PHYSICAL REVIEW C **66**, 022801(R) (2002)

Search for a resonance in the $^{14}N(p,\gamma)^{15}O$ reaction at E_p=127 keV

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(Received 24 June 2002; published 29 August 2002)

The $^{14}N(p,\gamma)^{15}O$ reaction regulates the energy produced by the CN cycle in main-sequence stars and in red giants. Recently, preliminary evidence was presented for a new resonance in this reaction, which would significantly increase the reaction rate for temperatures near 10^8 K. We have attempted to confirm this result and find no indication of a resonance near $E_p^{lab}=127$ keV. Our upper limit on its strength is $\omega\gamma \leqslant 32$ neV (95% C.L.), which is more than 2 orders of magnitude below the previously reported value.

DOI: 10.1103/PhysRevC.66.022801 PACS number(s): 25.40.Lw, 26.20.+f, 27.20.+n

The CN cycle is the main source of energy at some point in the life of every star. During quiescent stellar burning, $^{14}N(p,\gamma)^{15}O$ is the slowest reaction in the cycle and thus it regulates the rate of energy production. Nelson *et al.* [1] have reported preliminary evidence for a resonance in $^{14}N(p,\gamma)^{15}O$(g.s.) at a laboratory proton energy $E_p^{lab}=127(2)$ keV (or a center-of-mass energy $E_p^{\text{c.m.}}=117$ keV), which would correspond to a new state in ^{15}O at an excitation energy $E_x=7414(2)$ keV. This state was observed to decay exclusively to the ground state of ^{15}O and, from shell-model arguments, they assigned it a spin-parity, $J^{\pi}=1/2^{-}$. While this result may seem surprising at first glance, the (p,γ) threshold lies at a relatively high energy, and thus at a comparatively high level density. Therefore, it is difficult to argue against the possibility of a weak resonance that has so far escaped detection.

The contribution of this state to the thermonuclear reaction rate, $\langle\sigma \mathrm{v}\rangle$, can be written as

$$\langle\sigma \mathrm{v}\rangle=\left(\frac{2\pi}{\mu kT}\right)^{3/2}\hbar^2(\omega\gamma)_{\mathrm{r}}\exp\left(-\frac{E_{\text{c.m.}}}{kT}\right), \qquad (1)$$

where μ is the reduced mass, k is Boltzmann's constant, and $\omega\gamma$ is the resonance strength, which is defined by

$$\omega\,\gamma=\frac{2J_r+1}{(2J_t+1)(2J_p+1)}\,\frac{\Gamma_p\Gamma_\gamma}{\Gamma}. \qquad (2)$$

Here, J_r, J_t, and J_p are the spins of the resonance, target, and incident proton, respectively; and Γ_p, Γ_γ, and Γ are the proton and γ-ray partial widths, and the total width, respectively. Nelson *et al.* [1] derived a resonance strength $\omega\gamma=4.5(9)$ μeV, which has significance for the main-sequence evolution of massive stars and in red giants. For example, a star of solar mass and composition at the tip of the red-giant branch would have to adjust itself to an energy-generation rate increased by about a factor of 2 at canonical temperatures.

In view of the impact that this resonance has on the $^{14}N(p,\gamma)^{15}O$ reaction rate, it is important to confirm its existence by independent means. The previous measurement employed a thick deuterated-ammonia ice target and it is not clear if the target composition was stable under bombardment. Also, their γ-ray spectrum showed significant backgrounds from neutron-induced reactions. In fact, neutrons are expected to be produced in this target via two-step reactions [2], but it is not clear what effect this process may have had on the previous results. We have also searched for this state using the $^{14}N(p,\gamma)^{15}O$ reaction, with targets made by implanting nitrogen into tantalum backings. These targets are known from experience [3] to be both relatively free of contaminants and stable under bombardment with high-intensity proton beams.

