4 Nuclear Astrophysics

4.1 Radiative Capture Reactions

4.1.1 Measurement of the $^7\text{Li}(n,\gamma)^8\text{Li}$ Cross-Section at $E_n=1-1000$ eV.

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The flux of high-energy solar neutrinos is directly proportional to the low-energy $^7\text{Be}(\text{p}\gamma)^8\text{B}$ cross-section which is the most uncertain cross-section in the proton-proton chain. The rate for this reaction is determined from an extrapolation of existing $^7\text{Be}(\text{p}\gamma)^8\text{B}$ cross-section data ($E_p>100$ keV) to solar energies.

A recent measurement of the analyzing power in the $^7\text{Li}(\text{p}\gamma)^8\text{Be}$ reaction and its interpretation in terms of a substantial p-wave contribution may have implications for this extrapolation procedure [Cha94]. A similar p-wave contribution to the $^7\text{Be}(\text{p}\gamma)^8\text{B}$ cross-section would imply a substantial reduction in the predicted flux of $^8\text{B}$ neutrinos. 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 $^7\text{Be}$. Consequently, we have measured the analog reaction $^7\text{Li}(\text{n}\gamma)^8\text{Li}$ where p-wave capture would manifest itself as a deviation from the well-known $1/v$ behavior of the cross-section at low energies. Experimental details and preliminary interpretations were summarized in last year’s progress report.

No deviation from $1/v$ capture is observed and so clearly the mechanism that enhances p-wave capture for protons does not play a significant role for neutrons. Given that the respective capture processes take place at very different radii, it is easy to make some general speculations concerning the origin of the p-wave strength. However, a quantitative explanation will now have to account for both the proton- and neutron-capture results. A paper describing this work has recently been published [Bla96].


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4.1.2 Search for p-Waves in Low-Energy Proton Capture Reactions Relevant to the Solar Neutrino Problem

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The initial stages of a study of the $^7\text{Li}(p\gamma)^8\text{Be}$ reaction have been completed. A previous study of the ground state transition of the $^7\text{Li}(p\gamma)^8\text{Be}$ reaction at energies of $E_p(\text{lab})=80-0$ keV indicated the possibility of a large p-wave capture amplitude in this reaction. A similar p-wave component in the $^7\text{Be}(p\gamma)^8\text{B}$ reaction could seriously affect the extrapolation used to obtain the astrophysical S-factor. The present work examines this possibility by observing the closely related $^7\text{Li}(p\gamma)^8\text{Be}$ ($2^+\Gamma T=0+1$) reaction with polarized protons. In short, we have measured the analyzing power and relative cross-section for polarized proton capture to the third excited state of $^8\text{Be}$ at energies of $E_p=80-0$ keV. This state has the same spin and parity as the ground state of $^8\text{B}$ and is completely isospin mixed ($T=0+1$) with the fourth excited state. Collectively the $T=1$ portion of these states is the isobar analog to the $^8\text{B}$ ground state. The data show an isotropic cross-section and analyzing powers consistent with zero. A transition matrix element (TME) analysis of the data yields two solutions. One consists of 99.9% E1 strength (s-wave capture) and the other 99.9% M1 strength (p-wave capture). Direct capture calculations favor the E1 predominant solution. Based on this result, we conclude that p-waves are unlikely to be important in the $^7\text{Be}(p\gamma)^8\text{B}$ reaction. However, a definitive experimental proof requires showing that the s-wave capture E1 solution is indeed the physical one. This can be done by measuring the linear polarization of the outgoing $\gamma$-rays. An experiment which will use our new Compton Polarimeter in order to perform this measurement is being developed.

4.1.3 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 (e.g., [Cha94] for example) has led us to pursue measurement of the reaction cross-section for smaller energy bins. Previously, we have taken the full energy range data and deconvoluted it using the detector response function or binned it allowing for the extraction of information for smaller energy bins [Sch95, Sch96]. This method requires detectors with excellent energy resolution.
resolution and reactions with a high count rate to achieve reasonable statistics for the lowest energy points. For this purpose, the high-purity Ge detectors have been used in the past. Unfortunately, the efficiency of Ge detectors for the 17 MeV gammas produced in the $^7$Li(p,γ)$^8$Be reaction is very small, making them of limited use for the study of this reaction.

