PROCEEDINGS OF SCIENCE

Measurement of ^{23}Mg$+p$ resonance energies

Dale Visser,[a] **Chris Wrede**[*],[b,c] **Jac Caggiano,**[b] **Jason Clark,**[b] **Catherine Deibel,**[b] **Rachel Lewis,**[b] **Anuj Parikh,**[b] **and Peter Parker**[b]
[a] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[b] *Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06520, USA*
[c] *Department of Physics, University of Washington, Seattle, WA 98195, USA*

E-mail: `dale.visser@mailaps.org`, `wrede@u.washington.edu`, `jac.caggiano@pnl.gov`, `jclark@phy.anl.gov`, `deibel@phy.anl.gov`, `rachel.lewis@gmail.com`, `xrayburst@gmail.com`, `peter.parker@yale.edu`

Two inconsistent sets of ^{24}Al excitation-energy measurements have been used to determine resonance energies for the ^{23}Mg$(p,\gamma)^{24}$Al reaction. This discrepancy results in a factor of five variation in the calculated thermonuclear ^{23}Mg$(p,\gamma)^{24}$Al reaction rate at $T = 0.25$ GK, and presents a challenge to an imminent radioactive ion-beam measurement of this reaction that will rely on precisely known resonance energies. We have measured the ^{24}Mg(^{3}He,t)^{24}Al reaction using a 30-MeV ^{3}He beam from the tandem Van de Graaff accelerator at Yale University's Wright Nuclear Structure Laboratory. The Yale Enge magnetic spectrograph was used to momentum-analyze reaction products; a position-sensitive ionization drift chamber backed by a scintillator at the focal plane was used to identify tritons and measure the excitation energies of corresponding states in ^{24}Al. We find good general agreement with one of the two previous sets of measurements and determine an energy of $E_{c.m.} = 474(6)$ keV for what is thought to be the most important ^{23}Mg$(p,\gamma)^{24}$Al resonance astrophysically [the previous measurements yielded values of $E_{c.m.} = 499(5)$ and 458(10) keV]. A more precise thermonuclear ^{23}Mg$(p,\gamma)^{24}$Al rate will help to constrain the determination of nuclear flow out of the NeNa cycle, and production of $A \geq 20$ nuclides, in explosive hydrogen burning over a temperature range $0.2 < T < 1.0$ GK.

10th Symposium on Nuclei in the Cosmos
July 27 - August 1, 2008
Mackinac Island, Michigan, USA

PoS(NIC X)164

---

[*] Speaker.

1. Introduction

For decades, the $^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$ reaction [$Q_{p\gamma} = 1872.1(31)$ keV] [1] has been known [2, 3] to be a potential means for breaking out of the NeNa cycle to heavier nuclear species in explosive hydrogen burning. At stellar temperatures $T < 0.1$ GK, ^{23}Mg can be produced by the NeNa cycle, which is closed by its β^+ decay ($t_{1/2} = 11.3$ s) to ^{23}Na, followed by the $^{23}\mathrm{Na}(p,\alpha)^{20}\mathrm{Ne}$ reaction. At higher temperatures the $^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}(\beta^+\nu_e)^{24}\mathrm{Mg}$ sequence is expected to become competitive with the β^+ decay of ^{23}Mg, providing a nucleosynthetic path to heavier species together with the $^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$ reaction. Models of explosive hydrogen-burning environments, therefore, require an accurate determination of the $^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$ thermonuclear reaction rate to constrain the expected production of $A \geq 20$ elements.

Wallace and Woosley [2] initially evaluated the $^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$ reaction rate based on the contribution of a single resonance. By considering a direct-capture process and two additional resonances, Wiescher *et al.* [3] improved upon the calculation of Ref. [2]. Kubono *et al.* [4] then studied the $^{24}\mathrm{Mg}(^3\mathrm{He},t)^{24}\mathrm{Al}$ reaction at a beam energy of 60 MeV, and reevaluated the $^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$ reaction rate using their experimental constraints on the spins and excitation energies (±10 keV) of four ^{24}Al levels. However, a prior measurement of the $^{24}\mathrm{Mg}(^3\mathrm{He},t)^{24}\mathrm{Al}$ reaction at 81 MeV by Greenfield *et al.* [5] yielded ^{24}Al excitation energies with comparable precision that were systematically higher by ≈ 20 to 50 keV. Most recently, Herndl *et al.* [6] reevaluated the $^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$ reaction rate using all available (inconsistent) experimental information on ^{24}Al excitation energies. It was concluded that a single resonance at $E_r = 478(20)$ keV [$E_x(^{24}\mathrm{Al}) = 2349(20)$ keV] with $J^\pi = 3^+$ determines the $^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$ reaction rate for temperatures $0.2 < T < 1.0$ GK. The large uncertainty in this resonance energy is due to the inconsistent (^{3}He,t) measurements mentioned above, and leads to a factor of 5 variation in the reaction rate at $T = 0.25$ GK – a typical nova peak temperature – because of its exponential dependence on E_r. A better determination of this resonance energy would reduce the related uncertainty in the reaction rate, and aid future experiments that attempt to measure resonance strengths.