We performed this experiment at the Laboratory for Experimental Nuclear Astrophysics (LENA), located at the Triangle Universities Nuclear Laboratory. A 1-MV Van de Graaff accelerator provided proton beams at laboratory energies between 135 and 300 keV, and with beam currents of 100–150 μA. The beam entered the target chamber through a copper tube, which extended to less than 1 cm from the target. The tube was cooled by a LN_2 reservoir to trap potential target contaminants and biased to -80 V to suppress the emission of secondary electrons from the target. The target was cooled using chilled, deionized water. As mentioned above, the target consisted of ^{14}N implanted into a thick tantalum backing. The implantation energy and dose were 120 keV and 110 $\mu g/cm^2$, respectively. Previous measurements [4] of the $E_p^{lab}=278$-keV resonance yield as a function of proton energy, combined with the known resonance strength [5] imply a uniform composition with a Ta/N ratio of 0.72(11), which is consistent with the known saturation ratio [6].

Gamma rays were detected using a 135% HPGe detector placed at $\theta_{lab}=0°$ and at a distance of 9 mm from the target. The energy calibration and absolute efficiency were established using radioactive sources and the decays from well-known resonances in the $^{14}N(p,\gamma)^{15}O$ and $^{27}Al(p,\gamma)^{28}Si$ reactions. A 35.6-cm diameter $\times$ 40.6-cm long annulus of NaI(Tl) enclosed both the target and Ge detector. This detector geometry allowed us to record three types of events: Ge singles, Ge-NaI coincidences, and Ge signals without a corresponding event in the NaI detector within 5 μs. In the latter mode, the NaI served as a cosmic-ray veto while also suppressing events arising from γ-ray cascades. We examined the anticoincidence spectra for evidence of the new resonance.

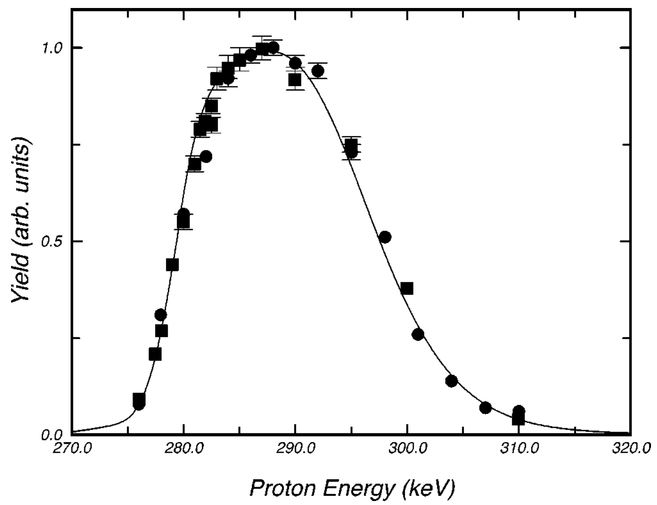

FIG. 1. Thick-target yield curves for the $E_p^{lab}=278$-keV resonance measured before (squares) and after (circles) the resonance search. Note that the measured resonance energy appears to be above 278 keV, which is a consequence of the fact that the implantation region does not extend to the surface of the target. The solid line is a calculation normalized to the data, assuming a stoichiometry of Ta/N=0.72.

The width of the yield curve for the 278-keV resonance (Fig. 1) implies a target thickness of about 22 keV at 127 keV. Consequently, we looked for evidence of a 127-keV resonance at $E_p^{lab}=135$ and 145 keV so that the resonance would occur well within the implantation region. This reduced the likelihood that target degradation would affect the measured yield and eliminated the need to correct for uncertainties in the resonance energy (± 2 keV [1]) and in the beam energy (± 1 keV). The resonance strength is related to the thick-target yield Y by the relation [7]

$$\omega\gamma = \frac{2\epsilon}{\lambda^2}Y, \tag{3}$$

where λ is the de Broglie wavelength of the incident proton and ϵ is the stopping power, both evaluated at the resonance energy (and in the center-of-mass system). The thick target yield is obtained from

