Astrophysical S Factor of $^{12}C(\alpha,\gamma)^{16}O$ from the Beta-Delayed Alpha-Particle Emission of ^{16}N

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The spectrum of low energy beta-delayed alpha-particle emission of ^{16}N was measured with high sensitivity; e.g., at $E_\alpha^L \approx 1$ MeV, a sensitivity for a beta-decay branching ratio in the range of 10^{-9} (to 10^{-10}) was achieved. We used previous theoretical work of Ji, Filippone, Humblet, and Koonin to extract from these data the astrophysical p-wave S factor for the $^{12}C(\alpha,\gamma)^{16}O$ capture reaction, and find $S_{E1}(300) = 95 \pm 16(\text{stat}) \pm 28(\text{syst})$ keV b. This result is crucial, for example, for understanding the last stages of a massive star before a supernova.

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The cross section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at low energies is crucial for understanding helium burning in stellar environments [1]. It has to be measured at (or extrapolated to) the Gamow window for helium burning at energies of 300 keV. Attempts to measure [2-6] this S factor have led to values ranging from 0 to 500 keV b, with a compiled [7] value of $S_{E1}(300) = 60^{+60}_{-30}$ keV b, and $S_{E2}(300) = 40^{+40}_{-20}$ keV b. A determination of the S factor with an error of approximately 20% is required for understanding the origin of elements heavier than ^{12}C as well as the last stages in the life of a massive star before a supernova collapse. The S factor is governed [8] by the reduced alpha-particle widths of the bound 1^- state at 7.1 MeV and the bound 2^+ state at 6.9 MeV in ^{16}O, which thus far could not be measured or calculated in a reliable way.

The beta-delayed alpha-particle emission of ^{16}N (with a total Q value of 3.26 MeV) was originally proposed for a possible measurement of the p-wave contribution (S_{E1}) to the total S factor. Additionally, the d-wave contribution (S_{E2}) could be determined from the ratio S_{E1}/S_{E2} (with a compiled value of 1.5), which is better measured than each individual S factor. This suggestion was further developed by Barker [9] in the 1970's, who used R-matrix theory to simultaneously analyze data on alpha-particle elastic scattering, the $^{12}C(\alpha,\gamma)^{16}O$ capture reaction, and the beta-delayed alpha-particle emission [10] of ^{16}N, to extract S_{E1} with a very large uncertainty. Barker also estimated the contribution from f-wave alpha particles allowed for beta decay.

More recently [11-13] specific predictions of the shape of the low energy beta-delayed alpha-particle spectrum of ^{16}N were published using similar R-matrix [12] and K-matrix [13] theories. The predictions of Refs. [11-13] are consistent with each other and suggest an interference of the bound 1^- state at 7.1 MeV with the broad 1^- state at 9.6 MeV that leads to a secondary peak at $E_\alpha^{\text{c.m.}} \approx 1.1$ MeV and a minimum in the vicinity of 1.4 MeV. It is shown that the height of the secondary peak is directly related to $S_{E1}(300)$. Depending on the exact value of $S_{E1}(300)$, the observation of the low energy interference peak requires the ability to measure the beta-decay of ^{16}N with a sensitivity for a branching ratio of the order of 10^{-9}.

The cross section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at low energies is very small due to the small Coulomb penetration factor (e.g., at 300 keV it is 10^{-8} nb). In the case of the beta-delayed alpha-particle emission, however, we expect a large enhancement. One enhancement is due to the fact that for lower energy alpha particles the corresponding beta-decay energy is larger; thus the rate for low energy beta-delayed alpha particles is increased, as the beta decay rate is approximately proportional to the energy to the fifth power. The branching ratio for the beta decay to the broad 1^- state at 9.6 MeV in ^{16}O was measured [10] to be $1.20(5)\times10^{-5}$. This branching ratio has been confirmed in a recent measurement [14] that we carried out at Michigan State University, where we measured it to be $1.3(2)\times10^{-5}$. This branching ratio corresponds to a matrix element for the beta decay to the broad 1^- state at 9.6 MeV approximately a factor of 4 smaller than the one for the bound 1^- state at 7.1 MeV. Thus in addition to the kinematical enhancement expected for low energy beta-delayed alpha particles, we expect an increased sensitivity to the reduced alpha-particle width of the bound 1^- state due to its larger matrix elements.

In this paper we report on measurements of the beta-delayed alpha-particle emission of ^{16}N with a background low enough to reveal the predicted interference peak [11-13] at $E_{\text{c.m.}} \approx 1.1$ MeV. Attention was given to the determination of the systematic uncertainties of the detection system and the use of a collection foil of finite thickness. A theoretical analysis of our data to extract S_{E1} is presented.

