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$^{14}N(n,p)^{14}C$ cross section from 61 meV to 34.6 keV and its astrophysical implications

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We have measured the $^{14}N(n,p)^{14}C$ cross section from 61 meV to 34.6 keV. Our data are in agreement with previous measurements made via the inverse reaction, but are approximately a factor of 2.5 larger than a recent direct measurement. As a result, our data support the astrophysical reaction rate used in most previous nucleosynthesis calculations over the recently recommended threefold reduction in this rate. Astrophysical implications of our new measurements are discussed.

The $^{13}C(\alpha,n)^{16}O$ and the $^{22}Ne(\alpha,n)^{25}Mg$ reactions are thought to be the two most promising neutron source candidates for the slow-neutron-capture or s process of nucleosynthesis. However, ^{14}N, via the relatively large $^{14}N(n,p)^{14}C$ cross section, is potentially a strong neutron "poison" during the operation of the chain of reactions involving the $^{13}C(\alpha,n)^{16}O$ neutron source, perhaps making this chain of reactions a net neutron consumer rather than a net producer of neutrons.

Recently, the first direct measurement of the $^{14}N(n,p)^{14}C$ cross section at energies ($E_n = 25.0$ and 52.4 keV) corresponding to s-process temperatures ($E_n \approx 30$ keV) was reported by Brehm *et al.*[1] Their result for the astrophysical reaction rate was approximately a factor of 3 smaller than the rate[2] used in most previous nucleosynthesis calculations. From the reduction in the reaction rate indicated by their measurements Brehm *et al.* concluded that: (i) ^{14}N plays a correspondingly smaller role as a neutron poison, (ii) the amount of ^{14}C produced is reduced, and (iii) it may be possible to produce a significant amount of ^{15}N during the s process[3] (previously ^{15}N was thought to be produced only during explosive nucleosynthesis[4,5]).

Although the data of Brehm *et al.*[1] lead to astrophysically very interesting conclusions, their data disagree with other measurements[6,7] upon which the previously accepted reaction rate is based.[8] At s-process temperatures, the most relevant previous data are the measurements of Gibbons and Macklin,[6] Sanders,[9] Johnson and Barschall,[10] and measurements of the thermal cross section.[7] Taken together, these previous measurements indicate that the cross section is two to three times larger than reported by Brehm *et al.* Also, Brehm *et al.* state that their data indicate the cross section has close to a $1/v$ shape in the region of their measurements, while at the same time their data are a factor of 2 smaller than a $1/v$ extrapolation of the cross section from the measured thermal value.[7] Hence, if both the value of the thermal cross section and the data of Brehm *et al.* are correct, the cross section must depart by about a factor of 2 from a $1/v$ shape between thermal energy and approximately 25 keV, but return to a $1/v$ shape over the region of energies measured by Brehm *et al.* However, there have been no reported measurements of the cross section between thermal energy and 25 keV, so the shape of the cross section in this region is unknown. Because the thermal cross section appears to be well known, the major motivation of the present work was to measure the shape of the $^{14}N(n,p)^{14}C$ cross section across the broad range from near thermal energy to approximately 35 keV. By using a "white" neutron source, the cross section was measured at all energies simultaneously, thereby minimizing the possible systematic uncertainties in the shape of the cross section which may arise from measurements made using monoenergetic sources.

The experimental technique used in these measurements has been published elsewhere,[11] so only the details of particular importance to the present measurements will be given here. The measurements were performed using the "white" neutron source at the Los Alamos Neutron Scattering Center (LANSCE). The data were taken in two parameter mode, pulse height (or proton energy) versus time-of-flight (or neutron energy). In this way measurements were made at all neutron energies simultaneously and the pulse-height spectrum at each energy could be used to monitor backgrounds. There was no measurable change with energy in the size of the small background under the peak from the $^{14}N(n,p)^{14}C$ reaction.

