PHYSICAL REVIEW C **75**, 055808 (2007)

Remeasurement of the 193 keV resonance in $^{17}O(p, \alpha)^{14}N$

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(Received 16 February 2007; published 15 May 2007)

A recently discovered resonance at 193 keV determines the thermonuclear rates of the $^{17}O + p$ reactions at temperatures important for the nucleosynthesis in classical novae ($T = 0.1-0.4$ GK). We report on a remeasurement of this resonance in the $^{17}O(p, \alpha)^{14}N$ reaction by using a different kind of target compared to the previous study. Special emphasis is placed on Monte Carlo simulations of the experiment in order to better understand certain effects that have been disregarded previously. Our measured value of the resonance strength amounts to $(\omega\gamma)_{p\alpha} = (1.66 \pm 0.17) \times 10^{-3}$ eV, in agreement with the previously reported result. As a byproduct of our study, we find that the inhomogeneity of the foil placed in front of the α-particle detector determines the resolution in the pulse-height spectrum, and thus constrains the signal-to-noise ratio in searches of very weak (p, α) resonances.

DOI: 10.1103/PhysRevC.75.055808 PACS number(s): 26.30.+k, 24.30.−v, 26.50.+x, 27.20.+n

I. INTRODUCTION

The $^{17}O + p$ reactions are of paramount importance for the nucleosynthesis in a number of stellar sites, including red giants, asymptotic giant branch (AGB) stars, massive stars and classical novae. In particular, the relevance of an expected resonance at ≈190 keV for the last scenario was pointed out by Coc *et al.* [1]. The observation of this resonance in the $^{17}O(p, \gamma)^{18}F$ reaction ($Q_{p\gamma} = 5606.5 \pm 0.5$ keV) was first reported in Fox *et al.* [2] and confirmed in a second, independent and consistent, measurement by Fox *et al.* [3]. The measured resonance energy and resonance strength amount to $E_R = 193.2 \pm 0.9$ keV and $(\omega\gamma)_{p\gamma} = (1.2 \pm 0.2) \times 10^{-6}$ eV, respectively. A subsequent study by Chafa *et al.* [4] measured this resonance in the $^{17}O(p, \gamma)^{18}F$ reaction and, in addition, discovered a resonance at the same energy in the competing $^{17}O(p, \alpha)^{14}N$ reaction ($Q_{p\alpha} = 1191.82 \pm 0.11$ keV). They also obtained an upper limit for the mean lifetime of the corresponding level at $E_x = 5789$ keV in the ^{18}F compound nucleus, showing that the previously reported value by Rolfs *et al.* [5] was erroneous. The experimental results reported by Chafa *et al.* [4] are $(\omega\gamma)_{p\gamma} = (3.4 \pm 0.6) \times 10^{-6}$ eV, $(\omega\gamma)_{p\alpha} = (1.6 \pm 0.2) \times 10^{-3}$ eV, and $\tau < 2.6$ fs. Their value for the (p, γ) resonance strength was subsequently revised by Chafa *et al.* [6] to $(\omega\gamma)_{p\gamma} = (2.2 \pm 0.4) \times 10^{-6}$ eV.

In the present work we report on a remeasurement of the 193 keV resonance in the $^{17}O(p, \alpha)^{14}N$ reaction. The purpose here is threefold. First, we felt that an independent measurement of the (p, α) reaction is worthwhile in view of the importance of this particular resonance for the nucleosynthesis in classical novae [2,4]. Second, although Chafa *et al.* revised their value of the (p, γ) resonance strength, the result of Ref. [6] still disagrees with the one from Refs. [2,3] by more than one standard deviation. The experimental techniques used were different: while Chafa *et al.* measured the (p, γ) strength using an activation method, Fox *et al.* performed in-beam measurements of the prompt emitted γ-rays. At this stage the source of the disagreement is obscure. But since Chafa *et al.* determined in their activation measurement the (p, γ) strength relative to the (p, α) strength of the same resonance, the above mentioned disagreement may also be reflected in (and perhaps arise from an incorrect value of) the (p, α) resonance strength. Therefore, our aim was to repeat the (p, α) measurement by using a different kind of target compared to the previous study. Third, a remeasurement of the (p, α) resonance gave us the opportunity to evaluate a commonly applied experimental technique and to test its application to the measurement of other, weaker (p, α) resonances by performing a series of Monte Carlo simulations.