The secondary ^{16}N nuclei were produced with the $^{15}N(d,p)^{16}N$ reaction, using 9 MeV deuterium beams from the Yale ESTU tandem accelerator. Beam intensities of the order of 2-5 μA were used. Typical production rates of 10^7 ^{16}N/sec were achieved, and the radioactive ions were stopped in the production target and transferred to the counting area with an efficiency of approximately 10%. The target was bombarded for 10 sec; then a chopper was inserted upstream near the accelerator position to stop the beam, and then the target was moved (during 4 sec) by an arm of approximately 1 m diameter to the counting position. After a counting period of 10 sec the target was moved back to the irradiation position. Because of the large neutron flux produced by 9 MeV deuterium beams, only one target was used, giving rise to a duty cycle on the order of 35%. The target surface was tilted at 7° with respect to the beam, so as to increase its effective thickness by approximately a factor of 8. We have calculated the range of the recoiling ^{16}N nuclei using a Monte Carlo [15] method. The collection of ^{16}N nuclei depends in a complicated fashion on the emission angles (both θ and Φ) and the energy and we found the foil thickness sufficient to stop most of the recoiling ^{16}N nuclei. We, however, do not stop most nuclei with energies higher than approximately 2 MeV or those emitted with angles larger than approximately 20°.

The target was composed of an approximately 80 μg/cm^2 Ti^{15}N foil backed by an approximately 250 μg/cm^2 Au. The thickness of the titanium-nitrite was measured with proton beams from a 1 MV model JN van de Graaff accelerator using the $E_L=429$ keV narrow resonance of the ^{15}N$(p,\alpha\gamma)^{12}$C reaction. The thickness of the gold backing was determined by measuring the shift in the observed resonance energy for a reversed target geometry (with the gold facing the proton beam). The target thickness was measured before and after the experiment. No significant deterioration in the target was found after one week of running with a total integrated beam bombardment dose of approximately 1 C. Data were collected over two weeks of running with a target of total thickness (gold plus titanium nitrate) of 400 keV for 1.8 MeV alpha particles, over three weeks with a 250 keV target, and over three weeks with a 170 keV target.

The large background due to beta decay was removed by measuring beta-alpha time of flight (TOF). The beta particles were measured with an array of twelve plastic scintillators spanning approximately 35% of 4π, placed 2 cm from the foil. The alpha particles were measured with an array of nine Si surface barrier detectors spanning approximately 6% of 4π, placed 9 cm from the foil. The count rate of each of the beta detectors was kept below 200 kHz. The silicon detectors counted at a total rate of approximately 10–20 Hz (due to energy deposited by beta particles above the threshold), with the actual rate for detected alpha particles being very small (of the order of 0.02 Hz in each detector), which allowed for small random coincidences and small pileup of β particles with alpha particles in the Si detector.

The Si detectors were 50 μm thick with an active area of 450 mm^2 and a maximum viewing angle restricted to less than 25°, so as not to increase the effective thickness of the foil for emerging alpha particles. The electronic threshold of the Si detector was set at 300–400 keV. For reducing energy deposited by beta particles in the Si detector, it is essential to use thin Si detectors, and unfortunately it was not possible to reduce the Si wafer below 50 μm thickness of such large area detectors. The detector energy response of the Si detector was measured using the ^{10}B$(n,\alpha)^7$Li reaction with a boron-oxide layer of approximately 5 μg/cm^2 areal thickness. Thermalized neutrons were produced by placing a Pu-Be neutron source outside the vacuum chamber with a wax layer, approximately 7 cm wide inside the chamber for neutron thermalization. This reaction yields narrow calibration lines at 841, 1014, 1472, and 1775 keV, spanning the entire region of interest. In addition, calibration lines of ^{148}Gd (3.183 MeV) and ^{209}Po (4.880 MeV) sources were used approximately every 6 h, to monitor energy gain shifts.

