Proton decay branching ratio for the 6.15-MeV ^{18}Ne level

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The ^{14}O(α, p)^{17}F reaction is an important trigger to the αp process in x-ray bursts. Only limited information is available from direct measurements of the reaction cross section, and the time-inverse ^{17}F(p, α)^{14}O reaction has been frequently used to constrain the astrophysical reaction rate. These time-inverse measurements must be complemented by inelastic ^{17}F(p, p')^{17}F* studies to constrain branches populating the first excited state of ^{17}F. Discrepancies in the literature are examined in relationship to directly measured ^{17}F(p, p')^{17}F* data, and it is shown that a resolution is possible. Claims of alternative spin assignments for the 6.15-MeV level are also discussed in relationship to the measured inelastic data.

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I. INTRODUCTION

The ^{14}O(α, p)^{17}F reaction is an important trigger reaction and pathway to the αp process in x-ray bursts. A type-I x-ray burst is thought to be initiated by accretion of hydrogen- and helium-rich material onto the surface of a neutron star in a close-coupled binary star system. The accreted material is burned under degenerate conditions, leading to the conversion of hydrogen to helium via the pp chains and helium to ^{12}C via the triple-α process. Hot CNO burning ensues, which in turn produces proton-rich nuclei whose β-decay lifetimes determine, in part, the energy generation rate at this stage. The peak of the burst is reached when the α-p chain [^{14}O(α, p)^{17}F(p, γ)^{18}Ne(α, p)^{21}Na, ...] is triggered and transitions to the rp process. As the trigger reaction, the rate of ^{14}O(α, p)^{17}F determines, in part, the conditions under which the burst is initiated and thus plays a critical role in understanding burst conditions.

Because of this importance, there have been several direct [1] and time-reverse [2,3] measurements of the ^{14}O(α, p)^{17}F reaction cross section as well as numerous stable beam studies of the relevant structure in ^{18}Ne [4,5]. The time-reverse measurements require additional studies of the inelastic ^{17}F(p, p')^{17}F* [6–8] reaction to constrain branches of the ^{14}O(α, p)^{17}F reaction populating the first excited state of ^{17}F. While inelastic scattering was observed for several ^{18}Ne levels, the first study to observe inelastic scattering from the 6.15-MeV ^{18}Ne level was reported in Ref. [6]. This level has been widely assumed to have $J^\pi = 1^-$ and to dominate the astrophysical reaction rate [2–4,9]. Constraining its proton-decay branches to the ground and first excited states of ^{17}F is therefore of critical importance.

The inelastic scattering data from Ref. [6] are reproduced in Fig. 1. Briefly, the yield of elastically and inelastically scattered protons from a ^{17}F beam were detected in the SIDAR silicon detector array [10]. The observed yields at each energy were corrected for the amount of beam impinged on the target and are plotted in Fig. 1. A fit to this data [along with elastic scattering and (p, α) reaction data] yielded a proton-decay branching ratio of $\Gamma_{p'}/\Gamma_p = 2.4$, and $\Gamma_{\rm tot} \sim 58$ keV [6], where Γ_p and $\Gamma_{p'}$ are the proton-branching widths for populating the ground and first excited states, respectively. This large branch to the first excited state increased estimates of the astrophysical ^{14}O(α, p)^{17}F rate by factors of 3 to 60 depending on the temperature.

More recently, He *et al.* [11] detected decay γ rays in coincidence with ^{17}F + p protons searching the 495-keV γ ray, signifying the decay of the first excited state in ^{17}F. Observation of such a γ decay in coincidence with low-energy scattered protons would indicate population of the first excited state via the ^{1}H(^{17}F,p')^{17}F* reaction. The resonance strength observed in Ref. [11] was roughly a factor of two larger than physically possible (assuming a ∼50-keV total width), and thus the authors surmised that the factor $\Gamma_p\Gamma_{p'}/\Gamma_{\rm tot}$ must be near its largest value, which occurs when $\Gamma_p = \Gamma_{p'}$.

