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Precision measurements of ^{20}Na, ^{24}Al, ^{28}P, ^{32}Cl, and ^{36}K for the rp-process

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Explosive hydrogen burning is expected to occur in classical novae and type I x-ray bursts at temperatures up to 2 GK. Energy generation and nucleosynthesis in these events depend on the thermonuclear rates of radiative proton capture reactions involving unstable reactants. For example, the ^{19}Ne$(p,\gamma)^{20}$Na, ^{23}Mg$(p,\gamma)^{24}$Al, ^{27}Si$(p,\gamma)^{28}$P, ^{31}S$(p,\gamma)^{32}$Cl, and ^{35}Ar$(p,\gamma)^{36}$K reaction rates are each expected to be dominated by one or two narrow, isolated resonances whose properties must be determined experimentally. First and foremost, the resonance energies must be known in order to approximate their contributions to the reaction rate and facilitate direct measurements with radioactive ion beams. By preparing thin ion implanted carbon foil targets at the University of Washington and measuring the ^{20}Ne(^{3}He,t)^{20}Na, ^{24}Mg(^{3}He,t)^{24}Al, ^{28}Si(^{3}He,t)^{28}P, ^{32}S(^{3}He,t)^{32}Cl, and ^{36}Ar(^{3}He,t)^{36}K reactions on them at 32 MeV with the Munich Q3D spectrograph, we have measured the ground state masses of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl and excitation energies in ^{32}Cl and ^{36}K to precisions on the order of 1 keV. We discuss our improvements on the thermonuclear rates of the ^{23}Mg$(p,\gamma)^{24}$Al and ^{35}Ar$(p,\gamma)^{36}$K reactions.

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1. Introduction

A knowledge of thermonuclear radiative proton capture reaction rates is needed to model energy generation and nucleosynthesis during explosive hydrogen burning in classical novae and type I x-ray bursts. The reactions on the even-Z, $T_z = -1/2$, $A = 19, 23, 27, 31$, and 35 nuclei have low Q values and therefore each reaction rate is dominated by one or two resonances whose contributions must be determined experimentally. Most importantly, the resonance energies must be known in order to facilitate indirect estimates of, and direct measurements of, the corresponding resonance strengths. We studied the ^{20}Ne(^{3}He,t)^{20}Na, ^{24}Mg(^{3}He,t)^{24}Al, ^{28}Si(^{3}He,t)^{28}P, ^{32}S(^{3}He,t)^{32}Cl, and ^{36}Ar(^{3}He,t)^{36}K reactions to determine resonance energies in the ^{19}Ne$(p,\gamma)^{20}$Na, ^{23}Mg$(p,\gamma)^{24}$Al, ^{27}Si$(p,\gamma)^{28}$P, ^{31}S$(p,\gamma)^{32}$Cl, and ^{35}Ar$(p,\gamma)^{36}$K reactions, respectively, using the relation $E_r = E_x - Q$.

2. Targets

Targets of ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, and ^{36}Ar were prepared at the University of Washington by implanting 3 - 6 μg/cm^2 of each of these ions into separate 30 μg/cm^2 natural-carbon foils [1]. For each target, four or six layers of material were deposited at different depths inside the foil by implanting at two or three different energies in equal amounts through each side of the foil. This produced a depth distribution of implanted material that was symmetric about the middle of the foil. Transverse uniformity was achieved by magnetically rastering the ion beam. This technique produced targets that were nearly identical to each other in thickness and profile despite the unique chemical properties of each element. For example, it prevented excessive oxidation in the case of Mg, eliminated the usual need for a chemical compound target in the case of S, and made the noble-gas element targets commensurate with the others. In addition, this technique produced isotopically pure targets, eliminating any background that would have otherwise been present from the isotopes ^{21,22}Ne, ^{25,26}Mg, ^{29,30}Si, ^{33,34,36}S, and ^{38,40}Ar. Employing such similar targets minimized the systematic uncertainties associated with target characterization.

3. Experiment

A $\approx$ 400-enA, 32-MeV ^{3}He^{2+} beam [2] was provided by the tandem van de Graaff accelerator at Maier Leibnitz Laboratorium and used to bombard each of the ion-implanted carbon-foil targets individually. Tritons from the (^{3}He,t) reactions on these targets were momentum analyzed using the Munich Q3D magnetic spectrograph and detected at the focal plane of the spectrograph using a gas proportional counter backed by a scintillator. Separate measurements were taken with the spectrograph positioned at 10° and 20°.