The twelve fast plastic beta detectors (Bicron BC418 0.6 cm thick, six of dimension 5×5 cm and six of dimension 2.5×2.5 cm) were coupled to twelve separate photomultiplier tubes placed outside the vacuum. The threshold on the beta detectors was set at 100 keV, which reduced the beta efficiency to about 25%. The β-α TOF response for 5 MeV alpha particles was measured using a ^{227}Ac source, and the TOF line shape for 0.6 to 5 MeV alpha particles was measured using beta-delayed alpha-particle emission of ^{8}Li from the reaction ^{7}Li$(d,p)^8$Li. The ^{7}Li target was fabricated with a calculated energy loss (for low energy alpha particles) that matched very well those of the ^{15}N target and allowed for the determination of the TOF line shape for alpha particles originating in the target. The measured time resolution (at 1 MeV) of approximately $\sigma=1$ nsec, was sufficient to remove the large background due to β-γ TOF. In addition, this time resolution was sufficient to remove (3.5σ) low energy signals from alpha particles that deposited a fraction of their energy in the detector due to partial charge collection in the Si detector. The background obtained over three weeks of running with all 108 pairs of β-α detectors defined a sensitivity for a branching ratio of approximately 2×10^{-9}. Data obtained with the two Si detectors with the highest threshold (and hence smaller background due to smaller random coincidences) yield a sensitivity for a branching ratio of approximately 7×10^{-10}.

The data were analyzed by projecting 50 keV energy slices of the two-dimensional TOF versus energy histograms onto the TOF axis. The area under the expected TOF peak (with centroid and width defined by the beta-delayed alpha-particle emission of ^{8}Li) was extracted, with a signal to background ratio of approximately 2 to 1 around $E_L\approx1$ MeV. The spectrum of beta-delayed alpha particles was corrected [15] for alpha-particle energy loss (in the 250 keV thick foil) and is plotted in Fig. 1(a). The spectrum exhibits the low energy interference peak predicted [11–13] by theory.

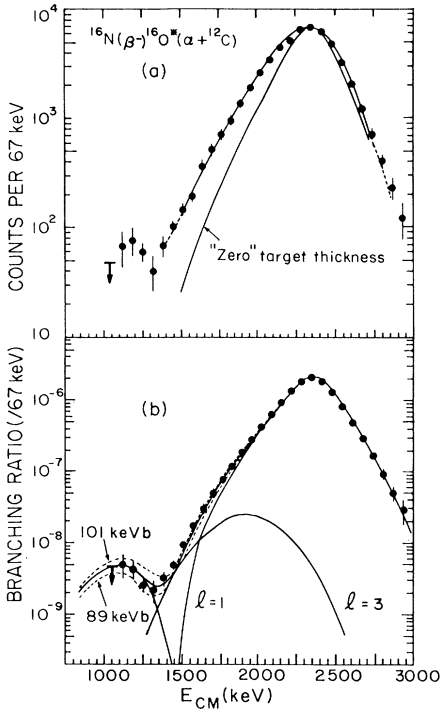

FIG. 1. The spectrum of beta-delayed alpha-particle emission of ^{16}N measured with a 250 keV thick target. (a) We also show the "zero" target thickness spectrum [10] and its convolution with the response function of our detector system, as discussed in the text. (b) We show the unfolded data (with effects of target thickness removed), together with the fit for $S_{E1}(300)=95$ keV b, the $l=3$ and $l=1$ components, and the curves for the extreme values allowed by the statistics (± 6 keV b).

We have measured the decay lifetime of the beta-delayed alpha particles, and observed the mean lifetime of 10 sec (half life 7 sec) of ^{16}N over the entire energy range. In addition, a control experiment with natural nitrogen target (99.6% ^{14}N) was carried out. No delayed alpha particles were observed in the control experiment, after two days of counting with similar beam conditions.

The line shape of the beta-delayed alpha-particle emission of ^{16}N, measured with a thin target [10], is also shown in Fig. 1(a). These data were collected with very high statistics in Ref. [10]. They are, however, governed at lower energies (below $E_{c.m.}=1.5$ MeV) by a large background from beta particles. In addition we have measured [14] with smaller statistics, the beta-delayed alpha-particle emission of ^{16}N implanted into a Si detector (i.e., "zero" thickness foil), using ^{16}N secondary beams from the A1200 fragment analyzer of the Michigan State University (MSU) K1200 cyclotron. The MSU data confirmed the earlier results of Ref. [10]. As can be seen in Fig. 1(a), the effect of the finite target thickness used in this experiment is to yield an asymmetric line shape of our data. The systematical uncertainty due to target thickness was studied by varying the target thickness (i.e., 400, 250, and 170 keV) and will be discussed in a long forthcoming article [16]. We have unfolded our data to remove effects of target thickness, as discussed below.

