Determination of the $^{14}O(\alpha,p)^{17}F_{g.s.}$ reaction rate by measurement of the $^{1}H(^{17}F,\alpha)^{14}O$ cross section

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The $^{14}O(\alpha,p)^{17}F$ reaction is important during the ignition phase of x-ray bursts, but significant uncertainties in this reaction rate have persisted due to uncertainties in the properties of excited states in ^{18}Ne and the unmeasured direct reaction cross section. The $^{1}H(^{17}F,\alpha)^{14}O$ reaction, the time-inverse of the $^{14}O(\alpha,p)^{17}F_{g.s.}$ reaction, was studied using a radioactive ^{17}F beam at the Holifield Radioactive Ion Beam Facility. The (p,α) reaction and (p,p) elastic-scattering cross sections were measured over the energy range of interest for x-ray bursts, corresponding to $E^{\alpha}_{\rm cm} = 1.0 - 2.6$ MeV. Resonances corresponding to states in ^{18}Ne with excitation energies $E_x = 6.0 - 7.7$ MeV were observed, and the direct reaction cross section determined.

In stellar explosions such as novae and x-ray bursts, ^{14}O is produced by successive proton captures on ^{12}C and ^{13}N. Hydrogen burning of ^{14}O is inhibited because ^{15}F is proton unbound, and significant abundances of ^{14}O may be accumulated due to its long half-life ($t_{1/2} = 71$ s). Sufficient temperatures to ignite the $^{14}O(\alpha,p)^{17}F$ reaction are not likely to occur in novae, and more than 5% of the envelope mass may accumulate in ^{14}O as a result [1]. Temperatures do reach a level to ignite the $^{14}O(\alpha,p)^{17}F$ reaction in x-ray bursts, driving the burst to its peak energy-generation rate and leading to the synthesis of heavy elements [2]. The rate of the $^{14}O(\alpha,p)^{17}F$ reaction is important for understanding these events since it determines the conditions under which the ^{14}O beta decay is bypassed.

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The density of states in the Gamow window in ^{18}Ne for the ^{14}O(α,p)^{17}F reaction is quite low. As a result, it is expected that the ^{14}O(α,p)^{17}F reaction rate will be dominated by contributions from a single resonance and the direct reaction cross section. The crucial resonance arises from the 1^- state in ^{18}Ne that is the mirror to the $E_x = 6.20$ MeV state in ^{18}O. A state observed in ^{18}Ne at $E_x = 6.15$ MeV has been tentatively identified as the important 1^- state, but the only property of the state accurately determined was the excitation energy [3]. Microscopic model calculations indicate that the direct reaction cross section constitutes a large fraction of the total reaction rate; however, this contribution is experimentally unconstrained and contributes as much as an order of magnitude uncertainty to the ^{14}O$(\alpha, p)^{17}$F reaction rate [4]. Other states in ^{18}Ne in the energy range $E_x = 6.0-7.5$ MeV may also contribute. A measurement of the ^{17}F$(p, \alpha)^{14}$O reaction at Argonne National Laboratory has reported the observation of 3 resonances with $E_x > 7.0$ MeV in ^{18}Ne [5]. The energies of the observed resonances are consistent with previously observed states in ^{18}Ne [3], but a precise resonance energy and resonance strength could only be established for highest-energy resonance at $E_x = 7.60$ MeV.

To address these uncertainties in the ^{14}O$(\alpha, p)^{17}$F reaction rate, we have measured the cross section for the time-inverse reaction, ^{1}H$(^{17}$F$, \alpha)^{14}$O, at the Holifield Radioactive Ion Beam Facility (HRIBF). A radioactive ^{17}F beam was produced using the ISOL technique [6], accelerated in the HRIBF tandem accelerator, and post-stripped in a thin carbon foil. The tandem analyzing magnet was used to select the 9^+ charge state to eliminate an ^{17}O contaminant from the beam and background from the ^{1}H$(^{17}$O$, \alpha)^{14}$N reaction. Polypropylene targets were used, and both reaction products were detected in coincidence in an array of silicon strip detectors. Alpha particles from the ^{1}H$(^{17}$F$, \alpha)^{14}$O reaction were detected in a large annular detector array [7] covering $\theta_{lab} = 10.5° - 25.8°$. Recoiling ^{14}O ions were detected in coincidence with the alpha particles in a smaller annular silicon strip detector spanning $\theta_{lab} = 3.4° - 6.7°$. This arrangement of detectors allowed about 70% of the ^{17}F$(p, \alpha)^{14}$O events to be detected in coincidence.

