

Measurement of the inelastic branch of the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction: Implications for explosive burning in novae and x-ray bursters

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A measurement of the inelastic component of the key astrophysical resonance in the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction for burning and breakout from hot carbon-nitrogen-oxygen (CNO) cycles is reported. The inelastic component is found to be comparable to the ground-state branch and will enhance the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction rate. The current results for the reaction rate confirm that the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction is unlikely to contribute substantially to burning and breakout from the CNO cycles under novae conditions. The reaction can, however, contribute strongly to the breakout from the hot CNO cycles under the more extreme conditions found in x-ray bursters.

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Astrophysical x-ray bursts have been interpreted as being generated by thermonuclear explosions in the atmosphere of an accreting neutron star in a close binary system [1]. These bursts are characterized by sudden enormous spikes in x-ray emission, lasting a few seconds, with repeating cycles on a time scale of hours to days. These spectacular astrophysical phenomena are now being studied in detail in a number of x-ray satellite observatory missions, including Chandra, XMM-Newton, and Integral. The extreme temperatures and densities open up new pathways for increased energy generation and nucleosynthesis. Thermal runaway reactions can be ignited through both the triple- α reaction and breakout from the hot carbon-nitrogen-oxygen (CNO) cycles into the rapid proton capture process (rp process). The rp process may thence proceed as far along the proton drip line as the Sb and Te isotopes, and may possibly be the origin of p nuclei, such as ^{92}Mo and ^{96}Ru [2,3]. In both the triple- α and CNO breakout mechanisms, energy generation increases rapidly as a function of temperature, and hence the rate of energy release can increase faster than the rate of cooling, ultimately leading to x-ray bursts [4]. In the period between bursts, energy is generated at a constant rate by the β -limited hot CNO cycles, the half-lives of the waiting point nuclei ^{14}O and ^{15}O being 71 and 122 s, respectively. As a consequence, novae ejecta are rich in the daughter products ^{14}N and ^{15}N . However, in x-ray burst scenarios, temperatures are such that these waiting points can be bypassed. In particular, the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction can trigger the breakout from the hot CNO cycles via the $^{17}\text{F}(p, \gamma)^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$ sequence [5].

The $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction rate is thought to be dominated by capture onto a single 1^- resonance $E_r = 1.04$ MeV, corresponding to an excited state in ^{18}Ne at 6.15 MeV [6]. The total width of the state is dominated by proton emission

and has already been studied using the elastic scattering of ^{17}F ions on protons in inverse kinematics [7]. The time reverse reaction $^{17}\text{F}(p, \alpha)^{14}\text{O}$ was later studied in inverse kinematics to obtain the first measurement of the much weaker partial α -decay width of the resonance [8]. A limitation of this latter approach is that it cannot take into account the inelastic reaction channel corresponding to the production of the $\frac{1}{2}^+$ first excited state at 0.495 MeV in ^{17}F in the astrophysical reaction. This reaction branch can be measured by studying the proton inelastic scattering reaction $^{17}\text{F}(p, p')^{17}\text{F}$, which is the method adopted in the present study. It is also the method reported in Ref. [9]. In that study, a thin $(\text{CH}_2)_n$ target was bombarded with ^{17}F ions in the region of the resonance energy ($E_{\text{c.m.}} = 2.22$ MeV for the $^{17}\text{F} + p$ entrance reaction channel), and inelastic and elastically scattered protons were detected and separated in energy in an annular silicon detector array [9]. A value of the ratio of inelastic scattering to elastic scattering of 2.4 was reported, indicating the inelastic contribution is dominant, although at the time of writing the present report no full value with error had been published.

