We review progress in studying two central problems in Nuclear Astrophysics: the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction rate at very low energies, of importance for estimating the Solar Neutrino flux, and the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate, of importance for stellar processes in a progenitor star prior to a super-nova collapse.

The $^7\text{Be}(p, \gamma)^8\text{B}$ reaction is one of the major source of uncertainties in estimating the $^8\text{B}$ solar neutrino flux and is critical for the Solar Neutrino Problem. The main source of uncertainty is the existence of conflicting data with different absolute normalization. While attempts to measure this reaction rate with $^7\text{Be}$ beams are under way we discuss a newly emerging method to extract this cross section from the Coulomb dissociation of the radioactive beam of $^8\text{B}$. We discuss some of the issues relevant for this study including the question of the E2 contribution to the Coulomb dissociation process which was recently measured to be small. The Coulomb dissociation appears to provide a viable alternative method for measuring the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction rate.

Several attempts to constrain the p-wave S-factor of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction at Helium burning temperatures (200 MK) using the beta-delayed alpha-particle emission of $^{16}\text{N}$ have been made, and it is claimed that this S-factor is known, as quoted by the TRIUMF collaboration. In contrast reanalyses (by G. M. Hale) of all thus far available data (including the $^{16}\text{N}$ data) does not rule out a small S-factor solution. Furthermore, we improved our previous Yale-UConn study of the beta-delayed alpha-particle emission of $^{16}\text{N}$ by improving our statistical sample (by more than a factor of 5), improving the energy resolution of the experiment (by 20%), and in understanding our line shape, deduced from measured quantities. Our newly measured spectrum of the beta-delayed alpha-particle emission of $^{16}\text{N}$ is not consistent with the TRIUMF('94) data, but is consistent with the Seattle('95) data, as well as the earlier (unaltered !) data of Mainz('71). The implication of this discrepancies for the extracted astrophysical p-wave s-factor is briefly discussed.

1 The Coulomb Dissociation of $^8\text{B}$ and the $^7\text{Be}(p, \gamma)^8\text{B}$ Reaction at Low Energies

The Coulomb Dissociation $^A\text{N}$ is a Primakoff $^A\text{N}$ process that could be viewed in first order as the time reverse of the radiative capture reaction. In this case instead of studying for example the fusion of a proton plus a nucleus (A-1), one studies the disintegration of the final nucleus (A) in the Coulomb field, to a

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proton plus the (A-1) nucleus. The reaction is made possible by the absorption of a virtual photon from the field of a high Z nucleus such as $^{208}Pb$. In this case since $\pi/k^2$ for a photon is approximately 1000 times larger than that of a particle beam, the small cross section is enhanced. The large virtual photon flux (typically 100-1000 photons per collision) also gives rise to enhancement of the cross section. Our understanding of the Coulomb dissociation process allow us to extract the inverse nuclear process even when it is very small. However in Coulomb dissociation since $\alpha Z$ approaches unity (unlike the case in electron scattering), higher order Coulomb effects (Coulomb post acceleration) may be non-negligible and they need to be understood. The success of the experiment is in fact contingent on understanding such effects and designing the kinematical conditions so as to minimize such effects.

Hence the Coulomb dissociation process has to be measured with great care with kinematical conditions carefully adjusted so as to minimize nuclear interactions (i.e. distance of closest approach considerably larger than 20 fm, or very small forward angles scattering), and measurements must be carried out at high enough energies (many tens of MeV/u) so as to maximize the virtual photon flux.

The Coulomb dissociation of $^8B$ may provide a good opportunity for resolving the issue of the absolute value of the cross section of the $^7Be(p, \gamma)^8B$ reaction. The Coulomb dissociation yield arise from the convolution of the inverse nuclear cross section times the virtual photon flux. While the first one is decreasing as one approaches low energies, the second one is increasing (due to the small threshold of 137 keV). Hence over the energy region of 400 to 800 keV the predicted measured yield is roughly constant. This is in contrast to the case of the nuclear cross section that is dropping very fast at low energies. Hence measurements at these energies could be used to evaluate the absolute value of the cross section.

An experiment to study the Coulomb dissociation of $^8B$ was performed at the RIKEN-RIPS radioactive beam facility. Indeed the results of the experiment allow us to measure the cross section of the $^7Be(p, \gamma)^8B$ radiative capture reaction and preliminary results are consistent with the absolute value of the cross section measured by Filippone et al. and by Vaughn et al., but not Kavanagh and Parker, as shown in Fig. 1.
1.1 Is There Evidence for an E2 Component?