The zero target thickness data of Ref. [10] were convoluted with the response function of our detector system, and the resulting curve fit our measured data as shown in Fig. 1(a). In this procedure we determine (semiempirically) the response function of our system. The response function arises from the measured integration interval (target width) and a low energy tail that is determined empirically by comparing our data with Ref. [10]. This response function is determined exactly over the range of available zero target thickness data and is extrapolated beyond this region [the convoluted extrapolation is shown in Fig. 1(a) as the dashed line]. The so obtained response function is thus well understood down to 1.4 MeV, as can be seen in Fig. 1(a). This procedure allows us to unfold our data and to remove effects of finite energy integration in our target. The unfolded data obtained (of the 250 keV thick target) are shown in Fig. 1(b). It represents the yield for a zero thickness target. A detailed description of the unfolding procedures as well as the data analyses and results can be found in Ref. [16] and will be published in a forthcoming long article [16].

The unfolded spectrum of beta-delayed alpha-particle emission of ^{16}N, shown in Fig. 1(b), was fit simultaneously with elastic scattering data and the $^{12}C(\alpha,\gamma)^{16}O$ data, using the R-matrix formalism developed in Ref. [12]. We used the fit parameters of Ji *et al.* [12] including the channel radius of 5.5 fm and the boundary condition parameter $B=-3.504$. The best fit was obtained for $S_{E1}(300)=95$ keV b. This fit exhibits a large sensitivity to the extracted S factor for the shape of the measured spectrum around 1.1 MeV, and we show in Fig. 1(b) the curves for extreme values of the S factor (± 6 keV b). Note that while the statistical uncertainty of our data at that region is of the order of 20%, the uncertainty in the extracted S factor is better than 10%. Such an enhanced sensitivity is expected for an interference effect.

In Fig. 1(b) we show the $l=3$ component of our fit. Only with the introduction of the small $l=3$ component was it possible to reproduce the line shape of the unfolded spectrum. A small $l=3$ component is suggested by the value of the yield at the minimum observed at 1.4 MeV. An $l=3$ component at 1.1 MeV that is equal to the value at 1.4 MeV [unlike the one shown in Fig. 1(b)] would reduce the extracted S factor by less than 15%.

The unfolded data shown in Fig. 1(b) are well defined in the region above 1.4 MeV, including the region above 1.5 MeV where the data [10] for zero target thickness were measured. In order to study the systematic uncertainty of our unfolding procedures we have varied the deconvolution function. Based on this analysis we conservatively estimate a systematic uncertainty of approximately 30% due to the unfolding procedures [16]. This systematic uncertainty overwhelms all other uncertainties (including theoretical uncertainties) [16] and the final quoted systematic uncertainty is approximately 30%.

We note that the S factor measured here is in agreement with a recent concurrent measurement of ^{16}N performed at TRIUMF [17] that reports $S_{E1}(300)=57 \pm 13$ keV b. While the two experimental procedures used in this experiment and in Ref. [17] are very different (thus lead to systematic uncertainties of different nature) the obtained S factors are in agreement. In addition while we present here an R-matrix analysis of the data, the authors of Ref. [17] use a K-matrix analysis and obtain similar results. However, we add that while in our analysis the contribution from an $l=3$ partial wave in the region of the low energy peak is negligible, it amounts to as much as 20%–30% in the data analysis of Ref. [17], which may explain the smaller central value of S_{E1} quoted in Ref. [17].

An attempt to extract the total $(E1+E2)$ S factor for this reaction from nonlaboratory measurements, was published by Weaver and Woosley [18]. For the compiled ratio $S_{E1}/S_{E2}=1.5$, they conclude $S_{E1}(300)=(1.7\pm0.5)\times60=102\pm30$ keV b. While the value presented here is in agreement with Weaver and Woosley, the value extracted in Ref. [17] is just outside the region allowed by the quoted uncertainties. We emphasize that for a cross section of the ^{12}C$(\alpha,\gamma)^{16}$O reaction which is twice the accepted value [7], the production of carbon from helium burning in massive stars, is negligible (below the 15% limit quoted in Ref. [18]), which leads to a substantial change in the predicted scenario of supernovae [18]. While the S factors reported in this work and suggested in Ref. [18] allow for such a possibility, the results of Ref. [17] exclude it. This possibility then calls for a new generation of precision experiments as performed here, with a reduced systematical error, to clarify the exact value of the S factor and the exact fate of a massive star at its last stages before a supernova.

In conclusion, we have measured the beta-delayed alpha-particle emission of ^{16}N with a background small enough to observe the predicted low energy interference peak. After unfolding the effects of the finite thickness of our foil we used these data to extract the S factor for the ^{12}C$(\alpha,\gamma)^{16}$O capture reaction to yield $S_{E1}(300)=95 \pm 6(\text{stat}) \pm 28(\text{syst})$ keV b.

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