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Neutron-spectroscopic factors for low-lying ^{16}N levels

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The magnitude of the ^{15}N$(n,\gamma)^{16}$N reaction rate in asymptotic giant branch stars depends directly on the neutron spectroscopic factors of low-lying ^{16}N levels. A new study of the ^{15}N$(d,p)^{16}$N reaction is reported populating the ground and first three excited states in ^{16}N. The preliminary spectroscopic factors are near unity as expected from shell model calculations, resolving a long-standing discrepancy with previous experiments. The data and analysis are presented.

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The site of the astrophysical production of Galactic ^{19}F is uncertain with supernovae, asymptotic giant branch (AGB) stars, and Wolf-Rayet stars as suggested possibilities [1]. AGB stars are the most likely as they are the only site observationally confirmed to produce ^{19}F [2]. Model calculations, however, have not yet been able to reproduce certain observed abundance correlations such as that of ^{19}F with ^{12}C [2], and it is unclear the extent to which nuclear physics uncertainties are contributing to the discrepancies. ^{19}F is thought to be made in AGB stars via the chain ^{14}N$(\alpha,\gamma)^{18}$F$(\beta^+)^{18}$O$(p,\alpha)^{15}$N$(\alpha,\gamma)^{19}$F. Free protons and neutrons are produced by the ^{14}N$(n,p)^{14}$C and ^{13}C$(\alpha,n)^{16}$O reactions, respectively, and further processing by *p*- and *n*-induced reactions must also be considered [2, 3]. In particular, one needs to consider the branching at ^{15}N between the ^{15}N$(\alpha,\gamma)^{19}$F and ^{15}N$(n,\gamma)^{16}$N reactions when calculating ^{19}F production. While there has been several recent publications studying the ^{15}N$(\alpha,\gamma)^{19}$F reaction [1, 4, 5], there have been few studies of the ^{15}N$(n,\gamma)^{16}$N reaction. The most recent study of the ^{15}N$(n,\gamma)^{16}$N reaction rate was performed in 1996 by Meissner *et al.* [6], where it was concluded that the rate is dominated by *p*-wave direct capture over almost all of the relevant temperature range with resonances only contributing at the highest of temperatures. The magnitude of the calculated direct capture rate depends directly on the neutron spectroscopic factors of low-lying ^{16}N levels, and thus a determination of these spectroscopic factors is critical for calculating the rate.

There has been one measurement of the neutron-spectroscopic factors for low-lying ^{16}N levels [7]. The ground state of ^{16}N and excited states at 121, 297, and 397 keV were observed with nearly equal spectroscopic factors of $\sim$0.5. This result was rather surprising as ^{15}N is a closed shell nucleus, and it was thought that low-lying ^{16}N levels were good single-particle levels with spectroscopic factors near unity [6, 7]. These expectations were further confirmed by OXBASH calculations in Ref. [6] where spectroscopic factors between 0.87 and 0.96 were predicted. Clearly, the low spectroscopic factors for this nucleus need experimental confirmation.

To investigate these discrepancies, a new measurement of the ^{15}N$(d,p)^{16}$N reaction has been performed at the Oak Ridge National Laboratory (ORNL) Holifield Radioactive Ion Beam Facility (HRIBF). A 100-MeV ^{15}N beam was used to bombard a 90-μg/cm^2 CD$_2$ target. Similar to previous studies [8], protons from the (d,p) reaction were detected at backward laboratory angles, 155°-169° (corresponding to 3°-8° in the center of mass) by the Silicon Detector Array (SIDAR) [9]. To confirm the identification of (d,p) protons, some of the data were taken in coincidence with ^{16}N recoils that were transported and separated from the primary beam by the Daresbury Recoil Separator [10]. Figure 1 shows the spectrum from SIDAR in singles and in coincidence with ^{16}N recoils. Additional detectors of the Oak Ridge Rutgers University Barrel Array (ORRUBA) type [11] were placed near 90° and were useful for for monitoring target stability via elastic scattering of target components during the run and for detecting (d,p) protons at larger center of mass angles. The ORRUBA strips were oriented parallel to the beam axis such that the position along the strip of a detected particle provided a good measure of the polar angle of the reaction product. Another smaller annular detector was placed at forward angles (9°-18°) to measure elastic scattering of the beam from the carbon in the target for beam current normalization. To determine this scattering rate, a surface-barrier detector was inserted into the beam path downstream of the target location, and a low-intensity beam ($\sim 10^4$ pps) was counted while scattered beam particles were measured in the forward-angle detector. Afterwards, the surface-barrier detector was retracted, and the beam was raised to full intensity. Typical beam intensities were limited to $\leq 3\times10^6$ ^{15}N/s to prevent

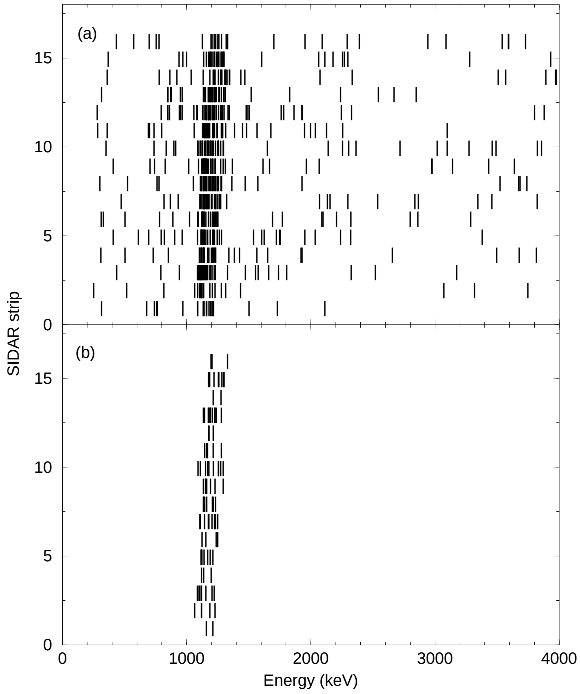

Figure 1: (a)Energy of detected particles observed in the various SIDAR strips. The laboratory angles range from 169° to 155° for strips 1 to 16, respectively. (b) Same as (a) but in coincidence with a ^{16}N recoil transported through the DRS. The band arising from ^{15}N$(d,p)^{16}$N is clearly identified.

target degradation. The lack of target degradation was verified by monitoring the rate of deuterium scattering over time and by checking that consistent target thickness measurements were obtained before and after the experiment.