In the following, we describe our experimental setup (Sec. II) and the experimental results (Sec. III). Conclusions are given in Sec. IV. Throughout this work, all kinematic quantities (energies and angles) are given in the laboratory system, unless noted otherwise.

II. EXPERIMENTAL SETUP

The experiment was carried out at the Laboratory for Experimental Nuclear Astrophysics (LENA), located at the Triangle Universities Nuclear Laboratory (TUNL). A 1 MV JN Van de Graaff accelerator supplied proton beams of up to 60 μA on target in the energy range of $E_p = 140-210$ keV. The bombarding energy was calibrated with the well-known $^{18}O(p, \alpha)^{15}N$ resonance at $E_R = 150.82 \pm 0.09$ keV [7]. The uncertainty in absolute energy and the energy spread were ±1 keV and 2.5 keV, respectively. The proton beam entered the target chamber through a liquid-nitrogen cooled copper tube that was biased to −300 V in order to suppress the emission of secondary electrons from the target and the beam collimator. The target and chamber formed a Faraday cup for charge integration. The beam was focused into a profile of ≈6 mm diameter on target. The target was placed at an angle of 45° with respect to the beam direction and was directly cooled using deionized water.

Targets of ^{17}O and ^{18}O were prepared by anodizing 0.5 mm thick tantalum backings in ^{17}O- or ^{18}O-enriched water; according to the supplier, the enrichments were 90.7% and

97.5%, respectively. These targets have been found [8] to be of well-defined stoichiometry (Ta_2O_5) with a target thickness that is precisely determined by the anodizing voltage. Prior to target preparation, the surface of the tantalum backing was etched [9] in order to remove some of the impurities that are a source of beam-induced background radiation. The thicknesses of the ^{17}O and ^{18}O targets were ≈34 keV at a bombarding energy of 193 keV and 151 keV, respectively. The targets were checked frequently and no degradation in yield or target thickness was observed during the course of the experiment. Note that a different kind of target was used by Chafa *et al.* [4,6]. Their targets were prepared by implanting ^{17}O or ^{18}O into 0.3 mm thick tantalum foils.

Reaction α-particles were detected in a silicon surface-barrier detector with an active area of 150 mm^2. A 2.0-μm-thick aluminized Mylar foil was placed in front of the detector to prevent the large number of elastically scattered protons from reaching the counter. The detector was mounted at a distance of 7.5 cm from the target and the angle was fixed at $\theta = 133^\circ$ with respect to the beam direction. An absolute detection efficiency (including the solid angle) of $\eta \approx 0.002$ was measured using a calibrated ^{241}Am source.

Dead times and amplifier gain stabilities were monitored throughout the experiment by using a precision pulse generator.

III. EXPERIMENTAL PROCEDURES AND RESULTS

Typical on- and off-resonance pulse height spectra, measured at bombarding proton energies of $E_p = 195$ keV and 192 keV, respectively, are shown in Fig. 1. The peak visible in the top part of the figure represents the reaction α-particles from the 193 keV resonance in ^{17}O$(p,\alpha)^{14}$N. The α-particles are emitted from the target with an energy of ≈1.0 MeV, but lose a large fraction of their energy (≈0.6 MeV) in the Mylar foil. As a result, the peak is located in a region corresponding to relatively small pulse heights. It can be seen that the α-particle peak is clearly resolved from the low-energy background that is presumably caused by electronic noise and by protons leaking through the Mylar foil. The α-particle peaks in the on-resonance spectra were fit with a number of different functions. A least-squares fit using a Gaussian function with intensity, position and standard deviation as free parameters gave consistent results with more complicated prescriptions.

