The Astrophysical Reaction Rate for the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ Reaction

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Abstract

Proton and alpha widths for a $3/2^+$ ($\ell_p = 0$) state in ^{19}Ne at $E_x = 7.1$ MeV have been extracted using the results of recent measurements of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction. This $\ell_p = 0$ resonance dominates the astrophysical reaction rates at temperatures $T_9 > 0.5$.

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Experiments with radioactive ion beams have opened new opportunities for the study of reaction processes which are important for a better understanding of explosive nucleosynthesis [1]. Explosive nucleosynthesis is thought to occur in the universe at various sites including nova and supernova explosions. The recent detection of γ lines from the decay of ^{26}Al in the interstellar medium [2] and of ^{56}Ni in SN 1987a [3] provides experimental evidence for the nuclear processes taking place in the universe. In this contribution we calculate the astrophysical reaction rate of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction, using for the first time experimental data [4].

Breakout from the hot CNO cycle and synthesis of heavier elements is believed to proceed through the nuclide ^{19}Ne which is produced either directly via the $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction or via the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction followed by the sequence $^{17}\text{F}(p,\gamma)^{18}\text{Ne}(\beta^+)^{18}\text{F}(p,\gamma)^{19}\text{Ne}$. ^{19}Ne is the starting point for the rp-process producing nuclei up to ^{56}Ni and beyond [5]. In the second reaction chain, however, there is a competing reaction, $^{18}\text{F}(p,\alpha)^{15}\text{O}$, which recycles material back into the CNO cycle. As described in Ref. 4 the measurement of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction using a radioactive ^{18}F beam yielded a resonance strength $\omega\gamma = 3.7 \pm 0.9$ keV for a state at 7.066 MeV excitation energy in ^{19}Ne . This state is 655 keV above the proton threshold. In order to extract the relevant widths from the measured cross section one additional piece of information is needed which was provided by the published value of $\Gamma_{\text{total}} = 40$ keV [6]. With this value a proton width $\Gamma_p = 6.7^{+2.2}_{-1.9}$ keV and a $\ell_p = 0$ spin assignment was obtained for this resonance. Since earlier $^{15}\text{N}(\alpha,\alpha)$ measurements [7] had found indications of a $3/2^+$, $7/2^+$ doublet at this excitation energy region in the mirror nucleus ^{19}F , the experimental value of 40 keV for the total width represents an upper limit only. In this contribution, the dependence of the proton width on this, or alternative assumptions is explored. Our result is then used to calculate the astrophysical reaction rate for the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction.

The limits for Γ_p and Γ_α set by the measurement of $\omega\gamma$ from the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction in Ref. 4 and $\Gamma_{\text{total}} = 40$ keV are shown by the light gray area in Fig. 1 where $\omega\gamma = \frac{4}{6} \cdot \frac{\Gamma_p \Gamma_\alpha}{\Gamma_p + \Gamma_\alpha}$ is plotted in the $\Gamma_p - \Gamma_\alpha$ plane. The range of values extracted for Γ_p under the assumption of $\Gamma_t = 40$ keV is represented by the intersection of the $\Gamma_t = 40$ keV line with the shaded area.

A recent $^{19}\text{F}(^3\text{He},t)^{19}\text{Ne}$ coincidence experiment [8] populating particle-unbound states in ^{19}Ne provides another basis for obtaining values for the proton and α widths. In this experiment a value of $\Gamma_p/\Gamma_\alpha = 0.58 \pm 0.06$ was measured for a peak corresponding to an excitation energy of 7.066 MeV in ^{19}Ne . Although a $3/2^+ - 7/2^+$ doublet might exist in ^{19}Ne in this energy region the shape of the angular distribution for the $(^3\text{He},t)$ reaction populating this peak favors an $\ell = 0$ assignment, consistent with a $3/2^+$ state. As shown in Ref. 9,10 $(^3\text{He},t)$ angular distributions for $\Delta J = 3$ show a minimum at 0° , while $\Delta J = 1$ transitions exhibit a maximum. From the black area in Fig. 1, which represents the intersection of the $\omega\gamma = 3.7 \pm 0.9$ keV and $\Gamma_p/\Gamma_\alpha = 0.58 \pm 0.06$ area, values of $\Gamma_p = 8.8 \pm 2.5$ keV, $\Gamma_\alpha = 15.1 \pm 5$ keV and $\Gamma_t = 24 \pm 6$ keV are obtained. We observe that the allowed range for Γ_p does not change much between the limits set by $\Gamma_p/\Gamma_\alpha = 0.58$ and $\Gamma_{\text{total}} = 40$ keV. The value for the alpha width is in good agreement with the value of ~ 10 keV for the $3/2^+$ state in the mirror nucleus ^{19}F measured [7] in $^{15}\text{N}(\alpha,\alpha)$ scattering.