4. Results and Conclusions

Peaks in the focal-plane position spectra corresponding to well known levels in the product nuclei ^{20}Na, ^{24}Al, ^{28}P, and ^{36}K were used for momentum calibration of the focal plane at each angle. The masses of ^{20}Na, ^{24}Al, ^{28}P were allowed to vary in the fits and the measured masses were

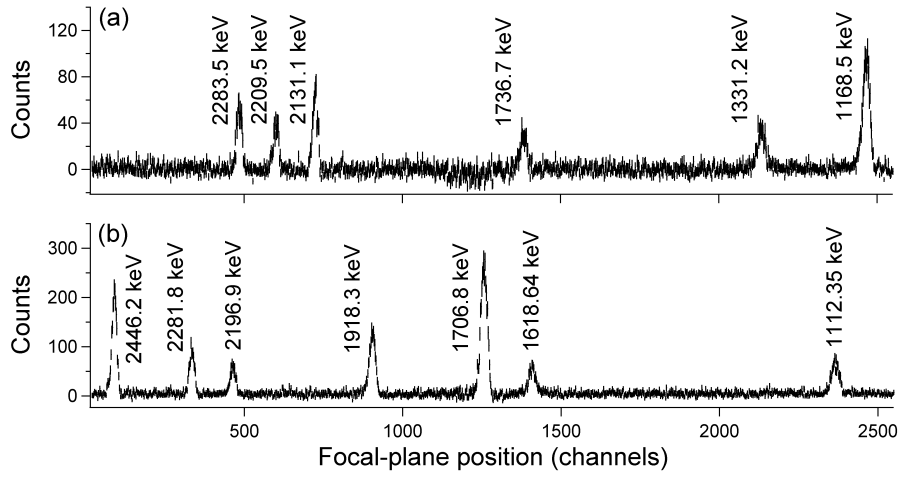

Figure 1: Q3D focal-plane position spectra of tritons from the (^{3}He,t) reactions leading to (a) ^{32}Cl and (b) ^{36}K, acquired using a beam energy of 32 MeV at $\theta_{lab} = 10^\circ$. Peaks are labeled by excitation energy.

determined by minimizing χ^2, with the ^{36}Ar(^{3}He,t)^{36}K reaction providing a calibration standard. A single ^{32}Cl peak was then used together with the fits to determine the mass of ^{32}Cl. This procedure led to mass measurements of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl with precisions of 1.1 or 1.2 keV [4]. All of these values represent substantial improvements in precision over the 2003 Atomic Mass Evaluation [3] and the ^{24}Al and ^{28}P masses were found to be inconsistent with Ref. [3] by $> 3\sigma$.

The excitation-energy measurements were mostly derived from the same spectra that were used for the mass measurements (Figure 1). Excitation energies in ^{32}Cl and ^{36}K were determined by fitting each triton peak with a Gaussian function, extracting the centroid, and applying the same focal-plane momentum calibrations that were used for the mass measurements [5].

Combining our new ^{23}Mg$(p,\gamma)^{24}$Al Q value of 1863.0(14) keV with the ^{24}Al excitation energy from the (^{16}O,$2n\gamma$) measurement of Ref. [6] yields an indirectly determined center of mass energy of 482.1(20) keV for the lowest-energy resonance, which dominates the reaction rate at nova temperatures. Similarly, the new ^{28}P mass may be used to recalibrate the (^{3}He,t) work of Ref. [7] yielding an indirectly determined energy of 485(5) keV. These values are consistent with the direct value of $485.7^{+1.3}_{-1.8}$ keV from Ref. [8], but inconsistent with the previous indirectly determined value of 473(3) keV [6]. Our measurement resolves the discrepancy between the directly [8] and indirectly [7, 6] determined values by confirming the assertion in Ref. [8] that the AME03 [3] value for the mass excess of ^{24}Al is likely at fault.

Due to the problems with the anticipated resonance energy, the ^{23}Mg beam energy was not optimal during the direct measurement [8] and the resonance was not necessarily activated in the constant-pressure region of the gas target. Consequently, a two-dimensional probability density function (PDF) in $(E_r, \omega\gamma)$ space was extracted (Fig. 2(a)) with a fairly large region of possible values for $\omega\gamma$. Folding our new indirectly determined value for E_r with the PDF from Ref. [8] yields the new PDF shown in Fig. 2(b). Our new constraint has nearly eliminated one mode of the bimodal distribution, which corresponded to a higher resonance strength, yielding a new value of $\omega\gamma = 26.6^{+15.4}_{-7.0}$ meV that may be compared with the previous value $\omega\gamma = 37.8^{+20.5}_{-15.4}$ meV. It is

