the 8362 keV state at the TUNL High Resolution Laboratory.

![Figure 4.2-4: Direct-capture data compared to theory for the 8362 keV state.](image)

In direct capture a proton is captured and a $\gamma$ ray is emitted in a single step. Direct capture occurs at all incident particle energies and the direct capture cross section is a smoothly varying function of the incident particle energy. By comparing observed cross sections to model calculations it is possible to determine the spectroscopic factors. The spectroscopic factors are related to the proton partial width which is used in the calculation of the reaction rate. The spectroscopic factors are related to the direct capture cross section...
by

$$\sigma_{\text{exp}} = \sum C^2 S \sigma_{\text{theory}}.$$  \hspace{1cm} (4.1)

We were only able to obtain upper limits for the direct capture cross sections into the 8362 keV state. The plot of cross section as a function of proton energy is given in Figure 4.2–4. Also on this plot are the theoretical cross sections from direct-capture model calculations for different angular momentum and $J^*$ values. Unfortunately we were unable to restrict the quantum numbers (and hence the $C^2S$ values) any further via the direct-capture method.

In the future we plan to run resonant capture at the TUNL HRL. This may allow us to further restrict the quantum numbers of the 8362 keV state and calculate a more accurate reaction rate for $^{26}\text{Mg}(p,\gamma)^{27}\text{Al}$.

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4.3 Explosive Hydrogen Burning

4.3.1 Measurement of the $^{17}\text{F}(p,\alpha)^{14}\text{O}$ Reaction Cross Section at the HRIBF

D.W. Bardayan, A.E. Champagne, C. Rowland, and R.C. Runkle for the RIBENS collaboration at the HRIBF

In stellar explosions the $^{14}\text{O}(\alpha\bar{p})^{17}\text{F}$ reaction may initiate a reaction sequence that boosts the energy produced in the explosion and leads to the production of heavier elements. Because of the extremely low rate of the $^{14}\text{O}(\alpha\bar{p})^{17}\text{F}$ reaction it is currently believed that this only occurs in extremely violent explosions such as in X-ray bursts. The reaction rate of the $^{14}\text{O}(\alpha\bar{p})^{17}\text{F}$ reaction remains quite uncertain. Stable beam spectroscopy measurements [Hah96] indicate that a $1^-$ state at $E_x = 6.150$ MeV in $^{18}\text{Ne}$ provides the dominant resonant contribution to the rate at temperatures less than 1 GK. The rate of the $^{14}\text{O}(\alpha\bar{p})^{17}\text{F}$ reaction at these temperatures depends upon the unknown spectroscopic properties (total and alpha-partial widths) of the 6.150-MeV state as well as upon the $\ell = 1$ direct reaction component and the sign of the interference between the resonant and direct components. In order to determine these unknown properties we have measured the time-reversed $^{1}\text{H}(^{17}\text{F}\alpha)^{14}\text{O}$ reaction using a radioactive $^{17}\text{F}$ beam at the HRIBF.

A $^{17}\text{F}$ beam bombarded a 100-μg/cm$^2$ polypropylene (CH$_2$)$_n$ target and the recoil alpha and $^{14}\text{O}$ ions were detected in silicon detectors. Our experimental configuration is shown in Figure 4.3-1. The alpha recoils are detected in the SIDAR [Bar99] which was run in “telescope” mode (i.e., a 100 μm thick detector backed by a 500 μm thick detector).

[Figure 4.3-1: A $^{17}\text{F}$ beam bombarded a polypropylene target. Recoil alpha ions were detected in the SIDAR (10° ≤ $\theta_{\text{lab}}$ ≤ 25°) with the first detector of 100 μm thickness and the second being 500 μm thick. This allowed for extraction of $\Delta E-E$ information for particle identification. The $^{14}\text{O}$ ions were detected in a smaller annular array that covers lab angles 3.2° ≤ $\theta_{\text{lab}}$ ≤ 6.5°.]
to discriminate between the events of interest and scattered protons and projectiles. The SIDAR is comprised of 128 segments with 16 radial (from 5 to 13 cm) and 8 azimuthal divisions. Additionally, the $^{14}\text{O}$ recoils were detected by a smaller annular silicon detector that subtends angles $3.2^\circ \leq \theta_{lab} \leq 6.5^\circ$. This detector is also highly segmented with 16 radial and 4 azimuthal divisions.