In May 1996 we began test runs with a system using two 10"x10" NaI detectors. Although the energy resolution is poor ($\approx 3\%$), 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 ±20 kV with an accuracy of better than 1 kV. The 80 keV incident proton beam can then be accelerated by the target bias to energies between 60 and 100 keV. We incremented the voltages in 5 kV steps and stored data for each incident proton energy 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 limited to about 20 minutes so that each energy was sampled about 70 times per day. This is important since it should average out systematic errors such as those which arise from changes in the beam energy, target thickness, or contamination effects. By subtracting spectra, the cross-sections for each 5 keV energy bin from 60 to 100 keV can then be determined. The result should be a reliable measurement of the energy dependence of the cross-section and therefore of the astrophysical S-factor. Preliminary results indicate a significantly different slope for capture to the ground and first excited states of $^8$Be, contradicting the usual pure direct S-wave capture assumption. A detailed analysis of these data is currently underway and additional runs are planned.

During the past run, we also spent some time studying the effect of the target voltage on the incident beam profile. There was no apparent effect. In addition to the capture data, the $^7$Li(p,α)$^4$He reaction was studied and will be used as a normalization reaction so that cross-sections can be calculated. We also hope to use the data already taken with this reaction to look for any effects of the target bias voltage on the incident beam current. Also, consistency checks are planned where the incident beam energy will be changed from 80 keV to 60 keV and the data will then be taken from 40 to 80 keV. The 60 to 80 keV data will then be measured both by “ramping up” from 60 keV and by “ramping down” from 80 keV.

These measurements should allow for a direct observation of the slope of the S-factor which should answer the question of the role of any p-wave capture in extrapolating data from 100 keV and above down to the astrophysical region.

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4.1.4 $^{7}$Li(p,$\gamma$)$^{8}$Be Absolute Cross-Section Measurement


Our previous analysis of the $^{7}$Li(p,$\gamma$)$^{8}$Be reaction [God96] provided detailed information about the relative cross-section and analyzing power for capture to the third excited state of $^{8}$Be. During the course of performing that experiment it was determined that an accurate evaluation of the absolute cross-section could not be obtained from the data. In order to perform this measurement a new setup was developed. The details of this setup are described below.

Recall that the solar neutrinos detected in $^{37}$Cl based detectors mostly come from the decay of $^{8}$B and that $^{8}$B is created in the sun from the $^{7}$Be(p,$\gamma$)$^{8}$B reaction. An accurate measurement of the cross-section at low energies for this reaction would be most useful especially in light of another recent low-energy experiment [Cha94] which has found evidence of substantial p-wave strength. Unfortunately a direct $\gamma$-ray measurement would be quite difficult since the (radioactive) target emits $\approx 400$ keV $\gamma$-rays yet the capture $\gamma$-ray is at $\approx 200$ keV. In fact in a typical experiment setup we would expect the ratio of these to be approximately one million to one. The third and fourth excited states of $^{8}$Be are completely isospin mixed ($T=0+1$) and collectively the $T=1$ component is the isobar analog to the $^{8}$B ground state. Marion et al. [Mar67] has shown that these isospin mixed states can be represented as:

$$
|16.63\rangle = 0.772 \ |T=0\rangle + 0.636 \ |T=1\rangle,
$$

$$
|16.92\rangle = 0.636 \ |T=0\rangle - 0.772 \ |T=1\rangle.
$$  \hspace{1cm} (4.1)

Both of these states have the same spin-parity as the $^{8}$B ground state and are approximately at the same energy [Auj88]. The isospin of the $^{8}$B ground state is $T=1$ and both the third and fourth excited states of $^{8}$Be are partially $T=1$ as shown above. By examining the $^{7}$Li(p,F)$^{8}$Be$^{*}$ reaction we hope to gain insight into the $^{7}$Be(p,F)$^{8}$B reaction. Of course items such as isospin selection rules, isospin mixing and Coulomb force effects will need to be considered.