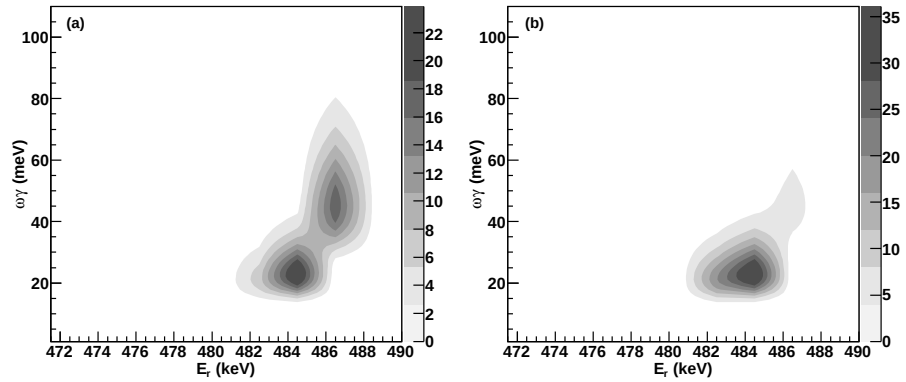

Figure 2: Two-dimensional probability density functions (PDFs) for the strength and c.m. energy of the lowest energy resonance in the ^{23}Mg$(p,\gamma)^{24}$Al reaction. Panel (a) is the result from Ref. [8]. Panel (b) is a new PDF derived by combining the PDF from panel (a) with the present constraint on resonance energy, $E_r = 482.1(20)$ keV.

noteworthy that our value for $\omega\gamma$, based on a direct measurement, is in excellent agreement with the indirectly determined values of 27 and 25 meV that were based on properties of the ^{24}Na mirror level [9] and the shell model [10], respectively.

We have reduced the uncertainties in the excitation energies of known ^{36}K levels by at least an order of magnitude, and find the excitation energies to be higher than the values from the (^{3}He,t) measurements of Ref. [11] by 12 to 37 keV. We find a new level in ^{36}K at $E_x = 2196.9(7)$ keV that corresponds to a ^{35}Ar$(p,\gamma)^{36}$K resonance energy of 538.5(9) keV. This new level together with the new excitation energies yields optimal analog assignments that are different than those used in Ref. [12] to calculate the commonly adopted thermonuclear ^{35}Ar$(p,\gamma)^{36}$K reaction rate.

The new results on ^{36}K have an interesting overall effect on the ^{35}Ar$(p,\gamma)^{36}$K reaction rate. The energies of the two dominant s-wave resonances have moved toward each other, such that both contributions to the ^{35}Ar$(p,\gamma)^{36}$K rate are amplified at the temperatures relevant to explosive hydrogen burning. As a result, the new central values for the reaction rate are higher than the previous estimates [12] by up to a factor of seven in the temperature range of interest to explosive hydrogen burning (Figure 3). The new rate is above the upper uncertainty bounds prescribed in Ref. [12] over a wide range of temperatures, and the uncertainties have been improved appreciably.

In the recent literature [13, 12, 14, 15] contradictory conclusions are reached about the importance of the ^{35}Ar$(p,\gamma)^{36}$K reaction to explosive hydrogen burning. On one extreme, this reaction is argued to be crucial to explosive hydrogen burning and recommendations are made to measure it directly using radioactive ion beams [13, 14, 15]. On the other extreme, it is argued that varying the rate of this reaction by a factor of 10 from the 1999 rate has only minor effects on nuclear energy generation and final abundances in novae and type I x-ray bursts, and that it was already sufficiently well understood at that time [12]. One recent study found that variations in the ^{35}Ar$(p,\gamma)^{36}$K reaction rate by only a factor of three could affect the overall energy generation type I x-ray bursts significantly [16]. More astrophysical modeling appears to be needed before a consensus is reached on the importance of this reaction to explosive hydrogen burning. Whether the ^{35}Ar$(p,\gamma)^{36}$K re-

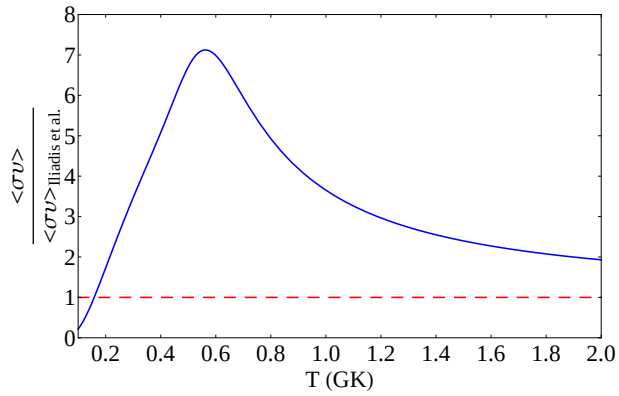

Figure 3: Ratios of the thermonuclear ^{35}Ar$(p,\gamma)^{36}$K reaction rates from the present work (solid, blue line) and Ref. [12] (dashed, red line) to the rates from Ref. [12].

action turns out to be crucial or not, we have made substantial changes and improvements to its thermonuclear rate and set the stage for a direct measurement.

The present results highlight the crucial role of stable ion beam facilities in determining thermonuclear radiative proton capture reaction rates on unstable targets via indirect measurements of resonance energies.

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