PROCEEDINGS OF SCIENCE

Mass measurements of ^{22}Mg and ^{26}Si via (p,t) reactions and Penning traps

J. A. Clark[1,2,3], A. Parikh[1], F. Buchinger[4], J. A. Caggiano[1], J. E. Crawford[4], C. Deibel[1], J. P. Greene[3], S. Gulick[4], J. C. Hardy[5], A. A. Hecht[3,6], J. K. P. Lee[4], A. F. Levand[3], R. Lewis[1], B. F. Lundgren[3], P. D. Parker[1], G. Savard[3], N. D. Scielzo[3], K. S. Sharma[2], I. Tanihata[3], W. Trimble[3], J. C. Wang[2,3], Y. Wang[2,3], C. Wrede[1], and Z. Zhou[3]

[1] *Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06520, USA*
[2] *Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB R3T 2N2, Canada*
[3] *Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[4] *Department of Physics, McGill University, Montreal, PQ H3A 2T8, Canada*
[5] *Cyclotron Institute, Texas A&M University, College Station, TX 77843-3366, USA*
[6] *Department of Chemistry, University of Maryland, College Park, MD 20742, USA*

Models of astronomical phenomena require a number of nuclear physics inputs to characterize the contribution of these events to the production of the observed elements. Masses and the excitation energy levels, spins, and partial and total decay widths of states are particularly important. Reported here are the mass measurements of ^{22}Mg and ^{26}Si which are required to understand the contribution of novae to the observed (or unobserved) galactic abundances of ^{26}Al and ^{22}Na. A description of the Canadian Penning trap mass spectrometer and Yale spectrograph which were used to determine these masses is presented and is followed by a brief description of the astrophysical consequences.

International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX
June 25-30 2006
CERN, Geneva, Switzerland

PoS(NIC-IX)081

1. Introduction

The success of models used to describe astronomical phenomena such as novae, x-ray bursts, and supernovae is determined by their ability to replicate the observational signatures of these events. Two examples of such observables are the abundances of the isotopes ^{26}Al and ^{22}Na which are detected by the β-delayed 1.809 MeV (^{26}Al, $t_{1/2}$=7.2$\times$10^5 yr) and 1.275 MeV (^{22}Na, $t_{1/2}$=2.6 yr) γ rays from the decay of these isotopes [1]. The dominant nuclear uncertainties in the contribution of novae to the abundances of these nuclides stem from uncertainties in the ^{25}Al$(p,\gamma)^{26}$Si and ^{21}Na$(p,\gamma)^{22}$Mg reaction rates [2, 3, 4]. Since the resonant components of the reaction rates depend exponentially on the resonance energy, $E_R = E_x - Q_o$, either the direct determination of the resonance energy or the indirect determination through measurements of the excitation energy, E_x, and ground-state Q_o values is necessary. We report here the measurements made of the masses of ^{22}Mg and ^{26}Si which are used to improve the precision of the required Q_o values.

The current mass evaluation (AME) [5], used two measurements published in 1974 [6, 7] to arrive at -397.0(13) keV for the mass excess of ^{22}Mg. Since the AME was published, a direct measurement [8] of the resonance energy of the 2^+ state had suggested that the mass excess of ^{22}Mg was 6 keV less than the value published in the AME. In addition, one of the measurements used in the evaluation [6] had been revised to account for the change in the Q value of the ^{16}O$(p,t)^{14}$O reaction [9] which was used as a calibration Q value during the original measurement [10]. The net effect was a decrease in the mass excess of ^{22}Mg by 3 keV which was insufficient to resolve the 6 keV difference noted in Ref. [8] and prompted independent measurements of the ^{22}Mg mass and the energy of the 2^+ state. As for ^{26}Si, only one measurement of its mass [6] was considered in the latest AME. Since recent studies of the structure of ^{26}Si above the ^{25}Al + p threshold have been made [11, 12, 13] and a measurement has been proposed at the ISAC facility at TRIUMF to directly study the ^{25}Al$(p,\gamma)^{26}$Si reaction [14], a remeasurement of the ^{26}Si mass is warranted.

