RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 58, NUMBER 1 JULY 1998

# Measurement of the properties of the astrophysically interesting 3/2$^+$ state at 7.101 MeV in $^{19}$F

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(Received 9 March 1998)

The isospin mirror of the $J^\pi = 3/2^+$ $^{18}\mathrm{F}+p$ resonance at $E_x = 7.070$ MeV in $^{19}$Ne has been measured in $^{19}$F via the $^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ reaction using the RHINOCEROS windowless gas target at the Stuttgart 4-MV Dynamitron facility. This resonance is measured to have the following properties: $E_x = 7.101 \pm 0.001$ MeV, $\Gamma_{\mathrm{tot}} = 28 \pm 1$ keV, and a strength of $\omega\gamma = 0.77 \pm 0.11$ eV (corresponding to $\Gamma_\gamma = 0.39 \pm 0.06$ eV). [S0556-2813(98)50607-3]

PACS number(s): 26.30.+k, 25.55.−e, 27.20.+n

In the possible breakout from the HotCNO cycle to the rp process via the $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$ reaction, $^{18}$F can be reached via the sequence $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}(e^+\nu)^{18}\mathrm{F}$ [1]. By taking advantage of the high $^{16}$O abundance on the surface of a white dwarf, $^{18}$F can also be produced via the reaction sequence $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}(e^+\nu)^{18}\mathrm{F}$. In order to determine if these sequences continue on towards the rp process or return to the HotCNO cycle, it is necessary to measure the branching ratio between the $^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}$ and $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reactions [2,3]. The resonant contributions to the rates of these two competing reactions are determined by the properties of the levels in the $^{19}$Ne compound nucleus just above the $^{18}\mathrm{F}+p$ threshold. The spectroscopy studies of Utku *et al.* [4] identified two resonances in $^{19}$Ne, at $E_x = 6.741$ and 7.070 MeV ($E_{\mathrm{c.m.}} = 330$ and 659 keV, respectively, in the $^{18}\mathrm{F}+p$ channel) as the two dominant resonances in determining the recycling/breakout rate from the HotCNO cycle to the rp process via the $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ and $^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}$ reactions. The spectroscopy measurements have determined that the 659-keV resonance has $\Gamma_{\mathrm{tot}} = 39 \pm 10$ keV (with $\Gamma_\alpha = 25 \pm 7$ keV and $\Gamma_p = 14 \pm 4$ keV). Direct studies of this resonance, using radioactive $^{18}$F beams at Argonne National Laboratory [5] and at Louvain-la-Neuve [6], are consistent with the spectroscopy measurements and have also indicated that this $^{19}$Ne resonance has $J^\pi = 3/2^+$. Although there had been an earlier suggestion of the $^{19}$F isospin mirror of such a