2. Experiment

To resolve the inconsistencies in the measured level energies of ^{24}Al, the energies of known ^{23}Mg+p resonances have been remeasured, and new resonances searched for at the Wright Nuclear Structure Laboratory at Yale University using the $^{24}\mathrm{Mg}(^3\mathrm{He},t)^{24}\mathrm{Al}$ reaction [13]. Calibrations were measured during the same set of runs via the $^{28}\mathrm{Si}(^3\mathrm{He},t)^{28}\mathrm{P}$ reaction. The Yale tandem Van de Graaff accelerated a beam of ^{3}He ions to a fixed energy of 30 MeV, which impinged on a natural MgO (267 μg/cm^2) or Si (302 μg/cm^2) target foil. An Enge magnetic spectrograph accepted light reaction products through a rectangular aperture, and momentum analyzed them. Tritons were focused on a detection plane spanned by a position-sensitive ionization drift chamber [7] over radii $70 < \rho < 87$ cm. It measured the position and the energy loss, ΔE, of the particles. The residual energy, E, of particles was deposited into a plastic scintillator. The $^{24}\mathrm{Mg}(^3\mathrm{He},t)^{24}\mathrm{Al}$ and $^{28}\mathrm{Si}(^3\mathrm{He},t)^{28}\mathrm{P}$ reactions were measured over a five-day period using a fixed magnetic-field strength of $B = 11$ kG, at spectrograph angles of $\theta_{lab} = 11^\circ$, 17.5°, 21°, and 26°, and with horizontal and vertical entrance-aperture settings of $\Delta\theta = \pm 30$ mrad and $\Delta\phi = \pm 40$ mrad, respectively.

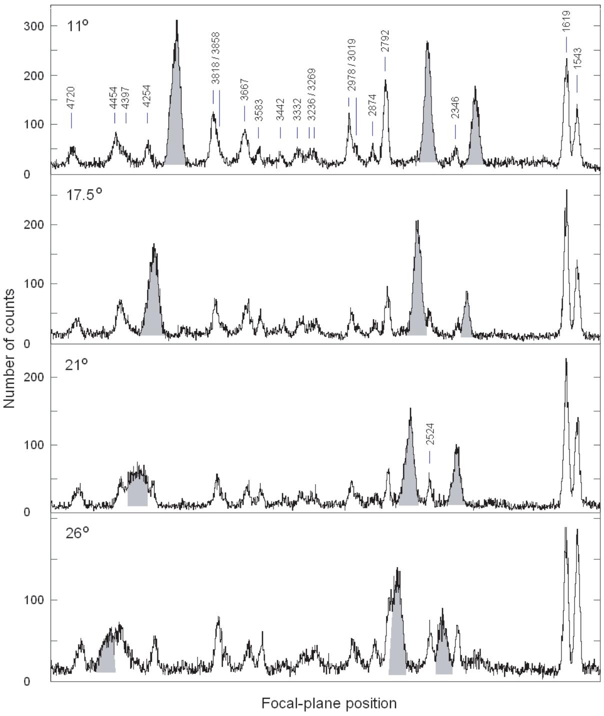

Figure 1: Focal-plane triton spectra from the ^{24}Mg(^{3}He,t)^{24}Al reaction at 30 MeV, corresponding to $1500 \lesssim E_x(^{24}\mathrm{Al}) \lesssim 4800$ keV determined in the present work (labeled). The spectra were acquired with $\theta_{lab} = 11°, 17.5°, 21°$ and 26° from top to bottom, and are shown shifted relative to one another so that the ^{24}Al excitation-energy scale is roughly matched. Background peaks of ^{12}N (g.s.), ^{16}F (721 keV) and ^{16}F (424 keV), from left to right, are shaded in gray.

