Progress in nuclear astrophysics using secondary-radioactive beams*

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

Several attempts to constrain the $p$-wave $S$-factor of the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction at Helium burning temperatures (200 MK) using the beta-delayed alpha-particle emission of $^{16}$N have been made. However, some discrepancy exists between the spectra measured at Seattle and that of TRIUMF. We have improved our previous Yale-UConn study of the beta-delayed alpha-particle emission of $^{16}$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 $^{16}$N is consistent with the Seattle('95) data, as well as an earlier experiment performed at Mainz('71) and is not consistent with the TRIUMF('94) data. The implication of this discrepancies for the extracted astrophysical $p$-wave $S$-factor is briefly discussed.

The $^7$Be($p, \gamma$)$^8$B reaction is one of the major source of uncertainties in estimating the $^8$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 $^7$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 $^8$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 $^7$Be($p, \gamma$)$^8$B reaction rate.

RESUMEN. Se revisa el progreso del estudio de dos problemas centrales en astrofísica nuclear: $^{12}$C($\alpha, \gamma$)$^{16}$O, de importancia en procesos estelares en estrellas progenitoras antes del colapso supernova y la reacción $^7$Be($p, \gamma$) a muy bajas energías, de importancia para estimar el flujo de neutrinos solares.

Varios intentos para restringir el factor $S$ de onda $p$ de la reacción $^{12}$C($\alpha, \gamma$)$^{16}$O a temperaturas de combustión de helio (200 MK) usando la emisión de partículas alfa beta retardadas de $^{16}$N se han hecho. Sin embargo, existen discrepancias entre los espectros medidos en Seattle y en TRIUMF. Hemos mejorado nuestro estudio previo en Yale-UConn de este proceso, aumentando nuestra muestra estadística (por más de un factor 5), la resolución en energía del experimento (por 20%) y el entendimiento de nuestra forma de línea, deducida de cantidades medidas. Nuestro

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nuevo espectro de la emisión de partículas alfa beta retardadas de $^{16}$N es consistente con los datos de Seattle (1995), así como con un experimento anteriormente realizado en Mainz (1971) no así con los datos de TRIUMF. La implicación de las discrepancias en la extracción del factor $S$ de onda $p$ se discute brevemente.

La reacción $^7$Be$(p, \gamma)^8$B es una de las fuentes de error más grandes en la estimación del flujo de neutrones solares de $^8$B y es crítica para el problema de los neutrones solares. La mayor fuente de error es la existencia de datos conflictivos con diferentes normalizaciones absolutas. Mientras se intenta medir esta reacción con haces de $^7$Be discutimos un nuevo método emergente para extraer esta sección eficaz con el rompimiento coulombiano del haz radioactivo de $^8$B. Discutimos algunas de las consecuencias relevantes de este estudio, incluyendo la cuestión de la contribución $E2$ al proceso de rompimiento coulombiano que recientemente se ha medido como pequeña. El rompimiento coulombiano parece proporcionar una alternativa viable para medir la sección $^7$Be$(p, \gamma)^8$B.

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1. HELIUM BURNING: THE $^{12}$C$(\alpha, \gamma)^{16}$O REACTION AND THE BETA-DELAYED ALPHA-PARTICLE EMISSION OF $^{16}$N

In this section we discuss progress [1] in studying the $^{12}$C$(\alpha, \gamma)^{16}$O reaction rate of importance for understanding helium burning [2] in massive stars. We study this reaction in its time reverse process using the beta-delayed alpha-particle emission of $^{16}$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 $^{16}$N data are not substantiated. And further confusion is generated by inconsistent data on the beta-delayed alpha-particle emission of $^{16}$N in addition to inconsistent data on the $^{12}$C$(\alpha, \gamma)^{16}$O reaction.

We emphasize that while data on the beta decay of $^{16}$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 $^{12}$C$(\alpha, \gamma)^{16}$O reaction has nothing to do with the beta-decay of $^{16}$N and can not be directly determined from the data on the beta-delayed alpha-particle emission of $^{16}$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 $^{16}$N.

1.1. THE TRIUMF RESULT

A measurement of the beta-delayed alpha-particle emission of $^{16}$N was performed at TRIUMF [3, 4]. 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: $S_{E1} = 81 \pm 21$ 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 reason 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.

1.2. 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 [5, 6]. 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 [7, 8].

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 μm 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 μg/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 [5, 6], 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 [7, 8]. 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.