Our previous studies showed that in order to extract information about the third excited state we must perform a coincidence experiment detecting the $\gamma$-rays and one of the two alpha particles from the decay of $^{8}$Be. We have used a large high-purity germanium (HPGe) detector to measure the $\gamma$-rays. The target was made by the evaporation of lithium metal (isotopically enriched to 99.99%) onto a 1/16” thick Al disc. Since the alpha particles
Figure 4.1-1: Conceptual diagram of chamber.

Figure 4.1-2: Top view of the experimental setup.
emerge 180° apart one will be directed towards the target and will be stopped in the Al backing. To detect the other alpha particle we used plastic scintillators placed in front of the target. Figure 4.1–1 shows a conceptual diagram of this and Figure 4.1–2 is a top view. The alpha distribution is relatively isotropic at these energies so we need to cover as much of $2\pi$ steradians as possible yet still keep the design relatively simple. The plan shown in these figures was easy to implement inexpensive yet still covers approximately 60% of the alpha decays. An additional and equally important benefit of this technique is that the energy distribution of the coincident alpha particles is not “smeared out” from 8.5 to 0 MeV (like our previous measurements) but is a Gaussian-like distribution and so an energy cut off can be established and reproduced.

![Graph](image)

Figure 4.1–3: Preliminary data for the $\gamma_3$ astrophysical S-factor shown with a direct-capture calculation. The vertical error bars represent statistical uncertainty only.

Some preliminary data have been obtained and data analysis is currently underway. The work of Zahnow et al. [Zah95] presents a detailed evaluation of the cross-section for capture to the ground state. By using direct capture and adding in M1 resonances (at $E_p=441$ and 1030 keV) we fit his data fairly well. We are extending these calculations to treat the third excited state and the related $^7\text{Be}(p\gamma)^8\text{B}$ reaction. Preliminary results indicate good agreement between the calculated and measured values of the absolute cross-section for capture to the third excited state of $^8\text{Be}$. This is shown in Figure 4.1–3.
4.1.5 Direct Capture Calculations for the $^7\text{Li}(p,\gamma)^8\text{Be}$ Reaction

M. A. Godwin and H. R. Weller

A previous study [Cha94] has shown evidence for significant p-wave capture strength of 18–95% in the $^7\text{Li}(p\gamma)^8\text{Be}$ reaction at $E_p=80-0$ keV. This remains unexplained although some have argued [Bar96] that sufficient p-wave strength can be obtained from the tails of the M1 resonances (at $E_p=441$ and 1030 keV) to explain the data. The observation of large p-wave capture is interesting because it could lower the astrophysical S-factor (previously extracted by extrapolation assuming pure E1 capture) by 7–38%. Of more significance are the implications on the closely related $^7\text{Be}(p\gamma)^9\text{B}$ reaction. As explained (see Section 4.1.4) this reaction is producing $^9\text{B}$ and in turn a large portion of the solar neutrinos detected by the Homestake experiment.

In order to better understand the effects of the M1 resonances and the source of the large p-wave capture strength we are performing a series of direct capture calculations. Here we use the computer code HIKARI to calculate the contributions from direct E1M1 and E2 capture and we add the known [Ajz88] M1 resonances at $E_p=441$ and 1030 keV. Our first goal is to reproduce the extensive ground state data of Zahnow et al. [Zah95]. Using resonance parameters from the $A=5$–20 data compilations [Ajz88] and adjusting the strengths of the resonances allow us to fit the data fairly well. Note that we require the two resonances to add constructively in the region between the two levels. Barker [Bar95] has come to the same conclusion and points out that this contradicts findings from shell-model calculations. The data and our fits are shown in Figure 4.1–4.