The cross section (plotted in Fig. 4.3-2) was measured at 21 beam energies spanning the

energy region important for explosive hydrogen burning $E_{\text{F}} = 40.1$–68.2 MeV ($E_x = 6.1$–7.7 MeV). The beam was post-stripped following the tandem accelerator and the HRIBF tandem analyzing magnet was used to select the $+9$ charge state which eliminated virtually all $^{17}\text{O}$ from the beam. Post-stripping significantly reduced the $^{17}\text{F}$ beam intensity on target but a high-purity beam was crucial to eliminate background from the $^{17}\text{O}(p\alpha)^{14}\text{N}$ reaction.

Data were collected at the lowest energy $E_{\text{F}} = 40.1$ MeV for 88 hours with an average current of $5 \times 10^7$ $^{17}\text{F}$/s and $10^4$ $^4\text{He}$–$^{14}\text{O}$ coincidences were observed. At the higher energies $\Gamma$ where $\Gamma E > 60$ MeV more than 50 coincident events were typically collected at each energy in less than 2 hours of running with average beam currents of $1–2 \times 10^6$ $^{17}\text{F}$/s on target. Evidence for a resonance is seen in the lowest energy measurements which corresponds to a state in $^{18}\text{Ne}$ at $E_x = 6.2$ MeV. At least three other resonances are observed in the higher energy measurements in the energy range $E_x = 7.0$–7.8 MeV. Data analysis to extract the resonance parameters is still in progress. In addition, measured cross sections at energies $E_{\text{F}} = 48$–55 MeV ($E_x = 6.6$–7.0 MeV) where no states in $^{18}\text{Ne}$ are known or expected accurately establishes the direct reaction cross section and its interference with $1^-$ states in $^{18}\text{Ne}$.

The $^{17}\text{F}(p\alpha)^{14}\text{O}$ cross section has now been measured for the first time over the range of energies important for determining the $^{14}\text{O}(\alpha\Phi)^{17}\text{F}$ reaction rate in stellar explosions. The

Figure 4.3-2: The measured $^{17}\text{F}(p,\alpha)^{14}\text{O}$ cross sections are plotted as a function of bombarding energy along with a prediction of the cross section based upon resonance and direct capture parameters from Hahn et al.
contribution from the most important resonances and the direct reaction cross section were
determined. This measurement allows the $^{14}$O($\alpha p$)$^{17}$F reaction rate to the ground state in
$^{17}$F to be determined from detailed balance to about 30% accuracy over most temperatures
of interest to astrophysics. However further measurements are required to better constrain
the $^{14}$O($\alpha p$)$^{17}$F* reaction to the $\frac{1}{2}^+$ first-excited state in $^{17}$F.


4.3.2 Measurement of the $^{18}$F($p,p$)$^{18}$F and $^{18}$F($p,\alpha$)$^{15}$O Excitation Functions for the Astrophysically Important 7.075-MeV State in $^{19}$Ne

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HRIBF

The observation of gamma rays from nova explosions would provide a rather direct
test of nova models [Lei87]. The most powerful emission in gamma rays immediately after
the explosion comes at energies of 511 keV and below originating from electron-positron
annihilation following the positron decays of proton-rich radioactive nuclei produced in the
explosion [Her99]. The main sources of positrons in nova envelopes are expected to be
$^{13}$N and $^{18}$F. When $^{15}$N ($t_{1/2} = 9.97$ m) decays the envelope is most likely too opaque for
gamma-ray transmission; therefore the decay of $^{18}$F ($t_{1/2} = 109.8$ m) is the most significant
for observations within the first several hours after the explosion. The amount of $^{18}$F that
is mixed into the cooler outer layers where it can only decay is severely constrained by
its destruction rate in the burning shells which is dominated by the $^{18}$F($p\alpha$)$^{15}$O reaction.
Unfortunately it has been found that the current uncertainties in the $^{18}$F($p\alpha$)$^{15}$O rate
result in a factor of 300 variation in the amount of $^{18}$F produced in models [Cos97]. It is
impossible to determine whether gamma-ray observations by orbital detectors are feasible
without a more precise value of the $^{18}$F($p\alpha$)$^{15}$O stellar reaction rate.