2. The Canadian Penning trap mass spectrometer

The Canadian Penning Trap (CPT) mass spectrometer [15, 16] makes precise mass measurements of nuclides created through fusion-evaporation reactions using beams from the ATLAS facility at Argonne National Laboratory. Ions of ^{22}Mg were created with a 3.5 MeV/nucleon ^{20}Ne beam incident upon a cryogenic ^{3}He target held at 700 mbar with entrance and exit windows of 1.3 mg cm^{-2} Ti. The ^{22}Mg ions produced in the reaction were focused and separated from the primary beam with a combination of a magnetic triplet, a velocity filter, and an Enge split-pole magnetic spectrograph [17]. A tuneable degrader, positioned at the focal plane of the spectrograph, reduced the energy of the ions before they entered a gas catcher [18] where the ions were thermalized in 200 mbar of purified helium gas. The ions were extracted from the gas catcher via a combination of gas flow and electric fields and were guided through an ion cooler towards an isotope separator as the helium was pumped away. Before they entered the isotope separator, the ions were accumulated within a small trapping potential and were periodically ejected. In this way the continuous ion beam was converted into a pulsed ion beam. The ion bunches were then captured in the isotope separator, a gas-filled Penning trap (B $\sim$ 1 T), where they were subjected to a mass selective cooling process [19] before they were transferred efficiently to a linear RF quadrupole (RFQ) ion trap with standard

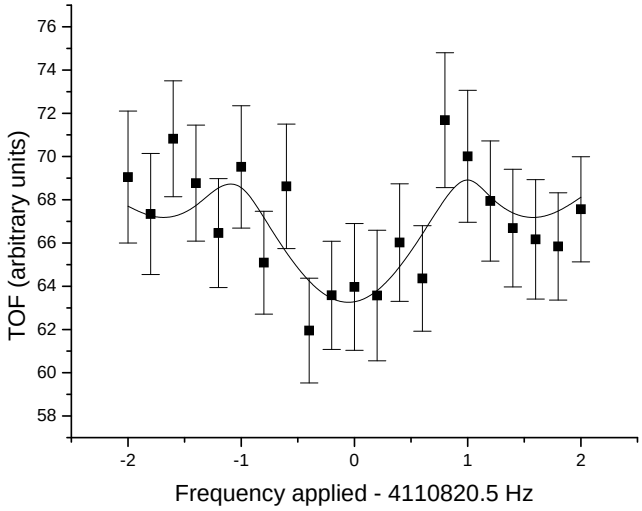

Figure 1: TOF spectrum of $^{22}Mg^{+}$ obtained with the Canadian Penning trap mass spectrometer.

ion optics. During transport, a fast voltage pulse, applied to one of the beam transport elements, efficiently suppressed isotopes outside a restricted range of masses before they were transmitted to the RFQ. The RFQ was used to accumulate several bunches of ions and cool the ions prior to their injection into the precision Penning trap (B $\sim$ 5.9 T) for the mass measurement. The mass, m, of the ions in the Penning trap was determined by measuring their cyclotron frequency, $\omega_c = qB/m$, where q is the charge of the trapped ion. The magnetic field strength, B, was periodically calibrated by measuring the cyclotron frequencies of $^{20}Ne^{+}$, $^{21}Ne^{+}$, $^{22}Ne^{+}$ and H_3O^{+}, whose masses are well known. The cyclotron frequency itself is measured by using the time of flight (TOF) method [20].

The mass excess of ^{22}Mg, as determined with measurements using the CPT [21], is -399.73(67) keV. A spectrum consisting of a subset of the data is shown in Fig. 1. Although this precise mass measurement agrees well with the recent results from an independent Penning trap apparatus [22], only 3 keV of the 6 keV discrepancy suggested by Ref. [8] is accounted for. The remaining 3 keV was removed following a more accurate measurement of the 2^{+} energy level [23]. All the recent measurements now yield consistent results, including those conducted with the Yale spectrograph [ΔM = -400.5(1.0) keV] [24] discussed below.