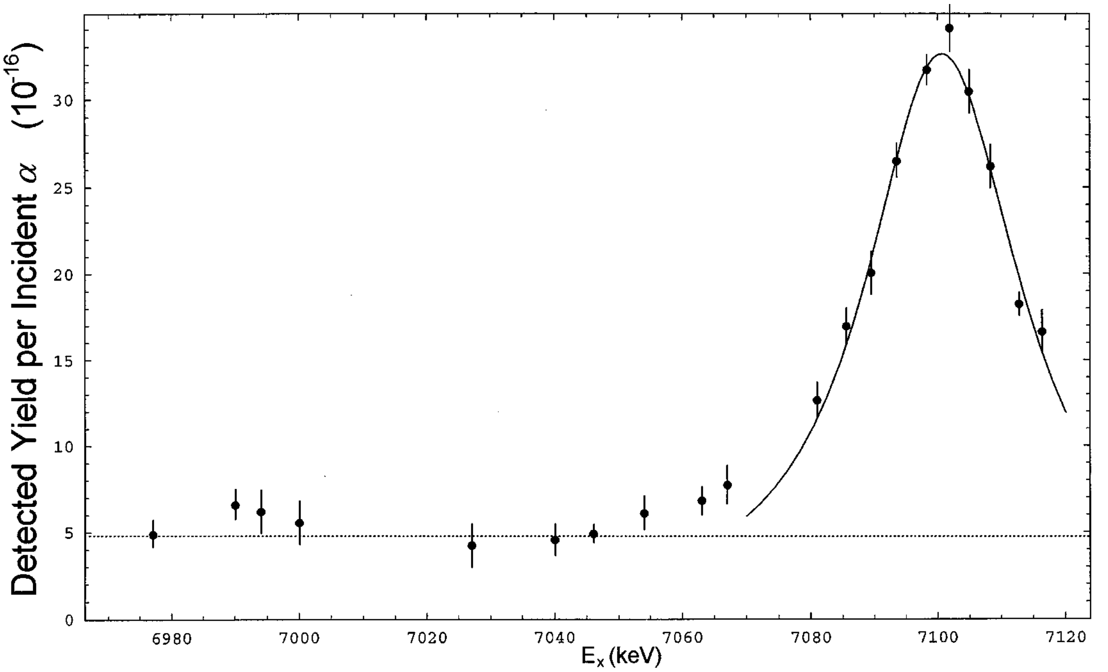

FIG. 1. The measured excitation function for the $R \Rightarrow 1.459$ MeV transition of the $^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ reaction, measured at $\theta_{\mathrm{lab}} = 90°$. The solid line is a least-squares fit to the data using a Breit-Wigner function folded with a 10 keV (c.m.) energy loss in the gas target. The solid curve has a width of 30 keV; the parameters of the intrinsic Breit-Wigner function are $E_x = 7101 \pm 1$ keV and $\Gamma_{\mathrm{tot}} = 28 \pm 1.1$ keV. The dotted line is constant background extrapolated from lower energies. (Higher energies were not possible due to the voltage limit of the 4-MV accelerator. The energy uncertainty in the data points is approximately the size of the dots.)

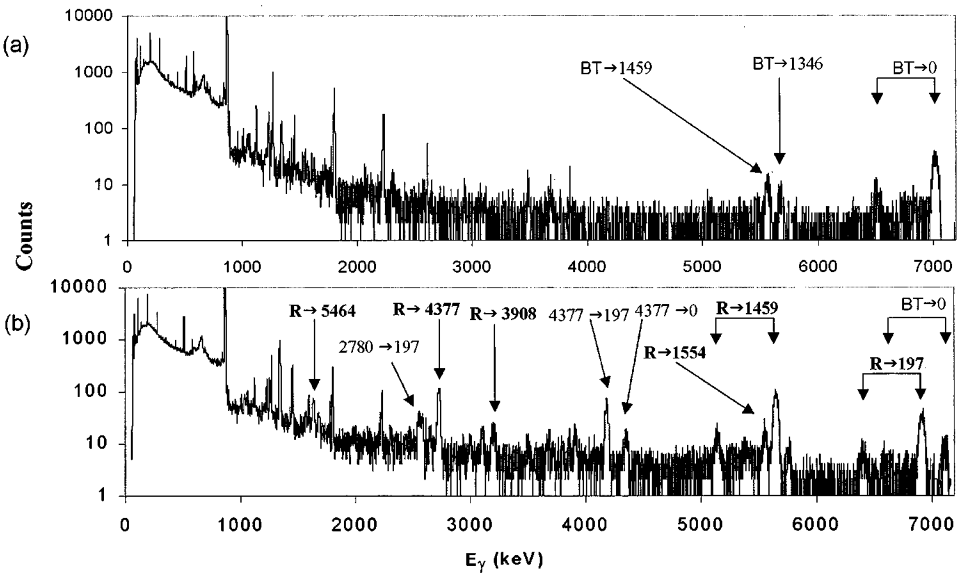

FIG. 2. Comparison of the gamma-ray spectra (a) at $E_\alpha = 3817$ keV (off resonance) and (b) at $E_\alpha = 3910$ keV (on resonance). Transitions that occur through the tails of broad resonances are labeled ''BT.''

state in the analysis of $^{15}$N($\alpha$,$\alpha$) elastic scattering ($E_x \approx 7.10$ MeV and $\Gamma_{\rm tot} \sim 10$ keV) [7], more recent studies of this region had not found supporting evidence for such a state, and there has been no corresponding 3/2$^+$, isospin mirror state listed in the standard compilations for $^{19}$F [8].

In order to better determine the properties of the 659-keV $^{18}$F+$p$ resonance, we have measured the $^{15}$N($\alpha$,$\gamma$)$^{19}$F reaction over the energy range $2.60 < E_\alpha < 3.93$ MeV ($6.066 < E_x < 7.116$ MeV) in order to search for the isospin mirror of this $^{18}$F+$p$ resonance and to measure its properties. The $^{15}$N($\alpha$,$\gamma$)$^{19}$F reaction was used in order to take advantage of the expected differences in the gamma-decay transitions from the well-established 7/2$^+$ state at $E_x = 7.114$ MeV ($\Gamma = 32$ keV) and the putative 3/2$^+$ state. Measurements were made using 50–80 $\mu A$ $^4$He beams from the University of Stuttgart 4-MV Dynamitron facility, incident on 99% enriched $^{15}$N$_2$ gas in a windowless, recirculating gas target, RHINOCEROS [9]. The length of the gas target was 6 cm, and the gas pressure was 1.5 mbar, corresponding to an energy loss of $\Delta E_\alpha = 13$ keV ($\Delta E_{\rm c.m.} = 10$ keV) for 3.9 MeV alpha particles; the target gas was continuously cleaned using a cryotrap and a zeolite adsorption trap. The beam energy was determined on the basis of the measured gamma-ray energies. Gamma-ray spectra were measured using a HPGe detector with a resolution of 2.18 keV at 1.33 MeV and an efficiency of 95.3% relative to a 3 in by 3 in NaI detector. This detector was surrounded by a BGO anti-Compton shield and was positioned at 90° with respect to the incident beam, with its front face ≈84 mm from the beam.