The $^{18}$F($p\alpha$)$^{15}$O rate is thought to be dominated at high temperatures by a resonance
near 660 keV ($E_x = 7.07$ MeV) in $^{19}$Ne [Utk98]. This state is thought to have $J^\pi = \frac{3}{2}^+$
and would be an s-wave resonance for the $^{18}$F + p system since the ground state of $^{18}$F has
$J^\pi = 1^+$. The properties of this state were uncertain because of discrepant results from
previous measurements [Cos97,Reh96]. These discrepancies (as much as a factor of 3 in
the width and 21 keV in the resonance energy) result in up to a factor of 3 variation in the
$^{18}$F($p\alpha$)$^{15}$O rate.

To resolve these discrepancies we have simultaneously measured the $^1H(^{18}Fp)^{18}F$ and
$^1H(^{18}FI\alpha)^{15}O$ excitation functions using a radioactive $^{18}$F beam at the HRIBF. Our method
utilized a thin (35 μg/cm²) polypropylene target which allowed for a more precise measurement of the resonance properties. Because the beam was contaminated by $^{18}$O ($^{18}$O/$^{18}$F ≈ 10), coincidence measurements were required to distinguish the events of interest from background events induced by $^{18}$O projectiles. For the $^1$H($^{18}$F,$p$)$^{18}$F measurement protons were detected in the Silicon Detector Array (SIDAR) [Bar99] in coincidence with recoil $^{18}$F ions detected by an isobutane-filled ionization counter which provided energy loss information for particle identification and allowed us to readily distinguish the $^{18}$F + $p$ scattering events from the more intense $^{18}$O + $p$ events. For the $^1$H($^{18}$F,$\alpha$)$^{15}$O measurement both the recoil $^4$He and $^{15}$O ions were detected in the SIDAR. The total energy of the event was reconstructed and this allowed the $^1$H($^{18}$F,$\alpha$)$^{15}$O events to be distinguished from the $^1$H($^{18}$O,$\alpha$)$^{15}$N events based on the different Q-values of these reactions. The excitation functions (shown in Figure 4.3–3) were measured at 15 beam energies between 10 and 14 MeV over the course of 3 days. A simultaneous fit of the two data sets has been performed and the preliminary best-fit resonance properties are shown in Table 4.3–1 along with the previously measured values.

While our measurement has resolved the discrepancies in the location and width of this state, the $^{18}$F($p$,$\alpha$)$^{15}$O rate is still uncertain at lower temperatures owing to the unknown properties of lower-energy states in $^{19}$Ne. Further work with $^{18}$F beams is planned at the HRIBF in order to address these uncertainties.


Table 4.3-1: A summary of the resonance properties from previous measurements is shown along with the preliminary best-fit results from this work. The uncertainties quoted from this work are purely statistical in nature.

<table>
<thead>
<tr>
<th></th>
<th>Ref. [Utk98]</th>
<th>Ref. [Cos95]</th>
<th>Ref. [Reh96]</th>
<th>This Work</th>
</tr>
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<tr>
<td>$E_r$ (keV)</td>
<td>659 ± 9</td>
<td>638 ± 15</td>
<td>652 ± 4</td>
<td>663.7 ± 0.5</td>
</tr>
<tr>
<td>$\Gamma$ (keV)</td>
<td>39 ± 10</td>
<td>37 ± 5</td>
<td>13.6 ± 4.6</td>
<td>36.9 ± 1.8</td>
</tr>
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<td>$\Gamma_p/\Gamma$</td>
<td>0.37 ± 0.04</td>
<td>0.4 - 0.6</td>
<td>0.37</td>
<td>0.40 ± 0.02</td>
</tr>
</tbody>
</table>


4.4 Helium Burning

4.4.1 Sub-Coulomb $\alpha$ Transfers on $^{12}$C


The rates of many astrophysically interesting $\alpha$-particle induced reactions are uncertain due to poor knowledge of the partial width in the $\alpha$-particle channel (reduced $\alpha$ width). Sub-Coulomb $\alpha$-transfer reactions are able to address this question with a minimum of uncertainties. For levels near the $\alpha$-separation threshold, the $Q$ values of the Li-induced $\alpha$-transfer reactions ($^6$Li$^7$) and ($^7$Li$^7$) are slightly negative which means that the outgoing deuterons or tritons will also have energies below the Coulomb barrier. Distorted-wave Born approximation (DWBA) calculations under these conditions are determined mainly by Coulomb potentials with very little dependence on nuclear potential parameters [Bas80]. The calculated cross sections are thus essentially model independent except for the absolute normalization which depends in turn on the reduced $\alpha$ widths of the level in question and the Li nucleus which contributed the $\alpha$ particle.