In a recent paper [Bar96] Barker attempts to account for the data of Zahnow et al. [Zah95] and Chasteler et al. [Cha94] simultaneously. Contrary to his earlier work [Bar95] these recent fits (using an R-matrix approach and an E1 direct capture calculation) have signs in agreement with shell-model calculations (destructive interference between the two levels). However we believe that there are some problems with these solutions. The R-matrix fit does agree with the 80 keV analyzing power data although underpredicts the cross section at least as measured by Zahnow et al. [Zah95]. On the other hand the direct
Figure 4.1-4: Direct capture plus M1 resonance calculations for the $^7\text{Li}(p,\gamma)^8\text{Be}$ astrophysical S-factor for the $\gamma_0$, $\gamma_1$, and $\gamma_3$ transition. The data of Zahnow et al. is shown for capture to the ground and first excited states.

capture calculation although fitting the low-energy cross-section data underpredicts the analyzing power.

The data we have gathered are for proton energies of 80–0 keV. Since over 80% of the yield arises from 80–60 keV we have performed calculations of the relative cross section and analyzing power at 70 keV as a function of angle. These results are shown in Figure 4.1-5.

Following the same procedure we have examined proton capture to the first and third excited states of $^8\text{Be}$. Unlike the ground state both of these levels are considered to be a mixture of $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ single particles.

The cross section for the first excited state has also been studied by Zahnow et al.
They report astrophysical S-factor values for $(\gamma_0 + \gamma_1)$ capture over a large energy range. Once again we have adjusted the resonance strengths to fit this data. The S-factor (or equivalently cross section) for capture to the first excited state is shown in Figure 4.1–4. The relative cross section and analyzing power at $E_p=70$ keV are shown in Figure 4.1–5.

For the $\gamma_3$ transition we have used the data of Sweeney [Swe69] to estimate the strength of the M1 resonance. In this paper the differential cross section for $^7\text{Li}(p,\gamma_3)^8\text{Be}$ at $\theta=120^\circ$ is given for proton energies of 441 and 1030 keV. Assuming an isotropic cross section we can calculate the S-factor and adjust the strength of the two M1 resonances to match this value. The calculations for S(E) are shown in Figure 4.1–4. Running these calculations at $E_p=70$ keV gives the relative cross-section and analyzing powers curves displayed in Figure 4.1–5. Also plotted here are the data of Godwin et al. [God96].

The work above shows that the $\gamma_0$ absolute cross section is well accounted for when both M1 resonances are added to the direct capture calculation. However the measured vector analyzing power ($\approx 0.4$) is about a factor of two greater than the calculations predict. Thus the M1 amplitude needs to be doubled and (since $\sigma \approx \text{amplitude}^2$) we need four times as much M1 strength. On the other hand the $\gamma_1$ and $\gamma_3$ calculations reproduce the measured cross-section and analyzing power data reasonably well.

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4.1.6 The $^7$Be($p,\gamma$)$^8$B Reaction


The Nuclear Astrophysics and Radiative Capture Groups at TUNL are preparing to measure $^7$Be($p,\gamma$)$^8$B at energies from 75 to 800 keV. Previous measurements of the cross-section for $^7$Be($p,\gamma$)$^8$B differ by 30% and do not extend below $E_p=130$ keV [Kav69Fil83]. The goal of the current experiment is to measure the cross-section at energies down to $E_p=75$ keV and resolve the discrepancy in the previous data by reducing systematic and statistical errors. This reaction is of particular interest because of its role in the production of solar neutrinos from the decay of $^8$B. Earth-based measurements of the neutrinos released from this reaction have shown large discrepancies with respect to the predictions of the standard solar-model. The current belief is that the uncertainty in the rate of the $^7$Be($p,\gamma$)$^8$B reaction is no longer a viable explanation for the solar-neutrino problem. However, an accurate measurement of this cross-section will play a role in a quantitative resolution of the problem.

For the low-energy part of this measurement, a high-current accelerator capable of producing beams with energies up to 220 keV is needed. Unfortunately, none of the accelerators currently at TUNL fulfill that need in their current configuration. To rectify this situation, the Direct Extraction Negative Ion Source (DENIS) at TUNL will be used as a positive ion source. In this configuration it can produce proton beams with currents in excess of 100 $\mu$A and energies of up to 75 keV. We have recently acquired a high voltage table, power supply and accelerator tube which will enable the entire target chamber and associated electronics to be biased up to 200 kV. This table connected to DENIS by a new beam line will provide us with sufficient beam current and an energy range of 50–275 keV. Assembly of this new facility will begin this Summer with tests of beam intensity, spot size and uniformity following. Ramping techniques similar to those described in 4.1.3 are being investigated.