The present experiment was performed at the CERN Radioactive Beam Experiment On-Line Isotope Mass Separator (REX-ISOLDE) facility [10]. A fully stripped $^{17}\text{F}^{9+}$ ion beam was selected to avoid intense isobaric contamination from ^{17}O ions. The beam energy 44.2 MeV ($E_{\text{c.m.}} = 2.46$ MeV) was chosen, so ions entered just above the resonance energy and stopped inside a ~ 40 μm thick $(\text{CH}_2)_n$ target. Elastic and inelastically scattered protons were detected in the laboratory angular range 15° – 50° using the double-sided silicon strip detector (CD) system, consisting of four Micron Semiconductor Ltd. (MSL) type QQQ/2, ~ 35 μm thick, ΔE detectors backed by four MSL type QQQ/1, ~ 0.5 mm thick, E detectors [11].

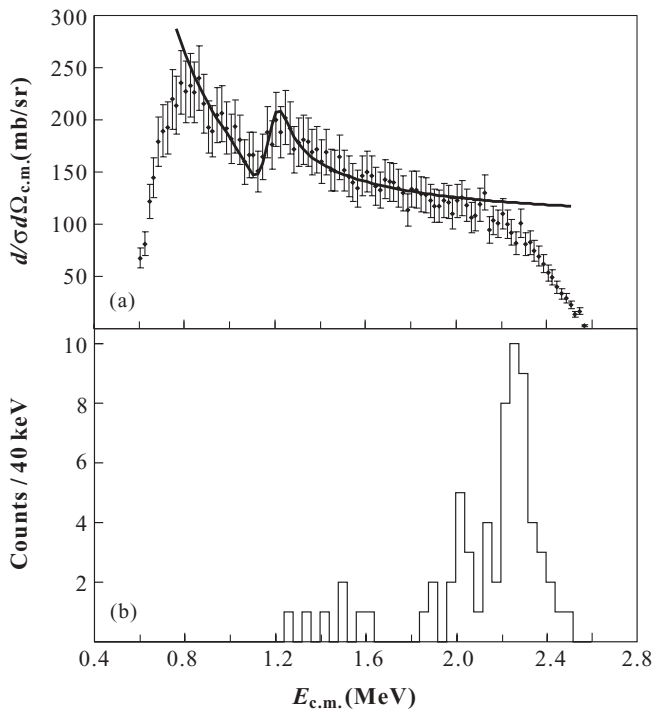


FIG. 1. (a) Center-of-mass energy spectrum for elastically scattered protons produced in the range $\theta_{c.m.} = 131.4^\circ$ – 149.5° by bombarding a thick $(\text{CH}_2)_n$ target with 44.2 MeV ^{17}F ions. The curved line represents an R -matrix fit to the data, with the strong known resonance, corresponding to a 5.10 MeV 2^+ state in ^{18}Ne , being clearly visible. (b) Center-of-mass energy spectrum for inelastically scattered protons measured over the full measured angular range. These events correspond to protons in coincidence with 495 keV γ rays from the peak shown in Fig. 2.

Figure 1(a) shows a proton center-of-mass energy spectrum from events in the range $\theta_{c.m.} = 131.4^\circ$ – 149.5° . The proton energies were calibrated using the method described in Ref. [12], where the midpoint of the down-sloping region of the highest energy events corresponds to the c.m. energy at the entry point to the surface of the target. An example of an R -matrix fit to the elastic scattering data is shown in Figure 1(a), with a known strong scattering resonance corresponding to the 2^+ state at an excitation energy of 5.10 MeV in ^{18}Ne being clearly visible [7]. Such R -matrix fits were used to estimate the integrated beam intensity of 8×10^8 particles with a $\sim 10\%$ uncertainty, corresponding to a time-averaged ^{17}F current $\sim 1.8 \times 10^3$ particles s^{-1} . This is approximately two orders of magnitude less than the ^{17}F beam intensity used in the study of proton elastic scattering from the 1^- resonance reported in Ref. [7], and consequently in the present study, this resonance would not be expected to be observed directly from elastic scattering.