A search for E2 component in the RIKEN data was performed by Gai and Bertulani. When the experimental resolutions are correctly taken into account, together with the correct RIKEN data, the best fit of the angular distributions is obtained with E1 amplitude alone. Our analysis invalidates previous claims.

In addition we have measured in a separate experiment detailed angular distributions for the Coulomb dissociation of $^8B$ in an attempt to extract the E2 amplitude directly. The $^{208}$Pb target and $^8B$ beam properties in this experiment were as in Ref., but the detector system covered a large angular range up to around 9° to be sensitive to the E2 amplitude. The E1 and E2 virtual photon fluxes were calculated using quantum mechanical approach. The nuclear amplitude is evaluated based on the collective form factor where the deformation length is taken to be the same as the Coulomb one. This nuclear contribution results in possible uncertainties in the fitted E2 amplitude. Nevertheless, the present results lead to a very small E2 component at low energies, below 1.5 MeV, of the order of a few percent, even smaller than the low value predicted by Typel and Baur. A recent reanalysis of the RIKEN2 data by Bertulni and Gai confirmed the small E2 extracted by Kikuchi.
et al. as well as the negligible nuclear contribution. Recently a possible mechanism to reduce the E2 dissociation amplitude was proposed by Esbensen and Bertsch.

1.2 Conclusions

In conclusion we demonstrate that the Coulomb dissociation provides a viable alternative method for measuring small cross section of interest for nuclear-astrophysics. First results on the CD of $^8B$ are encouraging for a continued effort to extract $S_{17}(0)$, of importance for the SSM. Our initial results are consistent with the lower value of the cross section measured by Filippone et al. and suggest a small value for the extracted $S_{17}(0)$; smaller than 20 eV-barn, and considerably smaller (30%) than assumed in the Standard Solar Model.

2 Helium Burning: The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ Reaction and the Beta-Delayed Alpha-Particle Emission of $^{16}\text{N}$

In this section we discuss progress in studying the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate of importance for understanding helium burning in massive stars. We study this reaction in its time reverse process using the beta-delayed alpha-particle emission of $^{16}\text{N}$, allowing us to add useful data and constraints on the reaction rate, and the extraction of the p-wave astrophysical S-factor. However, it appears that early hopes for deducing the p-wave astrophysical S-factor ($S_{E1}$) using the $^{16}\text{N}$ data are not substantiated. And further confusion is generated by inconsistent data on the beta-delayed alpha-particle emission of $^{16}\text{N}$ in addition to inconsistent data on the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction.

We emphasize that while data on the beta decay of $^{16}\text{N}$ may add useful constraint and may allow for extracting the (virtual) reduced alpha-particle width of the bound $1^-$ state, the sign of the mixing phase of the bound and quasi-bound $1^-$ states in the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction has nothing to do with the beta-decay of $^{16}\text{N}$ and can not be directly determined from the data on the beta-delayed alpha-particle emission of $^{16}\text{N}$. It turns out that this difficulty does not allow for unambiguous extraction of the p-wave S-factor even with the inclusion of the new data on $^{16}\text{N}$. Furthermore, a reanalysis of all existing data (including the $^{16}\text{N}$ data) by Gerry Hale demonstrates that a small S-factor solution could not be ruled out. In fact Hale’s best fit for the TRIUMF $^{16}\text{N}$ data is for an E1 S-factor approximately 20 keV-b. Interestingly, Hale’s best fit is consistent with a broader line shape. As we discuss below, such a broader line shape is observed in all other data sets, and it is quite possible that the narrow line shape of the TRIUMF data is an artifact of their data analysis.
2.1 The TRIUMF Result

A measurement of the beta-delayed alpha-particle emission of $^{16}N$ was performed at TRIUMF $^{17,18}$. The spectrum is observed with high statistics (approximately one million events) and indeed the TRIUMF collaboration claims to have deduced the p-wave astrophysical S-factor with high accuracy. Based on for example, their R-matrix analysis they quote a large value of: $S_{E1} = 81 \pm 21 \text{ keV} - b$. The E1 S-factor was previously uncertain by approximately a factor of 10 and we note the relatively high accuracy and the implication that they determined the interference of the two $1^-$ states in $^{12}C(\alpha, \gamma)^{16}O$ to be constructive (i.e. large S-factor).

As we demonstrate in this paper there is enough reasons to doubt the TRIUMF data, and furthermore we do not confirm the conclusion of the TRIUMF group that the p-wave S-factor of the $^{12}C(\alpha, \gamma)^{16}O$ reaction has been measured.