Our first measurements have focused on the $^{12}$C($\alpha$F$_1$)$^{16}$O reaction. The rate of this reaction in massive stars greatly affects the resulting ratio of $^{12}$C to $^{16}$O; the subsequent nucleosynthesis of heavier elements and the final fate of the star (i.e., black hole or neutron star). Some of the initial results have recently been published [Bru99].

In these initial measurements we were unable to detect the $\gamma$ decay of the 7.12-MeV $1^-$ state for the $^{12}$C($^7$Li$^7$)$^{16}$O reaction because this transition lies in a high-background region of the $\gamma$-ray spectrum. In November 1999 we made additional measurements of the $^{12}$C + $^7$Li reaction at University of Notre Dame. The setup was similar to our previous measurements but utilized Compton-suppressed Ge detectors which made it possible to resolve the decay of the 7.12 MeV state. A sample spectrum is shown in Fig. 4.4-1. This measurement when compared to measurements of ($^6$Li$^7$) to the same state will provide a consistency test of the reduced $\alpha$ widths determined from sub-Coulomb $\alpha$ reactions.

We have also investigated the usefulness of detecting charged particles for these reactions. The light-particle reaction products from sub-Coulomb transfer reactions are preferentially emitted at backward angles in the center-of-mass system. For normal kinematics e.g., $^{12}$C($^6$Li$^7$) this statement implies that the deuterons are primarily emitted at backward angles in the laboratory. For sub-Coulomb energies the back-angle deuterons have extremely low energies ($< 500$ keV) and are very difficult to identify in the presence of other reactions and intense elastic scattering backgrounds. We have instead utilized inverse kinematics where the deuterons are emitted at forward angles with significantly greater

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energies. We have made test measurements of the $^6\text{Li}(^{12}\text{C}^{12}\text{F})$ reaction using a $^{12}\text{C}$ beam produced by the DENIS II source and FN tandem at TUNL. The target was $^6\text{LiF}$ backed by a Ni foil. The foil was chosen to be of sufficient thickness to stop the incident $^{12}\text{C}$ beam and allowed the deuterons to pass through with minimal energy loss. The deuterons were detected with an $E - \Delta E$ Si detector telescope at forward angles. The test indicates that the deuterons can be detected with sufficient resolution to separate deuteron groups from the 6.92 and 7.12 MeV states.

Finally, we have performed measurements of particle-$\gamma$ correlations for $^{12}\text{C}(^{6}\text{Li}^{12}\text{F})^{16}\text{O}$. The correlation between the emitted charged particle and the $\gamma$ decay of the $^{16}\text{O}$ nucleus provides a very conclusive signature of direct $\alpha$ transfer. Since the recoil direction of the $^{16}\text{O}$ nucleus is directly related to the direction of the emitted deuteron, certain $\gamma-\alpha$ angular correlations can be inferred from the Doppler-shift distribution observed in the $\gamma$-ray spectrum. Note that the lifetimes of the 6.92- and 7.12-MeV states are sufficiently short ($\sim 10$ fs) that slowing down effects are negligible, while the lifetime of the 6.13-MeV state is so long (27 ps) that it nearly always decays at rest. In addition, the effects of detector resolution and finite detector size are small compared to the Doppler spread. The correlations are particularly straightforward to analyze for $\theta_\gamma = 90^\circ$ and $0^\circ$. An example spectrum is shown in Fig. 4.4–2. Note that the yield vanishes for energies corresponding to zero Doppler shift.

Our laboratory has recently obtained and installed a negative-ion sputter source which in the future should allow all of these measurements to be made in house. We are generally well equipped with charged-particle and $\gamma$-ray detectors to carry out the needed measure-
ments. Improved measurements of the $^{12}\text{C}(^7\text{Li},d)^{16}\text{O}(1^-)$ reaction would however require a better Compton suppression system than presently available. Future charged-particle measurements may also take advantage of the high-resolution capabilities of the Enge split-pole spectrometer. During the next year we plan to continue the charged-particle and angular correlation studies of sub-Coulomb $\alpha$-transfer reactions of $^{12}\text{C}$. We also plan to investigate other reactions which are of interest for astrophysical reasons or as further tests of the sub-Coulomb $\alpha$-transfer method.

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