The ^{14}N sample was produced by vacuum evaporation of the chemical adenine ($C_5H_5N_5$) to a thickness of 165 $\mu g/cm^2$ onto a 8.5-μm-thick aluminum foil. The protons from the $^{14}N(n,p)^{14}C$ reaction were detected with a silicon surface barrier detector of 10 μm thickness by 50 mm^2 in area. Representative pulse-height spectra are shown in Fig. 1. Because both the neutron flux and the $^{14}N(n,p)^{14}C$ cross section decrease with increasing energy, the statistical accuracy of the data becomes worse as the energy increases. The peak in the pulse-height spectrum was identified with the $^{14}N(n,p)^{14}C$ reaction by (i) calibrating the energy scale of the spectrum using ^6Li and ^{10}B samples, and (ii) substituting the 165 $\mu g/cm^2$ sample of ^{14}N with both larger and smaller samples and observing that the yield of the peak per unit of neutron flux was well correlated with the sample size.

The measurements were made relative to the $^6Li(n,\alpha)t$ cross section using a separate ^6Li sample (5 $\mu g/cm^2$ thick) and detector (100 μm thick by 300 mm^2 in area) as a flux monitor. The $^{14}N(n,p)^{14}C$ thermal cross section is known to better than 3% accuracy from two independent measurements,[12,13] so we did not measure absolute cross

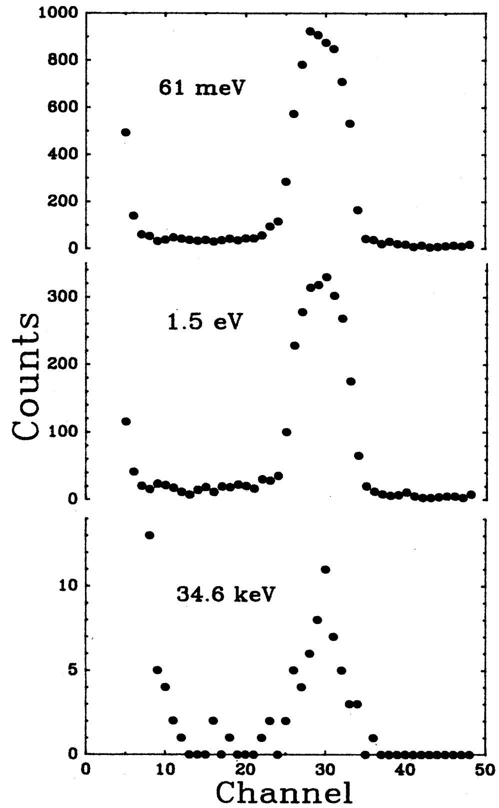

FIG. 1. Representative pulse-height spectra from our $^{14}N(n,p)^{14}C$ measurements. The laboratory neutron energy is indicated for each spectrum shown.

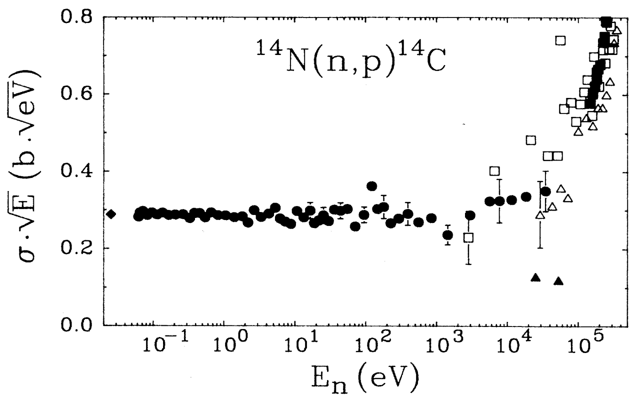

FIG. 2. The $^{14}N(n,p)^{14}C$ reduced cross section vs laboratory neutron energy. Shown are our data (solid circles), the direct measurements of Ref. 1 (solid triangles), Ref. 7 (solid diamond), and Ref. 10 (solid squares), and the inverse measurements of Ref. 6 (open triangles) and Ref. 9 (open squares).

sections, but instead normalized our data to the measured thermal cross section. Because there is a gap between our lowest energy measurement at 61 meV and thermal energy (25 meV), in making this normalization we assumed that the cross section follows a $1/v$ shape over this very small energy range. It is unlikely that any significant departures from a $1/v$ shape occur over this small energy range. The data were converted from yields to cross sections using the recommended thermal cross sections for ^{14}N (Ref. 7) and ^{6}Li (Ref. 14), and the latest evaluation[14] for the energy dependence of the ^{6}Li cross section.