3. Analysis

Particle groups (p,d,t,α) were identified by combining focal-plane position (∼momentum), ΔE, and E in 2D histograms. Tritons were selected cleanly by sorting the data offline through software gates in these histograms, and spectra of focal-plane position were plotted for the ^{24}Mg(^{3}He,t) ^{24}Al (Fig. 1) and ^{28}Si(^{3}He,t)^{28}P reactions at each spectrograph angle. Background peaks from the ^{16}O(^{3}He,t)^{16}F and ^{12}C(^{3}He,t)^{12}N$^{g.s.}$ reactions were identified kinematically in the ^{24}Al spectra. These were expected, and the spectrograph angles were chosen so that the locations of the background peaks would allow a clear observation of each astrophysically important ^{24}Al level at a minimum of three angles.

The spectra were analyzed using a least-squares fit of multiple gaussian functions of typical FWHM $\approx$ 40 keV, from which peak centroids were determined. Isolated, easily identifiable peaks corresponding to known excited states [8] of ^{28}P with $E_x < 5$ MeV, and with uncertainties as low as ±0.5 keV (but typically ±5 keV) were used for momentum calibration of the focal plane at each spectrograph angle. A universal uncertainty of ±3 keV was determined from a combination of statistical uncertainty and reproducibility. In addition, there was a ±3-keV uncertainty from the uncertainty in relative ^{24}Mg to ^{28}Si target thickness, and a ±4.1-keV uncertainty from the relative Q values of the ^{24}Mg(^{3}He,t)^{24}Al and ^{28}Si(^{3}He,t)^{28}P reactions, arising mostly from the uncertainties in the masses of ^{24}Al (±2.8 keV/c^2) and ^{28}P (±3 keV/c^2) [1]. Under the assumptions that the above uncertainties are mutually independent and gaussian distributed, they may be added in quadrature, which results in a ±6-keV uncertainty. Resonance energies for the ^{23}Mg$(p,\gamma)^{24}$Al reaction were determined from the relation $E_r = E_x - Q_{p\gamma}$.

4. Results

The uncertainties in E_x and E_r have been reduced by a factor of ≈ 3 over the most recent compilations [9, 6]. Much of the prior uncertainty was due to the systematically inconsistent results of Kubono *et al.* [4] and Greenfield *et al.* [5]. The present measurements are in good agreement with those of Ref. [4], and poor agreement with Ref. [5] which makes the existence of an unaccounted-for systematic error in Ref. [5] probable. The excitation energy of (what is thought to be) the most important resonance astrophysically was measured in the present work to be 2346(6) keV, in disagreement with the measurements of *both* Ref. [4] [2328(10) keV] and Ref. [5] [2369(4) keV]. The disagreement with Ref. [4] is somewhat surprising since the error bars in the present work overlap with those in Ref. [4] for every other cleanly resolved level.

Adopting the J^π assignments of Ref. [6], the ^{23}Mg$(p,\gamma)^{24}$Al reaction rate was recalculated using the presently determined resonance energies, and proton widths scaled accordingly. In Fig. 2 the ratio of the ^{23}Mg$(p,\gamma)^{24}$Al reaction rate from the present work to that determined in Ref. [6] is plotted for stellar temperatures $0.15 < T < 2.0$ GK. The uncertainty bands for both rates were derived by using the upper and lower limits of the resonance-energy uncertainties, and show that the rates are generally in agreement. The present measurements increase the recommended rate by $5-20$ % in the temperature range $0.19 < T < 1.9$ GK, and the 3-fold reduction in resonance-energy uncertainties reduces the related uncertainty in the reaction rate by a factor ≈ 3 in the temperature range $0.2 < T < 2.0$ GK (Fig. 2). The $E_r = 474$-keV resonance dominates the reaction rate for $0.2 < T < 1.9$ GK. Below 0.2 GK, the rate is dominated by direct capture. The resonance measured to have $E_r = 652(6)$ keV makes contributions of $1, 10, 22, 35,$ and 40 % to the rate at temperatures $T = 0.38, 0.68, 1.0, 1.5,$ and 2.0 GK, respectively. The $E_r = 920$ and 1002-keV resonances contribute $< 8\%$ and $< 2\%$ respectively to the rate for $T < 2.0$ GK. The present reduction in the uncertainty of the ^{23}Mg$(p,\gamma)^{24}$Al reaction rate, which is now certainly dominated by the unmeasured resonance strengths, will constrain the determination of nuclear flow out of the NeNa cycle during explosive hydrogen burning for $T < 1$ GK.

