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New ^{19}Ne resonance observed using an exotic ^{18}F beam

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Abstract. The rates of the ^{18}F$(p,\alpha)^{15}$O and ^{18}F$(p,\gamma)^{19}$Ne reactions in astrophysical environments depend on the properties of ^{19}Ne levels above the $^{18}\mathrm{F}+p$ threshold. There are at least 8 levels in the mirror nucleus ^{19}F for which analogs have not been observed in ^{19}Ne in the excitation energy range $E_x = 6.4$–7.6 MeV. We have made a search for these levels by measuring the ^{1}H$(^{18}\mathrm{F},p)^{18}$F excitation function over the energy range $E_{\mathrm{c.m.}} = 0.3$–1.3 MeV. We have identified and measured the properties of a newly observed level at $E_x = 7.420 \pm 0.014$ MeV, which is most likely the mirror to the $J^\pi = 7/2^+$ ^{19}F level at 7.56 MeV. This new level is found to increase the calculated ^{18}F$(p,\alpha)^{15}$O reaction rate by 16%, 63%, and 106% at $T = 1, 2$, and 3 GK, respectively.

PACS. 27.20.+n $6 \leq A \leq 19$ – 25.40.Cm Elastic proton scattering – 25.60.-t Reactions induced by unstable nuclei – 26.30.+k Nucleosynthesis in novae, supernovae, and other explosive environments

The proton-induced reactions on ^{18}F are of astrophysical interest for a variety of reasons. The amount of the long-lived radioisotope ^{18}F [1] produced in novae depends directly on the rates of the ^{18}F$(p,\alpha)^{15}$O and ^{18}F$(p,\gamma)^{19}$Ne reactions [2]. The synthesis of other isotopes (*e.g.*, ^{16}O, ^{18}O, and ^{19}F) also show a dramatic sensitivity to the rates of these reactions [3]. In higher-temperature environments such as X-ray bursts, there may be a transition to heavy element production via the reaction sequence ^{18}F$(p,\gamma)^{19}$Ne$(p,\gamma)^{20}$Na$(p,\gamma)^{21}$Mg ... [4]. Whether there is a significant flow through this reaction sequence depends sensitively on the competition between the ^{18}F$(p,\gamma)^{19}$Ne and ^{18}F$(p,\alpha)^{15}$O reactions, and thus we must know their relative rates in these high-temperature astrophysical environments.

To accurately calculate the rates of the ^{18}F$(p,\alpha)^{15}$O and ^{18}F$(p,\gamma)^{19}$Ne reactions, we must understand the level structure of ^{19}Ne above the proton threshold at $E_x = 6.411$ MeV. Despite numerous studies of ^{19}Ne (see ref. [5] and references therein), there still exist at least 8 levels in the mirror nucleus, ^{19}F, for which analogs have not been observed in ^{19}Ne in the excitation energy range $E_x = 6.4$–7.6 MeV. These unobserved levels may significantly enhance the $^{18}\mathrm{F}+p$ reaction rates, and thus their properties must be determined.

We have searched for these missing levels in ^{19}Ne by measuring the ^{1}H$(^{18}\mathrm{F},p)^{18}$F excitation function over the energy range $E_{\mathrm{c.m.}} \simeq 0.3$–$1.3$ MeV. A 24 MeV ^{18}F beam was accelerated at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF) and stripped to charge state $q = 9^+$ before the energy-analyzing magnet to reject an unwanted ^{18}O contamination in the beam. The ^{18}F beam was then used to bombard a thick 2.8 mg/cm^2 polypropylene CH$_2$ target in which the beam was stopped, and scattered protons from the ^{1}H$(^{18}\mathrm{F},p)^{18}$F reaction were detected at $\theta_{\mathrm{lab}} = 8°$–$16°$ by a double-sided silicon-strip detector (DSSD). Because the scattered protons lose relatively little energy in the target, measurements of the proton's energy and angle of scatter are sufficient to determine the center-of-mass energy at which the reaction occurred [6]. A measurement of the scattered proton energy spectrum at a fixed angle can thus be used to extract the excitation function for the ^{1}H$(^{18}\mathrm{F},p)^{18}$F reaction over a wide range of center-of-mass energies.

Data were collected in event mode for approximately 62 hours. Events identified as protons from their time-of-flight and energy [7] were sorted in two-degree angular bins, corrected for energy loss in the target, and are plotted in fig. 1. The number of counts per channel generally fell with increasing $E_{\mathrm{c.m.}}$, which was simply a manifestation of the Rutherford scattering cross-section. There were, however, significant deviations from Rutherford

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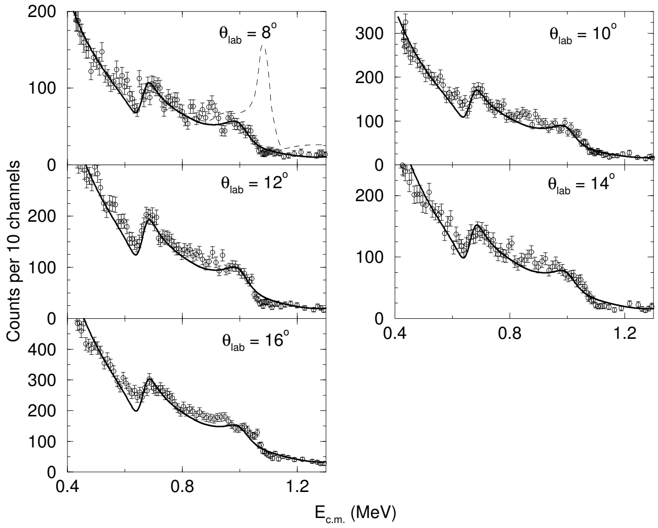