The excitation functions for the $E_R = 193$ keV resonance in ^{17}O$(p,\alpha)^{14}$N and the $E_R = 151$ keV resonance in ^{18}O$(p,\alpha)^{15}$N are shown in Fig. 2. Typical energy steps were 1–2 keV, with charge accumulations of ≈2.4−139 mC at each bombarding energy. It can be seen that, as expected, with increasing bombarding energy the yields increase strongly at the resonance energies, reach a flat plateau characteristic for a thick-target yield curve, and then decline, giving rise to a width that is consistent with the thickness of the target. No carbon deposit on the target was noticeable in our study and thus no correction for this effect was necessary.

The strength of the $E_R = 193$ keV resonance in ^{17}O$(p,\alpha)^{14}$N was obtained relative to the well-known strength of the $E_R = 151$ keV resonance in ^{18}O$(p,\alpha)^{15}$N from the expression [10,11]

$$\frac{\omega\gamma_{p\alpha}(193)}{\omega\gamma_{p\alpha}(151)} = \frac{\epsilon_{\rm eff}(193)}{\epsilon_{\rm eff}(151)}\frac{[\lambda(151)]^2}{[\lambda(193)]^2}\frac{N_{\rm max}(193)}{N_{\rm max}(151)} \times \frac{N_b(151)}{N_b(193)}\frac{B(151)}{B(193)}\frac{\eta(151)}{\eta(193)}\frac{W(151)}{W(193)}, \quad (1)$$

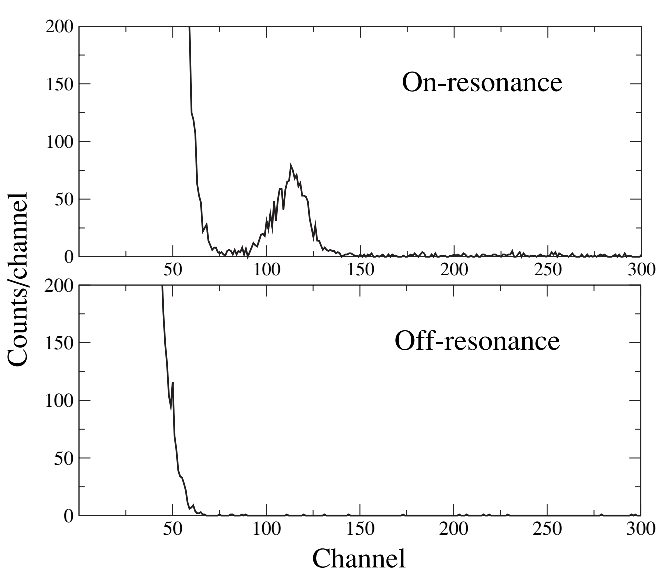

FIG. 1. On-resonance ($E_p = 195$ keV and $Q = 0.14$ C; top) and off-resonance ($E_p = 192$ keV and $Q = 0.011$ C; bottom) spectrum measured at the $E_p = 193$ keV resonance in ^{17}O$(p,\alpha)^{14}$N. The α-particle peak in the top part is clearly separated from the low-energy background.