$$Y=\frac{N_\gamma}{N_p\ B_\gamma\ \eta_\gamma\ W_\gamma}, \tag{4}$$

where N_γ, N_p, B_γ, η_γ, and W_γ are, respectively, the number of observed γ rays, the number of incident protons, the branching ratio, the detection efficiency, and the angular distribution of the γ rays in question. For the state of interest, $B_\gamma=1$. Although $W_\gamma=1$ for $J_r=1/2$, we have calculated angular distributions for a range of possible resonance spins, assuming *s*-, *p*-, or *d*-wave capture and $E1$, $M1$, or $E2$ radiation. The largest deviation from isotropy for our detector geometry was about 10% and thus we have set $W_\gamma=1$. In order to minimize systematic uncertainties related to beam integration and absolute detection efficiency, we determined

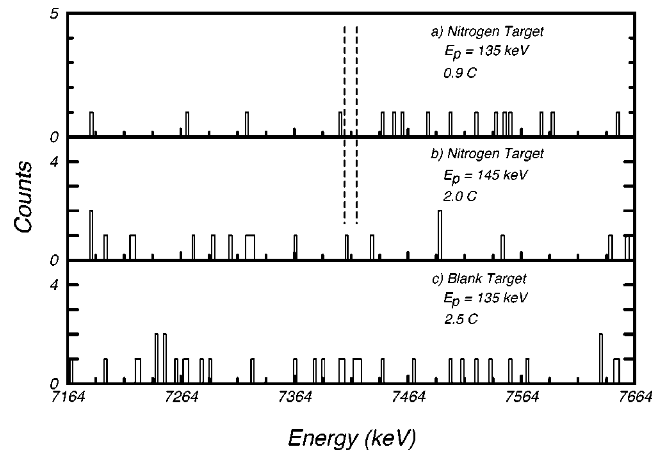

FIG. 2. Gamma-ray spectra from the Ge detector in anticoincidence with the NaI annulus for (a) $E_p^{lab}=135$ keV, (b) $E_p^{lab}=145$ keV, and (c) $E_p^{lab}=135$ keV (blank backing). The dashed lines show the region where 90% of the counts from a ground-state transition would be expected.

$\omega\gamma$ relative to the well-known value for the 278-keV resonance ($\omega\gamma=0.014(1)$ eV [5]) using the relation

$$\omega\gamma(127) = \omega\gamma(278)\ \frac{127\cdot\epsilon(127)Y(127)}{278\cdot\epsilon(278)Y(278)}. \tag{5}$$

It should be noted that the angular distribution for the 278-keV resonance is isotropic. Since the stopping powers enter into this expression as a ratio, our value for $\omega\gamma$ is relatively insensitive to uncertainties in either the absolute magnitude of the stopping powers or in target stoichiometry. The stopping powers were calculated with SRIM2000 [8] using our measured stoichiometry.

In order to determine the level of background in our measurement, we first collected spectra using a blank Ta backing (i.e., with no ^{14}N implanted) at $E_p^{lab}=135$ keV. A total charge of 2.5 C was deposited on the blank target. Subsequent runs were taken with the implanted ^{14}N target at $E_p^{lab}=135$ keV (0.89 C), 145 keV, (2.05 C), 160 keV (1 C), and 180 keV(1 C). Yield curves for the 278-keV resonance were collected at the beginning and end of these runs and between each energy change. There was no measurable degradation of the target or buildup of contamination during the whole period of bombardment, as shown in Fig. 1. Portions of spectra from the 135-keV, 145-keV, and blank-backing runs are displayed in Fig. 2. No events were detected in the region corresponding to $E_\gamma=7414$ keV in any runs with the ^{14}N target. In contrast, approximately 100 counts are expected, based on the strength quoted by Nelson *et al.* [1].