The inelastic proton scattering branch from the 1^- resonance was tagged by measuring 495.33(10) keV γ decays from the first excited state in ^{17}F using the highly efficient (9.1% for 495 keV γ rays) Miniball array [13]. Figure 2 shows a spectrum of γ decays in coincidence with protons detected in the CD [the timing resolution between the protons and the γ rays is ~ 75 ns, full width at half maximum (FWHM)]. The

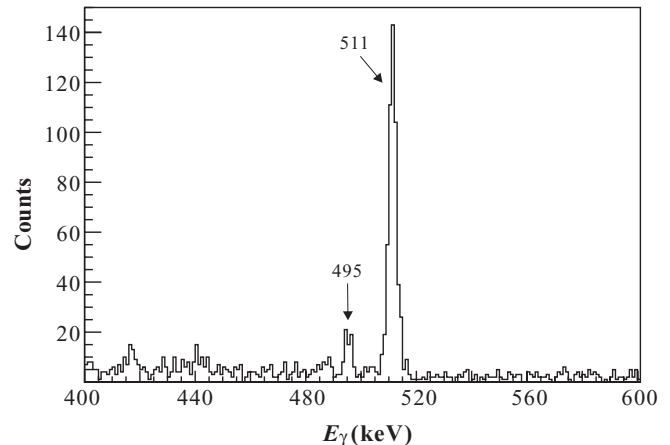


FIG. 2. γ -ray energy spectrum for events measured by the Miniball array in coincidence with protons in the CD detector system. The most intense peak corresponds to random proton scattering coincidences with annihilation radiation from the β^+ decay of the radioactive ^{17}F beam in the chamber. The other arrowed peak shows the deexcitation peak from the 495 keV first excited state in ^{17}F .

most intense peak is the positron annihilation peak from the decay of the radioactive beam in the chamber. Just below this peak, the 495 keV line is visible. Note, the line is not Doppler broadened, since the excited ^{17}F ions stop in the target before γ decaying, with the γ rays emitted isotropically from the $\frac{1}{2}^+$ first excited state, all other excited states in ^{17}F being proton unbound. However, this peak could be produced by direct scattering of the ^{17}F beam on protons continuously throughout the target. In Figure 1(b), we show the c.m. energy spectrum gated on the 495 keV γ -decay peak over the full range of proton detection angles. We see a peak with 44(7) events, at an energy of 2.26(6) MeV [equivalent to an excitation energy of 6.18(6) MeV], in agreement with the expected c.m. energy of the resonance of 2.22(1) MeV [7]. (Note, the peak has a FWHM of 120(60) keV, which is larger than but within errors consistent with the estimated intrinsic experimental resolution of 80 keV FWHM). We therefore conclude we have observed the inelastic branch to the first excited state in ^{17}F following decay of the 1^- resonance in ^{18}Ne .

Following the approach adopted in, for example, Ref. [7], we took the energy-integrated differential cross section associated with this peak and then used R -matrix calculations to predict an angular distribution for the reaction leading to a total angle-integrated cross section. The proton decay can only proceed by $l_p = 1$ emission, and the resonance is expected to be fed predominantly through $l_p = 1$ capture based on (d, p) studies of the analog state in the mirror nucleus ^{18}O [14]. From the R -matrix calculations, we estimated an error of $\sim 20\%$ in the integrated cross section arising from uncertainties in the proton angular distribution, and we took a mean value corresponding to isotropic proton emission. This leads to a value of 22(7) keV for $\frac{\Gamma_{p0} \times \Gamma_{p'}}{\Gamma}$, where Γ_{p0} represents the resonant elastic scattering branch. In Ref. [7], a value for Γ of 50(5) keV was obtained by an R -matrix fit to proton elastic scattering data. Taking this value implies a maximum value for $\frac{\Gamma_{p0} \times \Gamma_{p'}}{\Gamma}$ of 12.5 keV, corresponding to equal magnitude ground