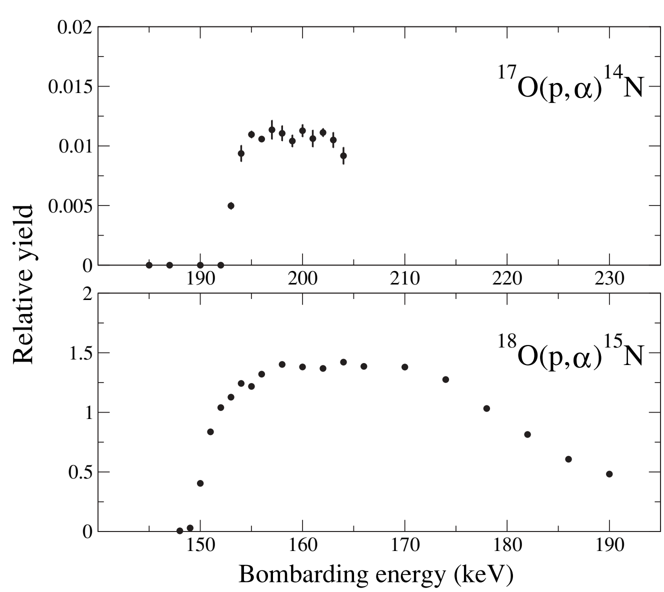

FIG. 2. Thick-target excitation function for the $E_p = 193$ keV resonance in ^{17}O$(p,\alpha)^{14}$N (top) and the $E_p = 151$ keV resonance in ^{18}O$(p,\alpha)^{15}$N (bottom). The yield curves were obtained by using enriched ^{17}O and ^{18}O targets and show a plateau at maximum yield in both reactions.

where $\omega\gamma_{p\alpha} = (2J+1)[(2j_p+1)(2j_t+1)]^{-1}\Gamma_p\Gamma_\alpha/\Gamma$ is the resonance strength, with J the resonance spin, j_p, j_t the spins of projectile and target, Γ_p, Γ_α, and Γ the proton partial width, α-particle partial width and total resonance width, respectively; ϵ_{eff}, λ, $N_{\max}$, N_b, B, η, and W denote the effective stopping power, de Broglie wavelength, the number of observed α-particle counts on the plateau of the thick-target yield curve, the number of incident protons, the branching ratio, particle detector efficiency, and the angular distribution of the reaction α-particles, respectively. All kinematic quantities in Eq. (1) refer to the center-of-mass frame. The labels "193" and "151" denote the $E_R = 193$ keV resonance in $^{17}\text{O}+p$ and the $E_R = 151$ keV resonance in $^{18}\text{O}+p$, respectively. Since the reaction α-particles populate the ground states of the residual nuclei ^{14}N or ^{15}N, the branching ratios are equal to unity. For the reference resonance strength we adopted the value $\omega\gamma_{p\alpha}(151) = 0.167 \pm 0.012$ eV [7,12], that is, the same value that was used by Chafa *et al.* [4].

Angular distributions of the emitted α-particles were not measured in the present study. First, the spin of the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ resonance at $E_R = 151$ keV is $J = 1/2$ and thus $W(151) = 1$. Second, the angular distribution for the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ resonance at $E_R = 193$ keV was already measured by Chafa *et al.* [4]. We used their result in order to correct our α-particle intensity that was measured at a fixed angle of $\theta = 133^\circ$. Note that the correction $[W_\theta(193) \approx 1.04]$ is much smaller than the expected error in the (p,α) resonance strength (see below) and thus is of minor importance.

The effective stopping powers (see, for example, Eq. (3) in Ref. [3]) were calculated using the code SRIM [13]. We find for the ratio a value of $\epsilon_{\text{eff}}(193)/\epsilon_{\text{eff}}(151) = 1.013 \pm 0.054$, where the uncertainty arises from the errors in the stoichiometry and in the stopping powers for the pure elements (oxygen and tantalum). The detection efficiencies were obtained by transforming the laboratory solid angle (measured using a calibrated ^{241}Am source; Sec. II) into the $^{17}\text{O}+p$ and $^{18}\text{O}+p$ center-of-mass frames, resulting in a ratio of $\eta(151)/\eta(193) = 1.0353 \pm 0.0034$. The number of observed α-particle counts on the plateau of the thick-target excitation functions was determined by using a least-squares fitting routine [14], resulting in a value of $[N_{\max}(193)/N_{\max}(151)][N_b(151)/N_b(193)] = (7.72 \pm 0.40) \times 10^{-3}$. For the ratio of de Broglie wavelengths we find $[\lambda(151)/\lambda(193)]^2 = 1.2730 \pm 0.0060$. With these values we obtain a strength of $\omega\gamma_{p\alpha}(193) = (1.66 \pm 0.17) \times 10^{-3}$ eV for the $E_R = 193$ keV resonance in $^{17}\text{O}(p,\alpha)^{14}\text{N}$. This result is in agreement with the value reported by Chafa *et al.* [4,11].