A representative density plot showing the number of coincident events as a function of the energy of the two detected particles is shown in Fig. 1 for an incident energy of 60.5 MeV. Events from the ^{1}H$(^{17}$F$, \alpha)^{14}$O reaction are visible as a line with a sum energy of 58.56 ± 0.35 MeV, in agreement with the total energy expected given the energy loss in the target (0.72 MeV) and the reaction $Q = -1.192$ MeV. The large background of coincident events seen in Fig. 1 are primarly protons and alpha particles from fusion-evaporation reactions on carbon in the CH_2 target. In addition to the energy, the angle and time of arrival for each particle were also measured. These quantities and their relationships allow events from the ^{17}F$(p, \alpha)^{14}$O reaction to be distinguished unambiguously. As an example, counts are also plotted as a function of particle energy and laboratory angle in Fig. 1 for events satisfying the energy-energy gate shown.

The ^{1}H$(^{17}$F$, \alpha)^{14}$O cross section was measured at 21 beam energies between $E(^{17}\text{F}) = 40.1 - 68.2$ MeV ($E_x = 6.1 - 7.7$ MeV), and the total cross section is shown in Fig. 2. For beam energies greater than or about 60 MeV, more than 50 coincident events were typically collected at each energy using a 100 μg/cm^2 CH_2 target at an incident current of $(1-2) \times 10^6$ ^{17}F$/s$. For energies below 55 MeV, thicker targets ($200 - 300$ μg/cm^2) were used due to the lower cross sections and beam currents (5×10^5 ^{17}F$/s$). Differential cross sections for ^{1}H$(^{17}$F$, p)^{17}$F elastic scattering were measured simultaneously at center-of-

mass angles between 128° and 159°. A representative excitation function is also shown in Fig. 2. The curves shown in Fig. 2 are calculated cross sections taken from the results of Hahn *et al.* [3]. The curves were all calculated using the same resonance parameters with the two curves in Fig. 2a indicating the two possible interferences between the resonance and direct contributions.

The uncertainties shown in Fig. 2 are statistical only. The target composition was determined by measurements of elastic scattering using low energy beams of ^{16}O. The detector efficiency was measured using a calibrated alpha source and ^{197}Au(^{16}O,^{16}O)^{197}Au scattering, and found to agree with that calculated from geometry. The integrated beam current was determined from the measured yields of ^{12}C(^{17}F,^{17}F)^{12}C elastic scattering at forward angles. The total systematic uncertainty is estimated to be less than 5% and is due primarily to uncertainties in ^{12}C(^{17}F,^{17}F)^{12}C elastic scattering cross sections.

Four resonances are evident in the data which correspond to previously observed states in ^{18}Ne at $E_x \approx$ 6.15, 7.07, 7.35 and 7.60 MeV. The arrows in Fig. 2 indicate their location. An R-matrix analysis of the measured cross sections is currently in progress