Data were taken for approximately 65 hours and a total of 4.6 $\times 10^{11}$ ^{15}N ions bombarded the target over the course of the experiment. A typical singles spectrum from the inner SIDAR strip is shown in Fig. 2. Two groups were observed corresponding to the ground state and first excited state in one group and the second and third excited states in the other group. While the resolution was not sufficient to separate the states, this did not negatively impact the goal of determining the total cross sections.

Cross sections were obtained for the population of these low-lying ^{16}N levels. Because coincidence data with ^{16}N recoils were only taken for part of the experiment, the singles spectra were used for peak sum extraction assuming a linear background. As can be seen in Fig. 2, there was relatively little background in the spectra, and thus background subtraction was straightforward. The combined differential cross sections for populating the ground and first excited states and for populating the second and third excited states are shown separately in Fig. 3. The uncertainties shown on the data points are purely statistical in nature. The cross sections extracted at the most forward center of mass angles were from the SIDAR detector, while those at larger angles were measured with the ORRUBA detectors.

The differential cross sections determined from the present measurements were analyzed within the framework of the distorted wave Born approximation (DWBA) using global optical model pa-

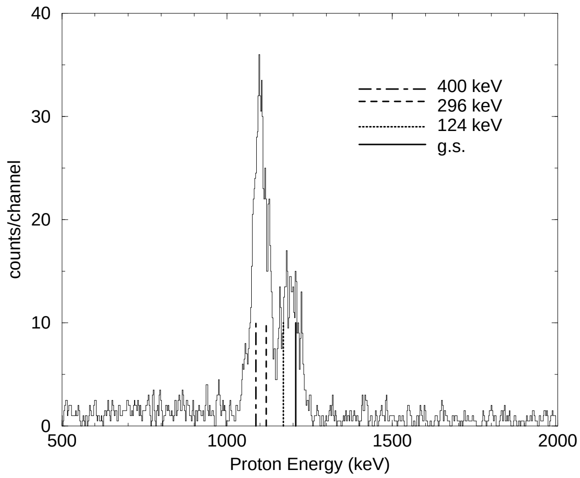

Figure 2: Singles energy spectrum observed in the inner strip of SIDAR. Lines show the expected positions of peaks from the ^{2}H(^{15}N,p)^{16}N reaction.

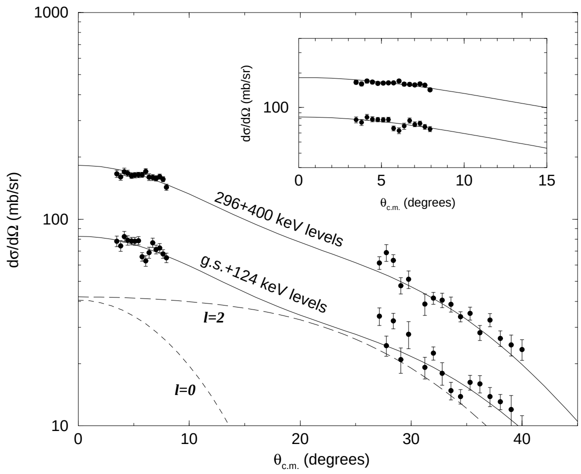

Figure 3: Differential cross sections for the ^{15}N(d,p)^{16}N reaction as a function of center-of-mass angle. The inset shows an expanded view of the SIDAR data. Since resolution of the closely-spaced levels was not possible, composite DWBA curves have been fitted to the data. The dashed curves show the contributions that were summed to fit the g.s.+124-keV cross sections.

rameter sets. The deuteron and proton parameters of Perey and Perey [12] were found to be well suited for the data, and these same parameters also reproduced well the published DWBA calculations from Ref. [7]. Calculations of the cross sections to populate individual ^{16}N levels were performed with the reaction code TWOFNR [13]. Since closely-spaced levels could not be resolved, the calculations were combined for the doublets allowing the relative strengths to vary as free parameters of the fit. The resulting composite angular distributions are displayed in Fig. 3 and well reproduce the shapes of the measured angular distributions. These calculations were then fitted to the measured data to determine the best values for the spectroscopic factors. Preliminary results indicate the spectroscopic factors are in the range 0.7-1.0, which agree well with the OXBASH calculations [6]. The uncertainties in the spectroscopic factors is estimated to be about 15% resulting mostly from uncertainties in the target thickness ($\sim$ 11%) and beam current normalization ($\sim$ 10%), while statistical uncertainties were only $\sim$3%. Additional model uncertainties are not considered. We do not believe that the difference in our spectroscopic factors and those extracted by [7] are the result of using different optical model parameters as we reproduce the DWBA calculations in Ref. [7] using our parameters. Future work includes finalizing the spectroscopic factors extracted for individual levels and updating the ^{15}N$(n,\gamma)^{16}$N reaction rate calculation.

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