Finally, Almaraz-Calderon *et al.* [5] populated the 6.15-MeV ^{18}Ne level via the ^{16}O(^{3}He,n)^{18}Ne reaction. The reaction neutrons were counted in an array of liquid scintillator neutron detectors in coincidence with decay protons that were detected by silicon detectors placed in the target chamber. A proton decay branching ratio of $\Gamma_{p'}/\Gamma_p = 0.27 \pm 0.16$ was extracted from this data set for the 6.15-MeV level [12]. This nearly factor of 10 discrepancy in the extracted proton decay branching ratios contributes a large uncertainty to the estimated ^{14}O(α, p)^{17}F astrophysical reaction rate.

An additional uncertainty arises due to the uncertain spin of the 6.15-MeV level. Since the measurement by Hahn *et al.* [4] of the angular distribution of neutrons populating the level in the ^{16}O(^{3}He,n)^{18}Ne reaction, it has generally been assumed that the 6.15-MeV level provides a 1^- resonance dominating the astrophysical reaction rate [2–4,9,11]. This common assumption was recently questioned in an arXiv preprint [13] that analyzed previous ^{17}F + p elastic scattering data [14]. In this data, a peak in the excitation function was observed near the resonance energy expected for the 6.15-MeV level, which could not be fit according to the authors of Ref. [13] with an $\ell = 1$ angular momentum transfer and thus cannot be a 1^- resonance. This is in contrast to the claim of a 1^- assignment by the authors of Ref. [14]. It should be noted that this peak in cross section has not been observed in numerous other lower statistics measurements of the ^{17}F + p excitation function [2,11,15].

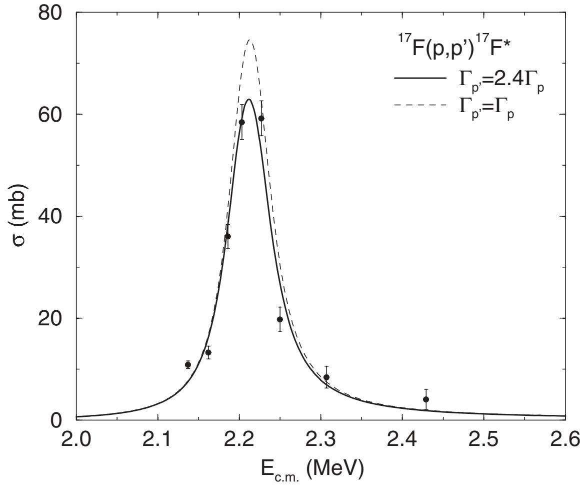

FIG. 1. Inelastic ^{17}F$(p, p')^{17}$F* data from Ref. [6] are shown along with a fit (solid line) with $\Gamma_p = 15$ keV and $\Gamma_{p'} = 35$ keV for the 6.15-MeV ^{18}Ne level. The dashed line shows the result when the constraint $\Gamma_p = \Gamma_{p'}$ from Ref. [11] is added.

To address some of these questions, the inelastic scattering data from Ref. [6] has been analyzed under some alternative assumptions. These data provide some of the most sensitive constraints on the properties of the 6.15-MeV level. Accurate excitation energies, widths, and partial widths can be extracted and implications of alternative spin assignments examined.

II. ANALYSIS

As stated previously, the data from Ref. [6] are reproduced in Fig. 1. The solid line in Fig. 1 shows a fit to the data assuming an energy resolution of 30 keV, which arises from the energy loss in the 59-μg/cm^2 polypropylene target. The multichannel R-matrix code MULTI [16] was used to reanalyze the elastic- and inelastic-scattering channels. The best fit was found for the following parameters, $E_r = 2.212 \pm 0.001$ keV, $J^\pi = 1^-$, $\Gamma_{p'} = 37.8 \pm 1.9$ keV, and $\Gamma_p = 15.9 \pm 0.7$ keV, which are in good agreement with the fit results from Ref. [6]. In Fig. 2, elastic scattering data (not published in Ref. [6]) are also shown along with the MULTI calculations using the best-fit parameters. Clearly the statistics in the elastic-scattering data are not sufficient to constrain the parameters of such a resonance. Also shown in Fig. 1 is the MULTI calculation using the suggestion from Ref. [11] that $\Gamma_{p'} = \Gamma_p$. This calculation seems to overestimate the ^{17}F$(p, p')^{17}$F cross section by ∼20%.