A recent precision measurement [10] using Gammasphere resulted in a complete ^{24}Al level scheme up to the $E_x = 2345.1(14)$-keV level. The Gammasphere work confirmed our measurement of $E_x = 2346(6)$ keV, which was not in good agreement with previous measurements [4, 5], and improved upon its precision. We used the 1617.0(8)- and 2354.1(14)-keV [$E_r = 473(3)$ keV] level energies from Ref. [10] to effectively eliminate the ±5.1-keV systematic uncertainty in our measurement, and adjust our 2524(6)-keV measurement of the excitation energy of the second level above the proton threshold in ^{24}Al with a result of 2523(3) keV [14]. This corresponds to a resonance energy of 651(4) keV. A measurement of its strength (and the strength of the 473-keV resonance) using the DRAGON facility at TRIUMF-ISAC is scheduled that will use a mixed ^{23}Na/^{23}Mg beam with an expected intensity ratio of 500/1 [12]. A resonance in the ^{23}Na$(p,\gamma)^{24}$Mg reaction at $E_{lab}(p) = 676.7(4)$ keV [8] [$E_r = 648.3(4)$ keV] with a strength $\omega\gamma = 640$ meV (to be compared with the predicted strength $\omega\gamma = 58$ meV [6, 13] of the 651-keV ^{23}Mg$(p,\gamma)^{24}$Al

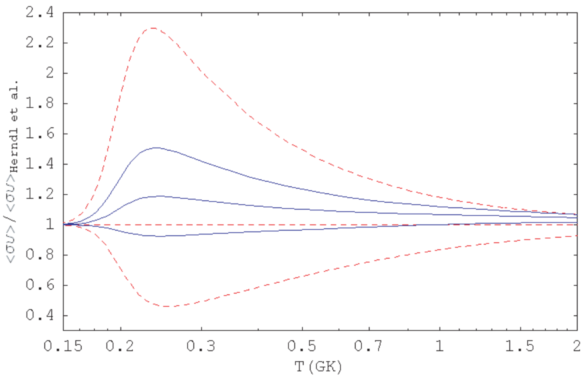

Figure 2: Ratio of the ^{23}Mg$(p,\gamma)^{24}$Al rate from the present work (solid blue) to that of Herndl *et al.* [6] (dashed red). The uncertainty bands represent only the uncertainty in the rate derived by taking upper and lower limits on E_r.

resonance) will present a challenge to that experiment. The more precise energy for the 651(4)-keV resonance will therefore be useful to its planning and interpretation.

5. Acknowledgments

We gratefully acknowledge the contributions of the WNSL staff. This work was supported by the U.S. Department of Energy under grants No. DE-FG02-91ER-40609 and DE-FG02-97ER-41020.

References

[1] G. Audi *et al.*, Nucl. Phys. **A729**, 337 (2003).

[2] R. K. Wallace and S. E. Woosley, Astrophys. J. Suppl. Ser. **45**, 389 (1981).

[3] M. Wiescher *et al.*, Astron. Astrophys. **160**, 56 (1986).

[4] S. Kubono *et al.*, Nucl. Phys. **A588**, 521 (1995).

[5] M. B. Greenfield *et al.*, Nucl. Phys. **A524**, 228 (1991).

[6] H. Herndl *et al.*, Phys. Rev. C **58**, 1978 (1998).

[7] A. Parikh, Ph.D. Thesis, Yale University, 2006.

[8] P. M. Endt, Nucl. Phys. **A521**, 1 (1990).

[9] P. M. Endt, Nucl. Phys. **A633**, 1 (1998).

[10] G. Lotay *et al.*, Phys. Rev. C **77**, 042802(R) (2008).

[11] D. A. Hutcheon *et al.*, Nucl. Instrum. Methods A **498**, 190 (2003).

[12] C. Vockenhuber, U. Greife *et al.*, TRIUMF EEC proposal S810 (unpublished).

[13] D. W. Visser *et al.*, Phys. Rev. C **76**, 065803 (2007).

[14] D. W. Visser *et al.*, Phys. Rev. C **78**, 028802 (2008).