We improved our previous Yale-UConn experiment [5, 6] 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. 3. The data shown in Fig. 1 was 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.
1.3. COMPARISON OF TRIUMF DATA TO OTHER DATA SETS

In Fig. 1 we also show our data compared to the Seattle [9] and TRIUMF [4] 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 [9] but do not confirm the TRIUMF data [4]. 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. Following the conclusion that our data is consistent with the Seattle data but not TRIUMF, as shown in Figs. 1 and 2, we received from Fred Barker [10,11] 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\(^-\) state in \(^{16}\)O [12]. This line was observed at 1.282 MeV [11], in perfect agreement with the energy measured many years later using high precision gamma spectroscopy; i.e., within 0.5 keV of the tabulated value of 1.2825 MeV [12]. In addition, all data sets (Mainz, TRIUMF, Yale, Seattle and new Yale-
UConn) agree on the location of maximum energy in the $^{16}$N data. We do not confirm the allegation that there is a problem with the energy calibration of the Mainz data, and that the energy of the parity state as observed by the Mainz group is wrong. The old Mainz('71) data 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. 3 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 $^{16}$N produced via the $^{15}$N$(d,p)^{16}$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.

1.4. COMPARISON OF TRIUMF('93) DATA TO TRIUMF('94)

This disagreement suggest 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 [3] as compared to TRIUMF('94) data [4]—as reanalyze by the graduate student James Powell. And in Fig. 4 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 [4], and clearly this demonstrate that the narrow line shape of the TRIUMF('93) data is an artifact of the analysis (i.e., energy miscalibration).
1.5. Conclusions

In this study we have not performed an $R$ (or $K$) matrix global fit of the data on $^{16}$N, elastic scattering and $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction data. It is clear that in view of the discrepant data (up to a factor of 3), extraction of the $E1$ S-factor needs further study. 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. In addition we note that in an extensive preliminary analysis performed by Dr. Gerry Hale [13] he showed that the TRIUMF $^{16}$N data [4] can not rule out a small S-factor solution.

In summary, 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. 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.
2. THE COULOMB DISSOCIATION OF $^8\text{B}$ AND THE $^7\text{Be}(p, \gamma)^8\text{B}$ REACTION AT LOW ENERGIES

The Coulomb dissociation [14] Primakoff [15] process, could be viewed in first order as the time reverse process of the radiative capture. 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 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 $^{208}\text{Pb}$. 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 [14] 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 [16, 17]. 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 then 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. Indeed when such conditions were not carefully selected [18, 19] the measured cross sections were found to be dominated by nuclear effects, which can not be reliably calculated to allow the extraction of the inverse radiative capture cross section.
Good agreement between measured cross section of radiative capture through a nuclear state, or in the continuum, was achieved for the Coulomb dissociation of $^6\text{Li}$ and the $^4\text{He}(d, \gamma)^6\text{Li}$ capture reaction [20], and the Coulomb dissociation of $^{14}\text{O}$ and the $^{13}\text{N}(p, \gamma)^{14}\text{O}$ capture reaction [21-23]. In addition we note that a test experiment on the Coulomb dissociation of $^{13}\text{N}$ [21] was also found to be in agreement with the $^{12}\text{C}(p, \gamma)^{13}\text{N}$ capture reaction.

The Coulomb dissociation of $^8\text{B}$ may provide a good opportunity for resolving the issue of the absolute value of the cross section of the $^7\text{Be}(p, \gamma)^8\text{B}$ 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 $^8\text{B}$ was performed at the RIKEN-RIPS radioactive beam facility [24]. Indeed the results of the experiment allow us to measure the cross section of the $^7\text{Be}(p, \gamma)^8\text{B}$ radiative capture reaction and preliminary results are consistent with the absolute value of the cross section measured by Filippone et al. [25], and by Vaughn et al. [26], but not Kavanagh [27]and Parker [28], as shown in Fig. 5.
2.1. IS THERE EVIDENCE FOR AN $E2$ COMPONENT?

A search for $E2$ component in the RIKEN data [24] was performed by Gai and Bertulani [29]. 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 [30].

In addition we have measured in a separate experiment [31] detailed angular distributions for the Coulomb dissociation of $^8$B in an attempt to extract the $E2$ amplitude directly. The $^{208}$Pb target and $^8$B beam properties in this experiment were as in Ref. 24, but the detector system covered a large angular range up to around $9^\circ$ to be sensitive to the $E2$ amplitude, as shown in Fig. 6, where we show the measured angular distributions and the fitted $E1$ and $E2$ components. Note that the $E1$ and $E2$ virtual photon fluxes are calculated using quantum mechanical approach as well as the non-negligible $l = 2$ nuclear component. 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 [17]. Recently a possible mechanism to reduce the $E2$ dissociation amplitude is proposed by Esbensen and Bertsch [32]. Further analysis including the $p$-$^7$Be angular correlation as discussed in Ref. 32 is in progress.

2.2. 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 $^8$B 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.

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