3. The Yale spectrograph

The Yale spectrograph sits at the end of a beamline in the tandem Van de Graaff accelerator facility of the Wright Nuclear Structure Laboratory at Yale University. Located at the focal plane of the Enge split-pole spectrograph [17] is a position-sensitive gas ionization drift chamber followed by a scintillator. The drift chamber is filled with typically 200 mbar of isobutane which is contained with two 0.25-mil aluminized-mylar windows. A uniform electric field is provided by a series of 10 equally spaced wires which form a voltage divider between a 0.25-inch aluminum plate (the cathode) held at negative potential and a grounded Frisch grid. High voltage (about 1500 V) is

applied to two sets of three wires each which lie above the Frisch grid to draw the electrons from the detector volume. The position of the ions passing through the detector volume is determined with 0.09”-wide by 1.4”-long lead-coated copper pick-up pads which lie above the high-voltage wires. A total of 220 pads are in series along the length of the wires and are separated by delay chips providing a delay of 5 ns between adjacent pads. As ions pass through the detector volume, the energy loss is detected by the cathode and the position of the ion along the focal plane detector is determined by the relative delay between the signals detected at opposite ends of the series of pick-up pads. These signals, in addition to the residual energy deposited in the scintillator, provide a means to select the particles of interest. Further detail is provided in Ref. [25].

Measurements of the mass of ^{22}Mg and ^{26}Si were made by studying (p,t) reactions between a 33 MeV proton beam and targets of ^{28}SiO (65 ug/cm^2 with a gold flash) and ^{24}MgO (67 ug/cm^2 on a 15 ug/cm^2 carbon backing). The energies of the tritons corresponding to the ground states of ^{26}Si, ^{22}Mg, and ^{14}O were used in conjunction with the beam energy and scattering angle to obtain Q_o values of the reactions after performing a momentum calibration of the focal plane with (p,d) reactions from both a 360 ug/cm^2 ^{25}MgO and a 140 ug/cm^2 Al target.

The top left spectrum in Fig. 2 shows the triton momenta corresponding to different states of ^{22}Mg from the ^{24}Mg(p,t) reaction with the Enge spectrograph set at 25°. For the same spectrograph angle, the states of ^{26}Si are seen in the bottom left of the same figure. The data shown represent 20 hours (top) and 13 hours (bottom) of collection with a proton beam intensity averaging 20 nA. In the case of the ground state of ^{22}Mg, a resolution of 10 keV was achieved.

Agreement between the ^{22}Mg results obtained with the Yale spectrograph and the compilation of recent measurements provides confidence in the ^{26}Si mass determined by the Yale apparatus. The result [ΔM = -7139.5(1.0) keV], however, is in disagreement with the only measurement used in the AME [ΔM = -7145(3) keV] [6], even after it was corrected for changes in the calibration reaction resulting in a mass excess ΔM = -7145.5(30) keV [26].

With the mass of ^{26}Si as determined using the Yale spectrograph, the contributions to the total reaction rate of ^{25}Al$(p,\gamma)^{26}$Si at nova temperatures is shown in top right panel of Fig. 2 and is dominated by the 1^+ and 3^+ states. The bottom right panel shows the ratio of the resonant rate contributions determined with the ^{26}Si mass presented here to the rates calculated with the mass reported in the AME. More details are given in Ref. [24]. A reduction in the rate by as much as 30% for T > 0.2 GK is possible if the ^{26}Si mass reported in the AME is replaced by the results obtained with the Yale spectrograph. These results would be strengthened with additional measurements of ^{26}Si states above the ^{25}Al + p threshold and experimental determinations for the γ and proton partial decay widths of these states. An independent confirmation of the ^{26}Si mass is also desirable.

This work was supported by the U. S. Department of Energy, Nuclear Physics Division, under Contract W-31-109-ENG-38, and by the Natural Sciences and Engineering Research Council of Canada.

References

[1] M. Hernanz and J. José, New Astronomy Reviews **48**, 35 (2004).