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as a means of reducing systematic errors in measurements of the energy dependence of the cross-section and thereby the S-factor.

In the interest of better statistics a 1 Curie $^7\text{Be}$ target will be produced by collaborators at LBNL. This target will produce a high flux of 477 keV $\gamma$-rays from the decay of $^7\text{Be}$ to $^7\text{Li}$. This will make it impossible to measure the $\gamma$-rays from $^7\text{Be}(p\gamma)^8\text{B}$ directly because at $E_p=200$ keV the 477 keV $\gamma$-rays will be 11 orders of magnitude more prevalent than the capture $\gamma$-rays. Therefore the reaction yield will be measured by detecting the $\alpha$-particles from $^7\text{Be}(p\gamma)^8\text{B}\rightarrow^8\text{Be}^*\rightarrow2\alpha$ the method of past experiments [Kav69 Fil83]. Unlike the previous experiments a surface barrier detector with a gas proportional counter will be used to detect the $\alpha$-particles. This detector has been constructed by collaborators at LBNL and has been shown to be capable of detecting protons down to 250 keV [Mol94].

A full calibration and test of the $\alpha$-detector and beam current integration is required and will be done at the 3 MeV laboratory at TUNL this August. This run will use a 0.1 Curie target and the measurement will map the $^8\text{B}$ resonance at 780 keV. The experimental setup includes a surface barrier detector at 160° to monitor backscattered protons a Cu beam wiper a collimator and an electron suppression ring. Initial testing of the beam current integration (BCI) components of the system has been planned for early July.

Even more important than the BCI and $\alpha$-detector is the determination of the composition, uniformity and surface contamination of the target as this was a significant source of systematic error in past experiments. Measurements of the composition of $^9\text{Be}$ targets that were created using the same chemistry as for the $^7\text{Be}$ target have been completed. These results were obtained with a 2 MeV deuteron beam where the observation of the $(d\gamma\gamma)$ and $(d\gamma\gamma)$ reactions enabled relative amounts of $^{16}\text{O}$, $^{12}\text{C}$, and $^{14}\text{N}$ to be determined. Destructive tests to confirm the target composition have also been planned. The strong 477 keV $\gamma$-ray from the actual target will enable the measurement of the areal density and distribution of the $^7\text{Be}$. This will be achieved by scanning across the target with a Pb collimator and $\gamma$-ray detector. To keep this carefully measured composition from changing due to carbon buildup during the run the vacuum system will use a turbomolecular pump a cryo pump and a long cold trap. Techniques for monitoring the status of the target and beam energy during the experiment are being developed since the cross-section at very low energies is a strong function of the beam-on-target energy.

The final low-energy cross-section measurements of $^7\text{Be}(p\gamma)^8\text{B}$ should begin in the Spring of 1997.


4.1.7 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 $^{9}\text{Be}(p\gamma)^{10}\text{B}$ using the TUNL Intense Polarized Ion Source (IPIS). 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 p-wave (M1) as well as s-wave (E1) strength for this reaction. This contradicts the standard assumption of pure s-wave capture used in extrapolating (p\gamma) cross-sections to obtain S-factors.

The cross-section for the $^{9}\text{Be}(p\gamma)^{10}\text{B}$ reaction is too low at 80 keV the maximum energy of the IPIS to be measurable in a reasonable amount of time. Therefore, the target was biased by $-20$ kV to increase the beam energy to 100 keV which increased the count rate by a factor of 5. Studies of changes in the beam profile as a function of target bias have shown that bias voltages from +20 to $-20$ kV do not change the optics of the system. To further increase the total count rate the energy integrated yield of this reaction was obtained from the $^{9}\text{Be}$ target which stopped a 100 keV beam completely.