Figure 1 shows the excitation function measured in the neighborhood of $E_x = 7.1$ MeV for the transition from the compound system to the $J^\pi = 3/2^-$ state at 1.459 MeV. This excitation function shows a clear maximum at $E_x = 7.1$ MeV. Figure 2 shows a comparison of the measured gamma-ray spectra on and off resonance. The transition from this resonance to the 1.459-MeV state and all the other gamma decays which also show a maximum at this same energy (Table I) are consistent with a $J^\pi = 3/2^+$ resonance; the transition to the 1.459-MeV state is not consistent with a $J^\pi = 7/2^+$ assignment. This resonance is then a clear candidate for the isospin mirror of the $J^\pi = 3/2^+$ $^{18}$F+$p$ resonance reported [4–6] in $^{19}$Ne. The Breit-Wigner fit (taking into account the $\Delta E_{\rm c.m.} = 10$ keV energy loss in the target) to this $^{15}$N($\alpha$,$\gamma$)$^{19}$F resonance, shown in Fig. 1, determines the following parameters for this resonance: $E_x = 7.101 \pm .001$ MeV and $\Gamma_{\rm tot} = \Gamma_\alpha = 28 \pm 1$ keV. (The earlier values of Smotrich *et al.* [7], $E_x \approx 7.10$ MeV and $\Gamma_{\rm tot} \sim 10$ keV, are not inconsistent with our results.)

The HPGe detector covered the central ±3 cm of the gas target, as defined by its entrance and exit apertures, subtending a solid angle of ≈0.6 sr at the center of the target, covering the angular range from 66° to 114° at the center of the target. The position dependence of the efficiency of the HPGe detector in this geometry (including the attenuation of its active and passive shielding) was measured by moving a calibrated $^{60}$Co source along the beam axis, ±10 cm from the center of the target. GEANT calculations were run at a series of other energies (from 110 to 7200 keV) for this geometry and were then normalized to the measured $^{60}$Co results. With the $E_x = 7.1$ MeV ($J^\pi = 3/2^+$) resonance centered in the gas target, the effective peak efficiency for this detector geometry for the 5.642-MeV transition was $1.6 \times 10^{-3}$. Based on these efficiencies, the measured [10] gas pressure profile along the beam path, and the measured branching ratios for the gamma decay of the 7.101-MeV

TABLE I. Gamma-decay transitions from $^{19}$F* (7.101 MeV).

| Transition | $(J^\pi)_f$ | % Branch |
|---|---|---|
| $R \Rightarrow 5.463$ MeV | 7/2$^+$ | 4±2 |
| $R \Rightarrow 4.378$ MeV | 7/2$^+$ | 18±3 |
| $R \Rightarrow 3.908$ MeV | 3/2$^+$ | 3±2 |
| $R \Rightarrow 1.554$ MeV | 3/2$^+$ | 6±3 |
| $R \Rightarrow 1.459$ MeV | 3/2$^-$ | 41±2 |
| $R \Rightarrow 0.197$ MeV | 5/2$^+$ | 28±2 |

TABLE II. Properties of $^{19}$Ne* (7.07 MeV).

| | $E_x$ (MeV) | $\Gamma_{tot}$ (keV) | $\Gamma_\alpha$ (keV) | $\Gamma_p$ (keV) | $\Gamma_\gamma$ (eV) | $J^\pi$ |
|---|---|---|---|---|---|---|
| $^{19}$F($^3$He,$t$)$^{19}$Ne [4] | $7.070\pm0.007$ | $39\pm10$ | $25\pm7$ | $14\pm4$ | | $(3/2^+)$ |
| $p(^{18}$F,$^{15}$O)$\alpha$ [5] | $7.063\pm0.004$ | $14\pm5$ | $8.6\pm2.5$ | $5.0\pm1.6$ | | $(3/2^+)$ |
| $p(^{18}$F,$\alpha)^{15}$O [6] | $7.049\pm0.015$ | $37\pm5$ | $19\pm4$ | $19\pm4$ | | $(3/2^+)$ |
| $p(^{18}$F,$^{19}$Ne)$\gamma$ [12] | | | | | $\leqslant 3$ | $(3/2^+)$ |
| $^{15}$N$(\alpha,\gamma)^{19}$F | | $\gtrsim 30$ | $\approx 30$ | | $\approx 0.39$ | $(3/2^+)$ |