2.2 The New Yale-UConn Experiment

A further measurement of the Beta-Delayed Alpha-Particle energy spectrum of $^{16}N$ at low energy was performed in continuation of the first generation Yale experiment $^{19,20}$. The final phase of this experiment was performed using the Yale ESTU tandem van de Graaff accelerator at the Wright Laboratory at Yale University during the summer of 1995 $^{21,22}$.

The $^{16}N$ was produced using a 70 MeV $^{15}N$ beam and a 1250 Torr, 7.5 cm long deuterium gas target with 25 $\mu m$ beryllium entrance and exit foils. The $^{16}N$ emerged from the gas target with a broad recoil energy spectrum, with the lower 1 MeV portion stopping in a thin (190 $\mu g/cm^2$) aluminum catcher foil tilted at 7° with respect to the beam. After the $^{16}N$ was captured, the catcher foil was rotated 180° into the counting area. While the arm rotated and the detectors counted, a tantalum beam chopper was used to block the beam far upstream. Each full production and counting cycle lasted 21 seconds, approximately twice the lifetime of $^{16}N$.

The counting area contained, as in our previous experiment $^{19,20}$, 9 thin Silicon Surface Barrier (SSB) detectors used to measure the energy and timing information of the alpha-particles in coincidence with an array of 12 fast plastic scintillator detectors, which measured the timing of beta-particles. This timing information was used to reduce (by more than a factor of 100 over the low energy range of interest) the background in our SSB array due to detection of beta-particles and due to partial charge collection in the SSB detector.

The line shapes of both the first and second Yale-UConn data sets are the same $^{21,22}$. In order to consider the line shape of both Yale-UConn data
sets, it is useful to consider a situation for a predicted spectrum which is constant in energy (or time). Clearly the yield at a specific energy (time) is directly proportional to the energy (time) resolution at that energy (time). In this case the energy (time) resolution is the integration interval. Hence our data need to be divided by the varying energy resolution for alpha-particles traversing our aluminum foil and the time resolution of our time of flight system. The time resolution of our experiment is measured directly in the data on the beta-delayed alpha-particle of $^{16}N$ as well as the beta-delayed alpha-particle emission of $^{8}Li$ which was also measured in our experiment using the same setup and the $^{7}Li(d,p)^{8}Li$ reaction. Hence the line shape in the current (and previous) experiment(s) is deduced from measured $\partial E/\partial x$ data and the measured time resolution of our experiment.

Fig. 2: New Yale-UConn data, corrected for line shape, compared with TRIUMF and Seattle theory curves (with reduced chi-squares). The theory curves have been averaged over the experimental energy resolution.

We improved our previous Yale-UConn experiment by: (1) A 20% improvement of our energy resolution (200 keV at 2.36 MeV), (2) More than a
factor of five increase in statistics (292,000 events), and (3) An understanding of our line shape deduced from measured quantities. Our results are shown in Fig. 2. The data shown in Fig. 2 were corrected for the energy dependence of the $\beta - \alpha$ coincidence efficiency and line shape, both deduced from measured quantities. The uncertainty of the three highest energy points include the uncertainty of the $\beta - \alpha$ coincidence efficiency.

2.3 Comparison of TRIUMF data to other data sets

In Fig. 2 we also show our data compared to the Seattle and TRIUMF theory curves averaged over the variable energy resolution of our experiment. Note that the theory curves are a good representation of their respective data, but they allow us to carry out the energy averaging also over the edges of the finite data. With the Seattle theory superimposed on our data we calculate a $\chi^2$ per data point of 1.4 and for TRIUMF theory 7.2. We conclude that our data confirm the Seattle data but do not confirm the TRIUMF data. Most notable is the absence of a well defined minimum at approximately 1.4 MeV as suggested by the TRIUMF data. The data in the vicinity of 1.4 is dominated by the f-wave contribution and hence essentially determines the f-wave contribution. A larger f-wave contribution (at 1.4 MeV) would naturally lead to a smaller p-wave contribution at the interference maximum (at 1.1 MeV) and thus a smaller p-wave astrophysical S-factor.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{ratio_plot.png}
\caption{Ratio of the energy averaged TRIUMF theory curve to the new Yale-UConn data.}
\end{figure}
Fig. 4: Ratios of (a) the TRIUMF data set to the Seattle data set and (b) the TRIUMF data set to the Mainz data set. Linear interpolations were used when necessary. Notice that the ratio plots are very similar to each other and to the plot in Figure 3 indicating that there are three data sets: the Mainz(’71), Seattle(’95), and the current Yale-UConn(’96) that agree with each other but disagree with the TRIUMF(’94) data.