The integrated current on target could only be measured indirectly with the target biased. A bleed off resistor could be used for this purpose but has not been implemented as of this writing. For the data obtained to date a silicon surface barrier detector viewed the $^{9}\text{Be}(p\alpha)^{8}\text{Be}$ and $^{9}\text{Be}(p\alpha)^{6}\text{Li}$ reactions. These two reactions have large cross-sections at 100 keV and can be used to measure the beam current and carbon buildup on the target. The detector was first placed inside the target chamber but it attracted secondary electrons because it was the closest object to the target. This problem was finally solved by placing it at the end of a long snout coming out of the top of the target chamber at a 55$^\circ$ angle. The detector was also shielded from elastically scattered protons by a thin Ni foil.

The $\gamma$-ray spectra were acquired using two large (130%) and three small (60%) high-purity germanium detectors (HPGe). The small HPGe detectors have thin $^{9}\text{Be}$ windows and can detect 20 keV X-rays which were produced in profusion by the secondary electrons from the biased target. A 1 mm sheet of Pb was placed between the small detectors and the target chamber to attenuate the X-rays. One of the large detectors was kept at 90$^\circ$ and the other was moved between 60$^\circ$ and 120$^\circ$. The three small detectors were arranged at 0$^\circ$, 40$^\circ$, and 50$^\circ$.

Analysis of the data has shown that $A_y(90^\circ)=0.25\pm0.05\Gamma$ implying that there is some p-wave strength. Future analysis will determine the cross-section and analyzing power as a function of angle. From this the total amount of p-wave strength will be determined. The $A_y(90^\circ)$ in $^7\text{Li}(p\gamma)^{8}\text{Be}$ has been shown to be partly due to resonance tails. This could
also be the case in $^{9}\text{Be}(p\pi)^{10}\text{Be}$ but the contributions of both direct and resonance capture have not yet been calculated.
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. Karwowski 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($p,\alpha$) and $^9$Be($p,\alpha^2$) reactions to be effective. A previous measurement [Sie73] found the low-energy cross-section in both reaction channels to be dominated by a broad ($\Gamma_{el} \approx 120$ 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 $^{10}$B (20 keV below the $^9$Be+$p$ threshold) has been established by many experiments but spin and parity assignments are not definitive. For example, an analysis of $^9$Be($^3$He,$d$) angular distributions [Bla80] favors negative parity for this state.

During the last year we have made additional angular distribution measurements with unpolarized beam at the energies where we have already taken analyzing power data.

The analyzing power data are particularly sensitive to the presence of the subthreshold state. The analyzing power predicted by previously reported $R$-matrix parameters is shown in Figure 4.2-1. The large analyzing power predicted in ($p,\alpha$) channel results from the subthreshold state. Our data clearly indicate that these parameters do not adequately describe the reaction mechanism. Further analysis is in progress.


4.2.2 A Comparison of $K$- and $R$-Matrix Parameterizations of s-Wave $^{16}O+p$ Elastic Scattering

C. R. Brune

Low-energy nuclear reaction data are often parameterized in terms of $K$- or $R$-matrix representations [Hum90; Lan58]. This type of analysis is particularly useful in astrophys-
Figure 4.2–1: Analyzing powers measured at a mean proton energy of 77 keV. The analyzing powers predicted by the $R$-matrix parameters of Sierk and Tombrillo [Sie73] are given by the solid curves.
cal applications where the parameterizations are used for extrapolating cross-section data to the needed energies often well below the range of laboratory measurements. A particularly important case is the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction whose rate is essential for understanding the evolution and nucleosynthesis of massive stars. The cross-section for this reaction at the needed energies is still uncertain due to the presence of bound states just below the $^{12}$C+$\alpha$ threshold. A recent example of $K$- and $R$-matrix fits to this reaction are given in Azuma et al. [Azu94]. While these analyses yield consistent results for the low-energy extrapolation there have been no systematic comparisons of the two techniques. There are significant differences in the two methods particularly in the way that the background (i.e. nonresonant) amplitude is parameterized.

The elastic scattering of s-wave protons by $^{16}$O provides a good test for these reaction theories. Like the p- and d-wave $^{12}$C+$\alpha$ reactions this system also has a barely bound state at $E_{c.m.} = -0.105$ MeV. It also provides an excellent opportunity to investigate the background terms as $^{17}$F has no other $^{1+}$ states up to $E=5.96$ MeV. In addition the reduced proton width of the subthreshold state is well-constrained by the direct capture cross-section into this state.