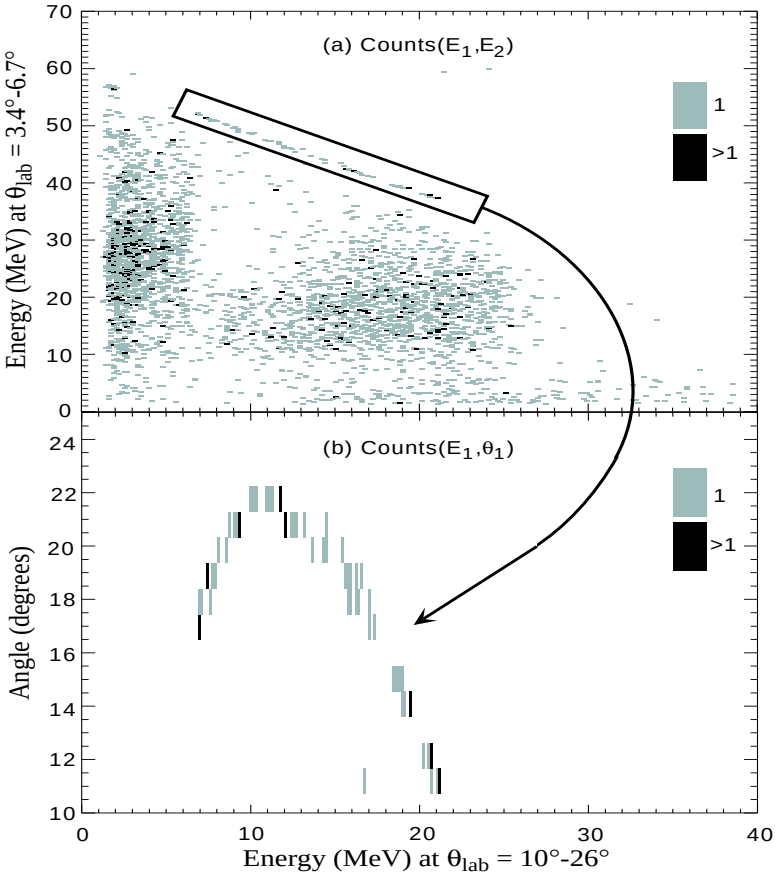

Figure 1. Data collected at a beam energy of 60.5 MeV with a 96 μg/cm^2 CH_2 target and a beam current of 1.1×10^6 s^{-1} for 5.8 hours. (a) Counts as a function of the energies of 2 particles detected in time coincidence. (b) Counts as a function of the lab angle and energy for events which fall into the energy-energy gate shown in (a).

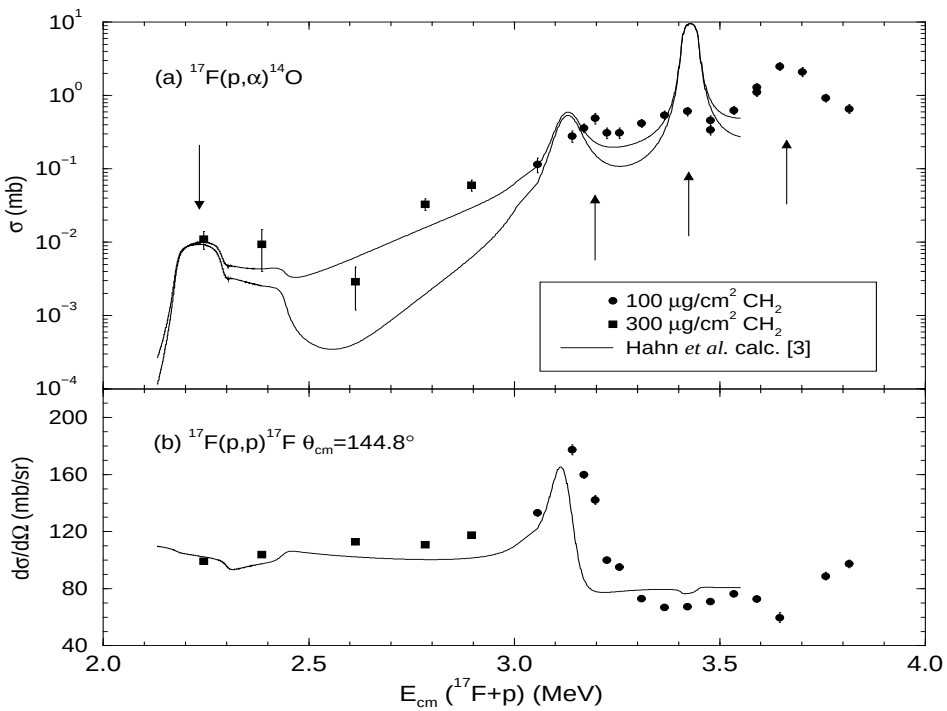

Figure 2. The ^{17}F$(p,\alpha)^{14}$O total cross section and ^{17}F$(p,p)^{17}$F differential scattering cross section at one representative angle.

to extract resonance energies and strengths. In addition, the cross sections measured at energies $E(^{17}\mathrm{F}) = 48 - 55$ MeV ($E_x = 6.6 - 7.0$ MeV), where no states in ^{18}Ne were known or expected, constrain the direct reaction cross section. It is anticipated that the $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}_{g.s.}$ reaction rate (to the ground state in ^{17}F) can be determined with reasonable accuracy (to about 30%) through a careful analysis of these cross sections and other recent data [3,5,8]. However, by measuring the time-inverse reaction using a ^{17}F beam in the ground state, we have not constrained the $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}^{\star}$ reaction branch to the $1/2^+$ first-excited state in ^{17}F. This branch may be significant and would increase the $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$ reaction rate. Further measurements are planned to constrain this remaining uncertainty in the $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$ reaction rate.

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