To determine a sensitivity limit from the statistics of our spectra, we employed maximum-likelihood estimation (MLE) with Poisson statistics for both the possible foreground and the background, as described by Hannam and Thompson [9]. The template used to describe the background was uniform with no structure, which accurately represents the data. The statistics from the run on the blank target indicate that a significant sample of the background can be collected within about 30 channels of the expected peak posi-

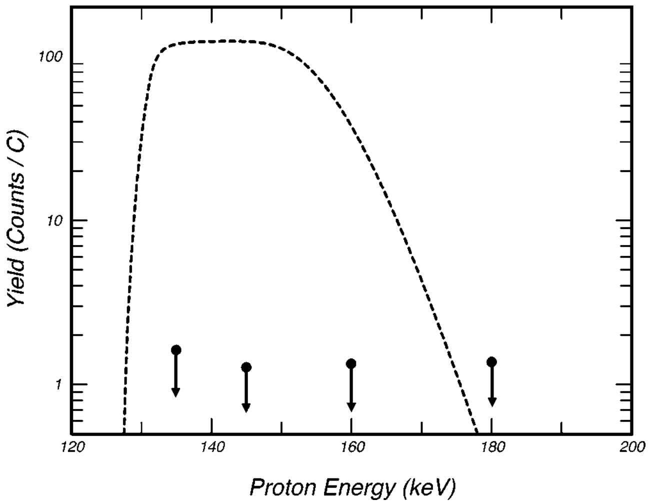

FIG. 3. Yield curve summarizing the search for an $E_p^{lab} = 127$-keV resonance. The expected yield, calculated using the strength quoted in Ref. [1] and our target profile, is represented by the dashed line.

tion. However, to be conservative, we estimated the background using bin widths of 81, 101, 121, and 201 channels, centered on the region of interest. The template for the signal was a Gaussian whose width was a convolution of the instrumental resolution (4.0 keV FWHM), the calibration uncertainty (1 keV), the uncertainty in the resonance energy (2 keV), and an estimated correction to account for Doppler broadening (4.2 keV FWHM). For all runs, the MLE estimate for the signal size is identically zero. The resulting upper limit does not vary between the four background regions listed above, which indicates that the background indeed has no structure and has been adequately sampled. The resulting 90% confidence limits on the number of counts per C of integrated charge are displayed in Fig. 3.

Since the 135- and 145-keV runs were both taken at the plateau of the expected yield curve, they can be combined to yield an upper limit on the resonance strength. The upper limit for the combined yield is 0.96 counts/C (95% C.L.), which corresponds to $\omega\gamma \leq 32$ neV (95% C.L.). This result is not strongly dependent upon our use of the MLE method. For example, if the background were completely ignored, the upper limit from Poisson statistics alone would be 1.02 counts/C. Our upper limit does not include any systematic uncertainties, which are dominated by the 7% uncertainty in $\omega\gamma$ for the 278-keV resonance. We have made conservative estimates of 5% each for the *relative* stopping power and charge collection efficiency. By comparison, the uncertainty in the relative detection efficiency is negligible (0.6%). The resulting 1-σ systematic uncertainty in $\omega\gamma$ is 3.4 neV. Since our counting statistics are not Gaussian-distributed, this systematic uncertainty should not be combined with our upper limit. However, if this were done, then the upper limit would rise from 32 neV to 32.7 neV.

Our upper limit on the strength of a possible resonance at 127 keV in the $^{14}N(p,\gamma)^{15}O$ reaction is $\omega\gamma \leq 32$ neV (95% C.L.), which is more than 2 orders of magnitude lower than the positive result of Nelson *et al.* [1]. Furthermore, we can set limits on the strength of any resonance in $^{14}N(p,\gamma)^{15}O$(g.s.) for 113 keV$\leq E_p^{lab} \leq$145 keV. For $E_p^{lab} = 113$ keV$-$123 keV, our 95% confidence limit on the resonance strength is 0.11 μeV, and for $E_p^{lab} = 123$ keV$-$145 keV, it is 34 neV. Since we find no evidence for a new resonance in the $^{14}N(p,\gamma)^{15}O$ reaction the reaction rate near 10^8 K is unchanged from its accepted value [10].

The authors would like to thank Richard O'Quinn and colleagues for their help in the construction of LENA. This work was supported in part by the U.S. Department of Energy under Contract No. DE-FG02-97ER41041.

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