Fig. 1. The proton energy spectra from the ^{1}H(^{18}F$,p)^{18}$F reaction are shown as a function of angle. The solid line shows the best fit assuming a $\frac{7}{2}^+$ resonance at $E_{\mathrm{c.m.}} \simeq 1.01$ MeV. The dashed line in the 8° spectrum shows the excitation function expected using the resonance parameters from ref. [5].

scattering at $E_{\mathrm{c.m.}} = 0.665$ MeV and 1.01 MeV where the cross-section abruptly rises and falls, respectively. The increase in cross-section at $E_{\mathrm{c.m.}} = 665$ keV arises from the previously observed $J^\pi = \frac{3}{2}^+$ scattering resonance [8]. Since the properties of this resonance are well known, it provided a convenient internal energy calibration. The sharp fall in cross-section near $E_{\mathrm{c.m.}} = 1.01$ MeV could not be explained using previously known levels and indicated the presence of a newly observed ^{19}Ne resonance.

Excitation functions were calculated with the R-Matrix code MULTI [9]. A good fit to the data was obtained (see fig. 1) using just three resonances: the $J^\pi = \frac{3}{2}^+$ resonance at $E_{\mathrm{c.m.}} = 0.665$ MeV, a newly observed $J^\pi = \frac{7}{2}^+$ or $\frac{5}{2}^+$ resonance near $E_{\mathrm{c.m.}} = 1.01$ MeV, and a broad s-wave resonance higher in energy. A simultaneous fit of the data sets obtained at each angle was performed by varying the properties of the resonance near $E_{\mathrm{c.m.}} = 1.01$ MeV, and leaving the properties of the known $E_{\mathrm{c.m.}} = 0.665$ MeV resonance fixed at the values measured in ref. [8]. The best fit ($\chi^2_\nu = 1.45$) was obtained for a $J^\pi = \frac{7}{2}^+$ resonance at $E_{\mathrm{c.m.}} = 1.009 \pm 0.014$ MeV ($E_x = 7.420 \pm 0.014$ MeV) with $\Gamma_p = 27 \pm 4$ keV and $\Gamma_\alpha = 71 \pm 11$ keV. A fit nearly as good ($\chi^2_\nu = 1.52$) was obtained for a $J^\pi = \frac{5}{2}^+$ resonance at the same energy with $\Gamma_p = 31 \pm 4$ keV and $\Gamma_\alpha = 71 \pm 11$ keV. A $J^\pi = \frac{5}{2}^+$ assignment, however, appears to be rather unlikely from a comparison with the mirror nucleus, ^{19}F. The only known candidates for an analog level are the $J^\pi = \frac{5}{2}^+$ ^{19}F state at $E_x = 7.54$ MeV and the $J^\pi = \frac{7}{2}^+$ ^{19}F state at 7.56 MeV [10]. The 7.54 MeV $\frac{5}{2}^+$ ^{19}F level is narrow ($\Gamma = 0.16$ keV) and is thus not a good candidate for the mirror to our newly observed level with $\Gamma \simeq 98$ keV. On the other hand, the $\frac{7}{2}^+$ ^{19}F level is rather broad ($\Gamma = 85$ keV [11]) and has no other obvious analog in ^{19}Ne. The newly observed ^{19}Ne level at $E_x = 7.420 \pm 0.014$ MeV is, therefore, most likely the mirror to the $J^\pi = \frac{7}{2}^+$ ^{19}F level at 7.56 MeV.

In addition to the best fit calculation, we also show in fig. 1 the calculated excitation function using the ^{19}Ne resonance parameters from ref. [5]. That calculation includes contributions from 13 resonances, most of which produce only minor perturbations to the excitation function. The one glaring discrepancy is for the expected contribution from the $\frac{5}{2}^+$ level at $E_{\mathrm{c.m.}} = 1.09$ MeV ($E_x = 7.500$ MeV). This level was observed in ref. [10] to have $\Gamma_p/\Gamma_\alpha \simeq 5.25$ and a 1σ upper limit of $\Gamma < 32$ keV. A width of 16 keV was adopted for this level in ref. [5], but clearly (as seen in fig. 1) the actual width is much smaller. This is not really surprising considering the width of the proposed analog level is only 0.16 keV [12]. Using the ratio of the proton- to the alpha-partial width measured in ref. [10], we can set an upper limit on the proton width of $\Gamma_p(7.500\,\mathrm{MeV}) < 2.5$ keV at the 90% confidence level.

We have made updated calculations of the ^{18}F + p reaction rates in ref. [7]. We find that the addition of the newly observed $7/2^+$ resonance increases the calculated ^{18}F$(p,\alpha)^{15}$O rate by 16%, 63%, and 106% at $T = 1$, 2, and 3 GK, respectively. The calculated ^{18}F$(p,\gamma)^{19}$Ne reaction rate (using γ widths from ref. [5]) is increased by about $\sim 7\%$ over the 1–3 GK range. At temperatures below this, the rates are dominated by resonances at $E_{\mathrm{c.m.}} = 330$ and 665 keV [5].

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