Following the conclusion that our data is consistent with the Seattle data but not TRIUMF data, as shown in Figs. 2 and 3, we received from Fred Barker a copy of the original communication from Waffler to Barker dated 5 Feb. 1971, which includes approximately 32 million events and a measured beta-particle background spectrum. This data set was originally taken in a study of the parity violating alpha decay from the 8.8719 MeV 2\textsuperscript{−} state in \textsuperscript{16}O. We first note that we do not confirm the allegation that there is a problem with the energy calibration of the Mainz data. We have in fact shown that the alteration of the Mainz data by the TRIUMF calibration can not be justified. Using the original unaltered Mainz data we observe that it agrees with the Seattle data (\(\chi^2\) per data point of 2.5) and disagrees with the TRIUMF data (\(\chi^2\) per data point of 123). In Fig. 4 we show using a linear scale, the ratio of the TRIUMF(94) data to other data sets. Note that the disagreement with the TRIUMF data in all cases is equally bad on the high and low energy sides of the main peak at 2.35 MeV. This together with the fact that all data sets agree on the low energy interference maximum, negates arguments of low energy tails. We conclude that indeed all other data sets that were measured with the \textsuperscript{16}N produced via the \textsuperscript{15}N(\textit{d}, \textit{p})\textsuperscript{16}N reaction including Mainz(71), Seattle(95) and Yale-UConn(96) agree with each other and exhibit the (same) disagreement.
with the TRIUMF(94) data.

2.4 Comparison of TRIUMF(93) data to TRIUMF(94)

This disagreement suggests two possible conclusions. One, that all data other than the TRIUMF data are wrong and only the TRIUMF data exhibit the true narrow line shape. Second, that the narrow line shape of the TRIUMF(94) data is an artifact of the coincidence data analysis.

In order to further investigate these two possibilities we have examined the TRIUMF(93) data as compared to TRIUMF(94) data – as reanalyzed by the graduate student James Powell. And in Fig. 5 we show the ratio of the TRIUMF(94) data to TRIUMF(93) data. Clearly the TRIUMF(93) data exhibit yet even a narrower line shape than TRIUMF(94). But the TRIUMF(93) data was already rejected by the TRIUMF collaboration, as discussed in [18], and clearly this demonstrates that the narrow line shape of the TRIUMF(93) data is an artifact of the analysis (i.e. energy miscalibration).

![Graph showing the ratio of TRIUMF(94) to TRIUMF(93) data with $\chi^2 = 30$.](image)

Fig. 5: Ratio of the TRIUMF(94) to TRIUMF(93) data. The narrower line shape of the TRIUMF(93) data is understood to be an artifact of the analysis.
2.5 Conclusions

We have reviewed the status of both data and analyses pertaining to the p-wave astrophysical S-factor of the $^{12}C(\alpha, \gamma)^{16}O$ reaction. We observe that more recent global R-matrix fit of the data on $^{16}N$, elastic scattering and $^{12}C(\alpha, \gamma)^{16}O$ reaction data does not allow us to rule out a small S-factor solution and does not confirm the strong statement of the TRIUMF collaboration that the S-factor is now known. The sign of the interference of the two $1^-$ states in $^{12}C(\alpha, \gamma)^{16}O$ data is not directly determined by data on the beta-decay of $^{16}N$, and thus this problem remains unsolved and needs to be studied via additional low energy data on the $^{12}C(\alpha, \gamma)^{16}O$ reaction itself.

We have improved our original data on the beta-delayed alpha-particle emission of $^{16}N$. A comparison of all four high statistics data on $^{16}N$ reveals three data sets: the Mainz('71), Seattle('95), and the current Yale-UConn('96) that agree with each other but disagree with the TRIUMF('94) data (by up to a factor of 3). The current situation with discrepant data on $^{16}N$, let alone disagreement on data on $^{12}C(\alpha, \gamma)^{16}O$ capture reaction, and disagreement in the extracted S-factor, do not allow us to conclude that the p-wave S-factor for the $^{12}C(\alpha, \gamma)^{16}O$ reaction is known with an accuracy sufficient for stellar evolution models, and we do not confirm neither the TRIUMF data nor the large S-factor quoted by TRIUMF with a relatively high accuracy.

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