Next, the case was considered where the values of $\Gamma_{p'}$ and Γ_p were reversed in Ref. [6]. Since the ^{1}H(^{17}F,p')^{17}F* excitation function can essentially be described by a Breit-Wigner cross section and that expression is symmetric with respect to the decay widths, it is possible that the values of $\Gamma_{p'}$ and Γ_p could have been reversed. In Fig. 3, the same calculation is shown where $\Gamma_{p'} = 15.9 \pm 0.7$ keV and $\Gamma_p = 37.8 \pm 1.9$ keV, and Fig. 2 shows the effect this reversal has on the elastic scattering calculation. The fit for the reversed values appears to describe the data equally well. Such a reversal would result in $\Gamma_{p'}/\Gamma_p = 0.42 \pm 0.03$, which would be within uncertainties of the value reported by Almarez-Calderon *et al.* [12].

An additional (albeit weak) constraint also comes from the comparison of (p, α) and (p, p') cross sections measured on resonance [2,6]. The ratio of cross sections on resonance is equal to the ratio of $\Gamma_{p'}/\Gamma_\alpha$ and was measured to be approximately 6500 [2,6]. Taking $\Gamma_\alpha = 2$ eV from previous estimates [4,7] results in a deduced decay width of $\Gamma_{p'} = 15$ keV, in agreement with the present fit results. Based upon these arguments, the adoption of values of $\Gamma_{p'} = 15$ keV and $\Gamma_p = 35$ keV would provide consistency between multiple data sets and resolve the discrepancy between the measured inelastic data [6] and the recent (^{3}He, n) measurements [5].

Finally, alternative spin assignments were considered for the 6.15-MeV level. In particular, a recent analysis by

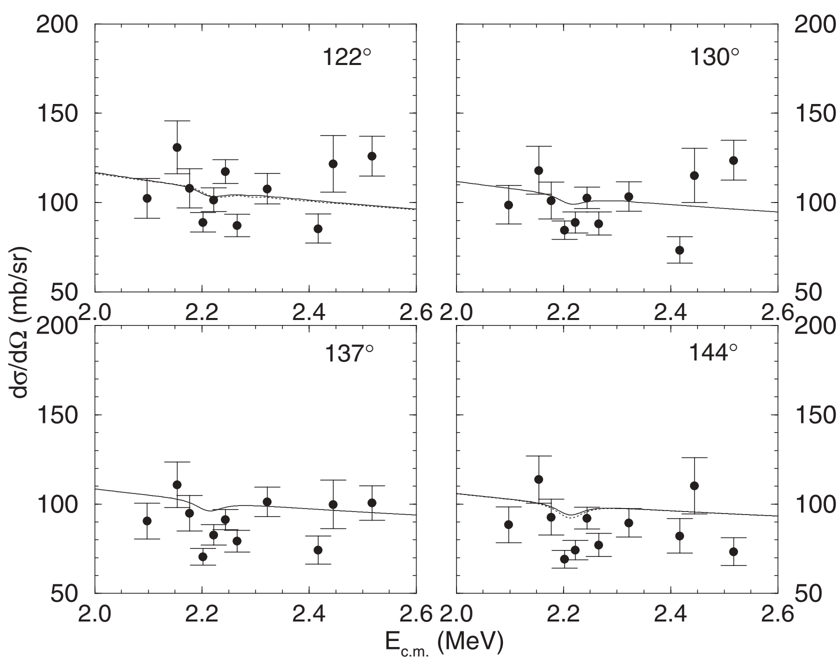

FIG. 2. Elastic ^{17}F + p data measured simultaneously with the inelastic data from Ref. [6] is plotted. The solid line shows the calculated excitation function from MULTI assuming the resonance parameters from [6]. Examples of the small changes that are produced when the values for the decay widths to the ground state and first excited state were reversed are shown by dashed lines in the 122° and 144° plots. Clearly the elastic data cannot be used to discriminate between the two possible best fits to the inelastic data.