Monte Carlo simulations using the code GEANT4 [15] were performed in order to better understand certain effects that may influence the deduced value of the resonance strength. The first effect we considered was the backscattering of reaction α-particles by the Mylar foil before they can be detected by the surface barrier counter. This effect may be energy dependent and thus could give rise to different α-particle detection efficiencies at $E_\alpha \approx 5.5$ MeV (^{241}Am), $\approx$1.0 MeV (from $E_R = 193$ keV in $^{17}\text{O}+p$) and $\approx$3.2 MeV (from $E_R = 151$ keV in $^{18}\text{O}+p$). The Monte Carlo simulations gave α-particle detection efficiencies that varied for these cases by less than 1% and thus backscattering has a negligible influence on the error budget of the deduced (p,α) resonance strength.

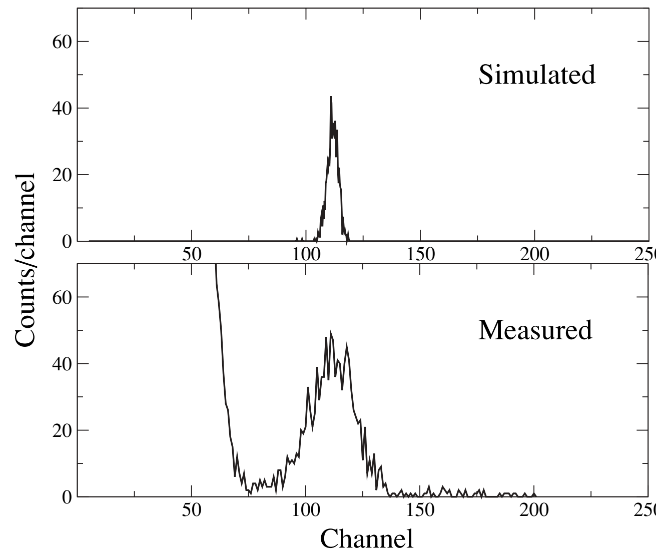

FIG. 3. Simulated (top) and measured (bottom) α-particle spectrum from the $E_p = 193$ keV resonance in $^{17}\text{O}(p,\alpha)^{14}\text{N}$. The Monte Carlo simulation (using GEANT4 [15]) assumes a perfectly uniform Mylar foil of 2.0 μm thickness, placed in front of the α-particle detector, and does not take the intrinsic resolution of the silicon detector into account ($\approx$20 keV). The FWHM of the α-particle peak in the top and bottom part amounts to 21 keV and 87 keV, respectively. The difference in peak widths arises most likely from foil inhomogeneities (see text). The amount of peak broadening caused by reaction kinematics is negligible in this context.

The second effect we considered was the straggling of the reaction α-particles in the Mylar foil. A measured and a simulated α-particle spectrum for the $E_R = 193$ keV resonance in $^{17}\text{O}(p,\alpha)^{14}\text{N}$, with the Mylar foil placed in front of the silicon detector, are compared in Fig. 3. It is evident that the measured width of the α-particle peak (FWHM= 87 keV) is much larger than the width of the simulated peak (FWHM=21 keV). The simulated peak shown in the top part of the figure has not been corrected for the intrinsic energy resolution of the detector ($\approx$20 keV, measured without the Mylar foil by using a ^{241}Am source) and its width is mainly caused by straggling assuming a perfectly uniform Mylar foil of 2.0 μm thickness. We attribute the difference in peak widths shown in Fig. 3 mainly to the inhomogeneity of the Mylar foil covering the particle detector. In fact, a comparison of the resolutions in the experimental and simulated spectra provides a quantitative estimate for the foil inhomogeneity, which in our case amounts to $\approx \pm 0.15\mu$m for a Mylar foil thickness of 2.0 μm. It is obvious that the degraded resolution caused by foil inhomogeneities will constrain the signal-to-noise ratio if the present experimental technique, which is commonly used in measurements of (p,α) reactions, is applied in searches of very weak resonances. Furthermore, we expect that foil inhomogeneities of this magnitude will permit a larger fraction of elastically scattered protons than previously anticipated to leak through the Mylar foil. These protons will contribute to the low-energy background in the pulse height spectrum.