This $\ell_p = 0$ transition to a $3/2^+$ state in ^{19}Ne has a strong influence on the astrophysical reaction rate for the $^{18}\text{F}(p,\alpha)$ reaction. In order to predict this rate the contributions from other states located in the excitation energy region must be considered. The upper limit for the cross section in the excitation energy range $E_x = 7.13 - 7.20$ MeV of 3.6 mb/sr [4] indicates that no strong state is excited above this resonance. The closest state in ^{19}Ne that needs to be taken into account is located at $E_x = 6.859$ MeV ($E_p = 448$ keV) with a spin assignment of $7/2^-$, based on the similarity of the $^{16}\text{O}(^6\text{Li},t)^{19}\text{Ne}$ and $^{16}\text{O}(^6\text{Li},^3\text{He})^{19}\text{F}$ reactions [11]. However, because of the high angular momentum ($\ell = 3$) the contribution from a $7/2^-$ state to the reaction rate is negligible. The next state to be considered is the 6.764 MeV state ($E_p = 353$ keV) which was assigned a $(3/2^-, 1/2^-)$ value in Ref. 12. Since the α width of this state has not been measured, we use the α width of the 6.787 MeV $3/2^-$ state in the mirror nucleus ^{19}F , appropriately scaled for the difference in the nuclear charges. For the proton width we (arbitrarily) assume a value of 5% of the single particle value. An uncertainty of a factor of 2 in both directions is attributed to the

reaction strength for this state. The reaction rate from an isolated resonance at $E = E_0$ was then calculated from the integral

$$N_A \langle \sigma v \rangle = N_A [8 / (\pi \mu (kT)^3)]^{1/2} \int_0^{\infty} \sigma(E) \exp(-E / kT) E dE \quad (1)$$

$$\text{where} \quad \sigma(E) = \pi \lambda^2 \omega \frac{\Gamma_p \Gamma_\alpha}{(E - E_0)^2 + \Gamma^2 / 4}, \quad (2)$$

N_A is Avogadro's number, μ the reduced mass, ω the spin statistical factor associated with the resonance at a c.m. energy E_0 , $\Gamma = \Gamma_p + \Gamma_\alpha$, and λ the de Broglie wave length, respectively. The parameters entering the calculations and the uncertainties are summarized in Table 1. In the evaluation of the integral the energy dependence of the proton width has been taken into account. The reaction rate from equation (1) is plotted as a function of T_9 in Fig. 2. Since at low energies contributions from lower lying states in ^{19}Ne need to be considered, only the range above $T_9 = 0.4$ is shown in Fig. 2. One can clearly see that the reaction rate above $T_9 = 0.5$ is dominated by the $\ell_p = 0, 3/2^+$ state at 7.066 MeV. It should be noted that while the $3/2^+$ spin value for this state was chosen in light of the tentative assignment from the α scattering measurements [7] and a $1/2^+$ assignment would result in different values for the proton- and α -widths, the astrophysical reaction rate would remain unchanged. For the assumed width of 4.5 eV, the $3/2^-$ state at 6.741 MeV gives the dominant contribution to the reaction rate in the $T_9 < 0.5$ range. Estimates [13] of the $^{18}\text{F}(p, \alpha)^{15}\text{O}$ reaction rate at $T_9 = 0.6$ based on theoretical arguments are shown by the different symbols in Fig. 2. Deviations of over a factor of 10 are observed.

In summary a $3/2^+$ state at $E_x \approx 7.1$ MeV in ^{19}Ne was found to have a strong influence on stellar reaction rate for the $^{18}\text{F}(p, \alpha)$ reaction which returns the ^{18}F material back into the CNO cycle. The overall influence of ^{18}F towards production of ^{19}Ne and its contribution towards the rp-process requires a measurement of the $^{18}\text{F}(p, \gamma)^{19}\text{Ne}$ reaction. With improvements of the efficiencies in the areas of ion source and particle detection, measurements of Γ_γ / Γ_p of 10^{-3} should be possible. Preparations towards these experiments are underway.

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Table 1. Energies and widths used in the reaction rate calculations shown in Fig. 2.

The proton widths for the $7/2^-$ and $3/2^-$ states were calculated from the single particle limits assuming a reduced width of $\Theta^2 = 0.05$.

$J\pi$	E_x (MeV)	E_{cm} (MeV)	Γ_p (keV)	Γ_α
$3/2^+$	7.066	0.655	8.8 ± 2.5	15.1 ± 5
$7/2^-$	6.861	0.450	1.8×10^{-5}	3
$3/2^-$	6.742	0.329	4.5×10^{-3}	3

Figure Captions:

Fig. 1. Limits for Γ_p and Γ_α set by the measurements of $\omega\gamma$ and the upper limit for $\Gamma_t = \Gamma_p + \Gamma_\alpha$ (shaded area). The black area indicates the widths consistent with the measurement of $\Gamma_p/\Gamma_\alpha = 0.58 \pm 0.06$ from Ref. 8 (see text for details).

Fig. 2. Astrophysical reaction rate calculated from the resonance parameters for the $3/2^+$ and $3/2^-$ states given in Table 2. The contribution from the $7/2^-$ state is negligible. The different symbols represent reaction rates at $T_9 = 0.6$ from various earlier calculations.

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