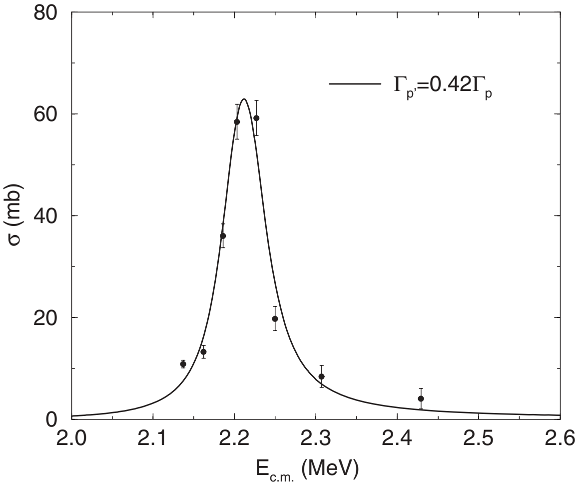

FIG. 3. The same as Fig. 1 but the fit has reversed the values for the decay widths to the ground state and first excited state.

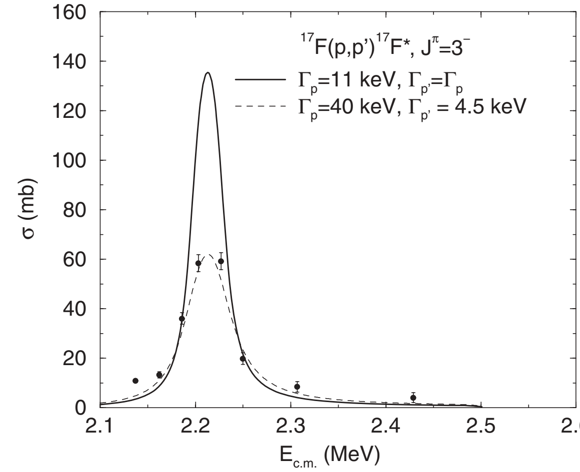

FIG. 4. Calculations were performed assuming a spin parity of 3^- for the observed resonance. The resonance can only be fit for this assignment if the partial decay widths disagree with previous measurements.

He *et al.* [13] of a small peak previously measured in ^{17}F$(p, p)^{17}$F elastic scattering data suggested that the spin parity of the 6.15-MeV level was actually 3^-. This small peak was not observed in other lower statistics measurements [2,11,15] and this work (Fig. 2), and it is unclear if the peak observed in Ref. [14] was due to some other reaction channel such as inelastic scattering. The best fit in He *et al.* [13] of this peak was obtained with $J^\pi = 3^-$ and $\Gamma_p = 10$–12 keV. The authors [13] do not address the inelastic channel in their discussion, and thus we assume the first author would contend $\Gamma_{p'} = \Gamma_p$ as previously published [11]. In Fig. 4, a MULTI calculation is shown assuming the resonance parameters from He *et al.* [13] and $\Gamma_{p'} = \Gamma_p$ [11]. This calculation greatly overestimates the observed ^{17}F$(p, p')^{17}$F cross section. Also shown in Fig. 4 is a calculation for a 3^- resonance where the partial widths are allowed to vary. A reasonable fit was obtained for $(\Gamma_p, \Gamma_{p'}) = (40, 4.5)$ keV or the reverse of this. The first case, however, would not be consistent with elastic analysis in He *et al.* [13], and the reverse assignment would disagree with the branching ratios measured in Refs. [5,12].

III. CONCLUSIONS

In conclusion, significant discrepancies exist in the literature concerning the proton-decay branching ratios to the ground and first excited state in ^{17}F from the 6.15-MeV ^{18}Ne level. The branching ratio affects interpretation of ^{1}H(^{17}F,α)^{14}O measurements and their extrapolation to the astrophysically important ^{14}O$(\alpha, p)^{17}$F reaction. It is shown that a possible resolution of some discrepancies is obtained when reversing the relative proton branching ratios from Ref. [6], and good fits are obtained for $\Gamma_p = 37.8 \pm 1.9$ keV and $\Gamma_{p'} = 15.9 \pm 0.7$ keV. This would result in a branching ratio consistent with recent ^{16}O(^{3}He$,n)^{18}$Ne(p) measurements [5,12]. Additionally, it is found that the alternative spin assignment $J^\pi = 3^-$ as recently suggested for the 6.15-MeV level [13] results in inconsistencies between the measured ^{1}H(^{17}F$,p')^{17}$F* data and other data sets [5,14]. A more comprehensive analysis including several higher lying ^{18}Ne levels and the inclusion of ^{1}H(^{17}F$,\alpha)^{14}$O data is in progress [17].

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