state, the integrated yield for this resonance determines its strength as $\omega\gamma = 0.77\pm0.11$ eV, corresponding to $\Gamma_\gamma = 0.39 \pm 0.06$ eV. As part of this experiment, similar $^{15}$N$(\alpha,\gamma)^{19}$F measurements of the $E_{c.m.} = 2.911$-MeV ($7/2^-$) resonance [$E_x(^{19}$F$) = 6.925$ MeV] determine $\omega\gamma = 8.4\pm2$ eV in agreement with previous measurements, $\omega\gamma = 9.7\pm1.4$ eV [8].

The properties of the $^{19}$F*(7.101) state can be used to provide quantitative estimates of the corresponding properties of its isospin mirror state $^{19}$Ne*(7.07). Assuming that these two states have the same reduced alpha-width, $\theta_\alpha^2$, then we can write

$$(\Gamma_\alpha)_{^{19}\mathrm{Ne}^*} = \left[\frac{\rho}{F_\ell^2+G_\ell^2}\right]_{^{15}\mathrm{O}+\alpha}\left[\frac{F_\ell^2+G_\ell^2}{\rho}\right]_{^{15}\mathrm{N}+\alpha}(\Gamma_\alpha)_{^{19}\mathrm{F}^*}. \tag{1}$$

(As a cautionary note, it should be pointed out that this is not a rigorous assumption [11].) As shown in Table II, the resulting value of $\Gamma_\alpha = 30$ keV for the $^{19}$Ne*(7.07) state is consistent with the values measured in the $^{19}$F($^3$He,$t$)$^{19}$Ne spectroscopy experiment [4] and in the Louvain-la-Neuve $^{18}$F$(p,\alpha)$ experiment [6]. A value of $\Gamma_\alpha = 30$ keV corresponds to a reduced width,

$$\Gamma_\alpha = \frac{3\hbar}{R_n}\sqrt{2E/\mu}\left(\frac{1}{F_\ell^2+G_\ell^2}\right)\theta_\alpha^2, \tag{2}$$

of $\theta_\alpha^2 \approx 0.05$. Similarly, a proton width of $\Gamma_p = 14$ keV corresponds to $\theta_p^2 \approx 0.26$.

Under the assumption of equal values for $\Gamma_\gamma$ for these mirror states, the gamma width for the $^{19}$Ne*(7.07 MeV) state will be $0.39\pm0.06$ eV, which is roughly an order of magnitude smaller than the limit set by Rehm [12], further reducing the role of this resonance in any $^{18}$F$(p,\gamma)^{19}$Ne breakout from the HotCNO cycle to the rp process. On the basis of what is currently known [4] about the $^{18}$F$(p,\gamma)^{19}$Ne reaction, the 6.741-MeV $^{19}$Ne state ($E_R = 330$ keV) is expected to be the dominant resonance for this reaction in the temperature range $T_9 < 1$. On the basis of a comparison of the $^{20}$Ne$(d,t)^{19}$Ne and $^{20}$Ne$(d,^3$He$)^{19}$F reactions [4], this state has been shown to be the isospin mirror of the $^{19}$F*(6.787 MeV; $3/2^-$) excited state which has a measured $\Gamma_\gamma = 5.5\pm0.8$ eV [8]. The most significant remaining uncertainties in the astrophysical rate of the $^{18}$F$(p,\gamma)^{19}$Ne reaction concerns the location of the isospin mirrors for the $^{19}$F*(6.891 MeV) and $^{19}$F*(6.989 MeV) states and their proton widths, as well as the gamma width for the $^{19}$F*(6.989 MeV) state. However, the $^{18}$F$(p,\gamma)^{19}$Ne reaction rate is currently a factor of $10^3$ to $10^4$ times slower than the competing $^{18}$F$(p,\alpha)^{15}$O reaction over the temperature range $0.5 < T_9 < 1$, and it is unlikely that these resonances could increase the current $^{18}$F$(p,\gamma)^{19}$Ne reaction rate by more than a factor of two or three.

We wish to thank Prof. Dr. U. Kneissl for his general support of this project by making available the necessary beam time. We are also indebted to the Dynamitron staff (headed by H. Hollick) for providing the beam and especially to J. Lefevre for his work to reach the maximum voltage of the accelerator. Further we wish to thank the Deutsche Forschungsgemeinshaft for supporting nuclear astrophysics at Stuttgart (Ha962/18) and the U.S. Department of Energy for its continuing support of this program at Yale (DE-FG02-91ER-40609).

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