The resulting reduced cross sections are shown in Fig. 2. The representative error bars shown on our data depict the one-standard-deviation relative errors only. For $E_n < 10$ eV, the error bars are smaller than the size of the data points. The relative uncertainties are dominated by counting statistics, but also include a small (maximum of approximately 2%) contribution from the uncertainty in the energy dependence of the ^{6}Li cross section across the energy range measured. A normalization uncertainty of approximately 3.5% was calculated from the published uncertainties in the ^{14}N (Ref. 7) and ^{6}Li (Ref. 14) thermal cross sections. The details of the cross-section normalization procedure, the collimation, the data acquisition techniques, the neutron energy resolution, and the small correction to the data due to the anisotropy of the $^{6}Li(n,\alpha)t$ cross section have been published elsewhere.[11]

Our measurements indicate that the $^{14}N(n,p)^{14}C$ cross section has very nearly a $1/v$ shape except at the highest energies measured. Our data are compared to previous measurements in the same energy range in Fig. 2. Direct measurements of the $^{14}N(n,p)^{14}C$ cross section are shown as solid symbols, while open symbols represent measurements made via the inverse $^{14}C(p,n)^{14}N$ reaction. As can be seen in Fig. 2, the data of Brehm *et al.*, for which the quoted uncertainties are smaller than the size of the data points, are approximately a factor of 2.5 smaller than our results. The two measurements in this range made via the inverse $^{14}C(p,n)^{14}N$ reaction are those of Sanders[9] and those of Gibbons and Macklin.[6] We converted the data of Sanders to $^{14}N(n,p)^{14}C$ cross sections using detailed balance. Sanders estimated an absolute uncertainty in his data of 30% at the $E_p = 1.16$ MeV resonance, and states that the cross sections at other energies may be subject to an additional error due to an (unmeasured) energy dependence of the neutron detector efficiency. This 30% uncertainty is depicted by the error bar on the lowest energy data point of Sanders in Fig. 2. No estimate of the relative uncertainty was given by Sanders. The data of Gibbons and Macklin were normalized to those of Sanders at the $E_p = 1.31$ MeV resonance and hence are also quoted as having a 30% absolute uncertainty as is indicated by the error bar on their lowest energy data point in Fig. 2. Their relative uncertainty is given as 2%. We obtained the data of Gibbons and Macklin from Ref. 15 where the data had already been converted to $^{14}N(n,p)^{14}C$ cross sections. The data of Johnson and Barschall were also obtained from Ref. 15 and are included in Fig. 2 for completeness although there is no overlap in energy between their data and ours. No uncertainty was given for the data of Johnson and Barschall. From a comparison of the data in the resonance region, it had been noted by Ferguson and Gove[16] that the energy scale for the measurements of Gibbons and Macklin is 18 keV lower than that of Sanders. As can be seen in Fig. 2 however, the opposite seems to be the case for at least some of the range of energies of concern here. There appears to be a systematic shift to higher energy or lower cross section in the data of Gibbons and Macklin compared to those of Sanders and those of Johnson and Barschall.

The reaction rate[2] used in most previous nucleosynthesis calculations was originally determined by Bahcall and Fowler[8] and was based on the inverse data of Gibbons and Macklin[6] and the thermal cross section.[7] Because our measurements are normalized to the same thermal value used by Bahcall and Fowler, and because our data agree with those of Gibbons and Macklin to within the experimental errors, our results as well as the other available data[6,7,9,10] in this energy range support a $^{14}N(n,p)^{14}C$ reaction rate at least as large as that calculated by Bahcall and Fowler over the threefold reduction in this rate recommended by Brehm *et al.*[1] Therefore, our measurements indicate that ^{14}N would be a stronger neutron poison during the possible operation of the $^{13}C(\alpha,n)^{16}O$ *s*-process neutron source than the data of Brehm *et al.* imply. Our results also seem to rule out the *s*-process as a source of significant amounts of ^{15}N if the production of this isotope is dependent upon an approximate twofold reduction in the $^{14}N(n,p)^{14}C$ reaction rate of Bahcall and Fowler as indicated by the preliminary calculations of Jorissen and Arnould.[3]

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