$K$- and $R$-matrix fits to the experimental phase shifts were carried out. These results were compared to a potential-model calculation which reproduced the experimental phase shifts and the $^{16}$O(pF) cross-section into the $^{1+}$ state. The value of the reduced proton width of the bound state obtained from the $K$-matrix fit disagreed with the value found with the $R$-matrix fit and also with the value inferred from the capture cross-section into this state. A $K$-matrix analysis of the potential-model calculation revealed that the background contribution to the $K$-matrix is significantly more complicated than previously assumed. It thus appears that the nature of the $K$-matrix background in other cases such as the $^{12}$C+$\alpha$ reactions warrants further study. A paper describing this work has been published in Nuclear Physics A.


4.3 Radioactive Beams

4.3.1 Nuclear Astrophysics at HRIBF

J. C. Blackmon and A. E. Champagne for the RIBENS collaboration

Reactions involving radioactive nuclei play an important role in stellar explosions such as novae\textsuperscript{,} supernovae\textsuperscript{,} and X-ray bursts. Under the extreme temperatures and densities of these events, nuclear reactions occur on time scales as short as seconds. Thus, the radioactive products of one nuclear reaction may undergo a consecutive reaction before they have time to decay. Reactions involving radioactive isotopes may provide much of the energy generation in these events and produce elements not commonly produced in other astrophysical environments. Our understanding of such astrophysical phenomenon depends upon detailed knowledge of certain nuclear reactions involving radioactive isotopes. The work of the RIBENS collaboration at the Holifield Radioactive Ion Beam Facility (HRIBF) is centered on absolute cross-section measurements of these reactions using radioactive ion beams.

The Daresbury Recoil Separator (DRS) has been installed at HRIBF as the primary endstation for nuclear astrophysics experiments. Because these experiments are to be conducted in inverse kinematics, the scattered beam and recoiling reaction products emerge at small angles with nearly equal momentum. The DRS separates the reaction products from the incident beam in two long (1.2 m) crossed-field velocity filters. In addition, there are 12 other magnetic elements which provide a q/m focus of the recoil particles. The physical installation of the separator is complete including two new diagnostic chambers (constructed at TUNL) which have been installed to assist in the determination of the optimal operating parameters. The computer control system for the separator is currently being developed.

The two elements of the focal-plane detector system which will be used in commissioning, a carbon-foil microchannel plate detector and a \( \Delta E-E \) gas ionization counter, have been tested in experiments at Yale University. Two target chambers, one for use with large Si detectors and one for use with arrays of BaF detectors, are currently under construction at TUNL. The focal plane detectors and target chamber will be installed in late Summer 1996 and stable beam commissioning of the separator is scheduled for early Fall 1996.

The first beams at HRIBF will be proton-rich beams produced by particle transfer reactions. The radioactive atoms are produced in a high temperature target and diffuse into an ion source where they can be ionized and extracted. Beams of \( ^{17}\text{F} \) and \( ^{18}\text{F} \), important nuclei in the hot-CNO cycle, are currently under development. We have performed a series of activation/release measurements on various refractory oxides to determine a possible target for production of fluorine beams. This is a particularly crucial test owing to the extreme

\textsuperscript{1}Involving TUNL, Oak Ridge National Laboratory, Yale Univ., Colorado School of Mines, Notre Dame, Louisiana State Univ., Univ. of Bombay, Indian Inst. of Tech., and Univ. of Liverpool.
reactivity of fluorine. The samples were first activated via the $^{18}$O(p,$\alpha$)$^{18}$F reaction. The activity was then measured, the samples heated, and the activity remeasured to determine the activity released. We have observed near total release of $^{18}$F from a fibrous Al$_2$O$_3$ mesh when heated to temperatures greater than 1400° C. An example of the data from a release measurement where the sample was heated to 1700° C is shown in Figure 4.3–1. While these results are encouraging, “online” testing is required to determine if the release times are fast enough to allow for release of $^{17}$F.