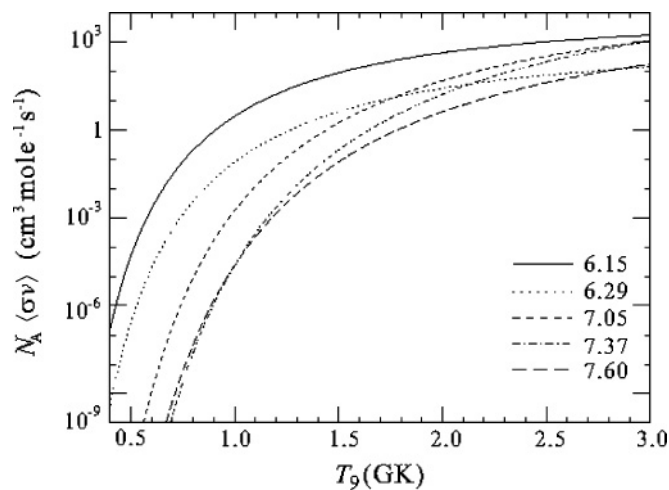


FIG. 3. Resonant contributions to the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction rate incorporating the latest results from the present paper. For resonances above the 6.15 MeV state, resonance parameter values were taken from Ref. [8].

and inelastic proton branches. The mean value for the present experimental data exceeds this value and is consistent with a strong inelastic proton branch approximately equal to the ground-state branch at the $\sim 1\sigma$ level. In the work of Blackmon *et al.* [9], a strong inelastic proton branch was reported, with a value for $\frac{\Gamma_{p'}}{\Gamma_{p0}}$ of ~ 2.4 with no error quoted. Such a value agrees at the 1.7σ level with the present experimental value for $\frac{\Gamma_{p0} \times \Gamma_{p'}}{\Gamma}$. If the more precise value for Γ of 58(2) keV, also reported in Ref. [9], is used, agreement is obtained at the 1.5σ level. In the present work, we would therefore conclude that the inelastic branch does have a comparable influence on the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction rate to that of the ground-state branch from the key 1^- resonance, but not to the relative degree suggested in Ref. [9].

The resonant reaction rate is plotted in Fig. 3 including the new information on the inelastic component from the present work, assuming approximately equal inelastic and ground-state branches, and taking other resonance parameters from the work of Harss *et al.* [8]. Figure 3 clearly shows the

dominant influence of the 1^- resonance at 6.15 MeV in ^{18}Ne for the key burning temperatures of astrophysical interest up to ~ 3 GK. The calculated rate assumes $\Gamma_\alpha = 3.2_{-2.0}^{+5.0}$ eV for this resonance [8], the only fully published measurement so far, although it should be noted that a more precise value of 8(2) eV was subsequently reported by Blackmon *et al.* [9]. The present results confirm that it is unlikely that the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction can bypass the β^+ decay of ^{14}O in the hot CNO cycles in the temperature and density conditions found in novae explosions.

A key remaining uncertainty in the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction rate affecting the energy region of interest for x-ray bursters is the interference between the resonance capture onto the 1^- state and the direct $l_\alpha = 1$ capture, which may be constructive or destructive [6]. Thick target measurements have been performed in the first direct study of the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction and have been reported in Refs. [14,15]. However, although the excitation function is shown in the energy region of interest, no new quantitative information is derived on the resonance characteristics or its interference with direct scattering [15,16].

In summary, we have applied a new highly sensitive technique, using a relatively low intensity radioactive beam, to measure the inelastic component of the key 1^- resonance in the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction. We conclude that this will enhance the reaction rate, contributing approximately equally to the ground-state component of the reaction rate. The rate confirms that the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction is unlikely to be a dominant component in the hot CNO cycles in novae environments. For the triggering of the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ reaction in x-ray burster scenarios, it would be desirable to have new, more precise measurements of Γ_α for the key 1^- resonance and to explore the interference between resonant and direct $l_\alpha = 1$ capture in this burning region.

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