IV. SUMMARY AND CONCLUSIONS

We reported on a remeasurement of the recently discovered $E_R = 193$ keV resonance in $^{17}O(p,\alpha)^{14}N$ by using anodized oxygen targets instead of implanted targets that were prepared in the previous study of Chafa *et al*. [4]. Our measured value for the resonance strength amounts to $\omega\gamma_{p\alpha}(193) = (1.66 \pm 0.17) \times 10^{-3}$ eV and is in agreement with the result reported in Ref. [4]. Our measurement of the (p,α) resonance has not resolved the disagreement in the measured (p,γ) resonance strengths reported in Refs. [2–4,6]. The source of the disagreement remains obscure.

We also reported on an effect that will become important in searches of very weak, unobserved (p,α) resonances using the present experimental technique. We find evidence that the inhomogeneity of the foil commonly placed in front of a particle detector (in order to prevent the large number of elastically scattered protons from reaching the counter) will both cause a significant degradation of the energy resolution (an effect that is much greater than the degradation of the energy resolution due to straggling in a perfectly uniform foil) and will permit a larger number of elastically scattered protons to leak through the foil and to contribute to the background in the low-energy part of the pulse height spectrum. Consequently, it is of major advantage to use highly uniform detector foils in future searches of weak (p,α) resonances.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Department of Energy under Contract No. DE-FG02-97ER41041.

[1] A. Coc, M. Hernanz, J. José, and J.-P. Thibaud, Astron. Astrophys. **357**, 561 (2000).
[2] C. Fox *et al*., Phys. Rev. Lett. **93**, 081102 (2004).
[3] C. Fox *et al*., Phys. Rev. C **71**, 055801 (2005).
[4] A. Chafa *et al*., Phys. Rev. Lett. **95**, 031101 (2005).
[5] C. Rolfs, I. Berka, and R. E. Azuma, Nucl. Phys. **A199**, 306 (1973).
[6] A. Chafa *et al*., Phys. Rev. Lett. **96**, 019902(E) (2006).
[7] H. W. Becker *et al*., Z. Phys. A **351**, 453 (1995).
[8] D. Phillips and J. P. S. Pringle, Nucl. Instrum. Methods **135**, 389 (1976).
[9] D. A. Vermilyea, Acta Metall. **1**, 282 (1953).
[10] C. Iliadis, *Nuclear Physics of Stars* (Wiley-VCH, Weinheim, 2007).
[11] Note that Eq. 1 in Chafa *et al*. [4] contains a mistake. Both mass ratio terms are cubed in the proper expression. This correction, however, is small and does not change their measured (p,α) resonance strength significantly.
[12] H. Lorenz-Wirzba, P. Schmalbrock, H. P. Trautvetter, M. Wiescher, C. Rolfs, and W. S. Rodney, Nucl. Phys. **A313**, 346 (1979).
[13] J. F. Ziegler and J. P. Biersack, computer program SRIM, 2003.
[14] D. C. Powell *et al*., Nucl. Phys. **A644**, 263 (1998).
[15] S. Agostinelli *et al*., Nucl. Instrum. Methods A **506**, 250 (2003); we used the low-energy extensions of GEANT4 according to www.ge.infn.it/GEANT4/lowE/index.html; for the low-energy library of α-particle stopping powers we employed the results of: ICRU Report 49, International Commission on Radiation Units and Measurements, Bethesda, MD, USA (1993).