[2] J. José *et al.*, Astrophys. J. **520**, 347 (1999).

[3] C. Iliadis *et al.*, Astrophys. J. Suppl. Ser. **134**, 151 (2001).

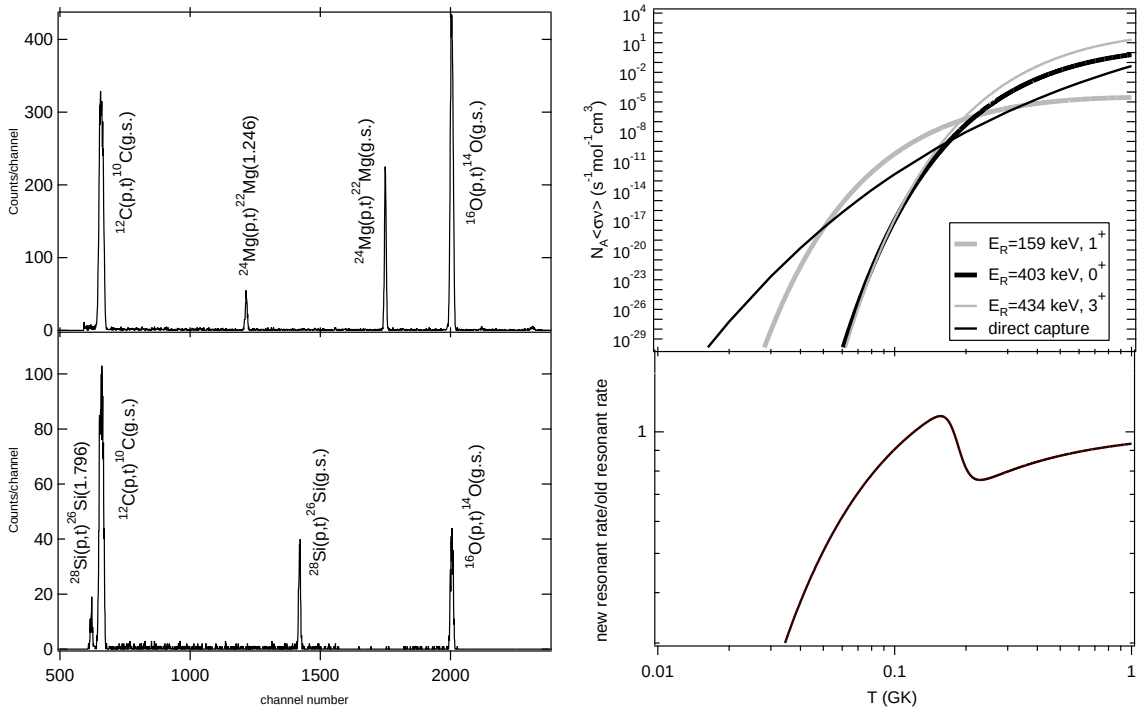

Figure 2: The left figure shows the triton momentum spectra at the focal plane of the Yale spectrograph for the ^{24}Mg$(p,t)^{22}$Mg reaction (top) and the ^{28}Si$(p,t)^{26}$Si reaction (bottom). Also note the peaks resulting from (p,t) reactions on the carbon and oxygen present in the targets. The top right figure shows the contributions to the total reaction rate of ^{25}Al$(p,\gamma)^{26}$Si with the ^{26}Si mass determined by the Yale spectrograph. The bottom right figure is a comparison, in terms of a ratio, between the total contribution to the resonant rate as calculated with the ^{26}Si mass determined with the Yale spectrograph to that determined with the ^{26}Si mass from the AME.

[4] C. Iliadis *et al.*, Astrophys. J. Suppl. Ser. **142**, 105 (2002).

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

[6] J. C. Hardy *et al.*, Phys. Rev. C **9**, 252 (1974).

[7] J. A. Nolen *et al.*, Nucl. Instrum. Methods **115**, 189 (1974).

[8] S. Bishop *et al.*, Phys. Rev. Lett. **90**, 162501 (2003).

[9] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).

[10] J. C. Hardy *et al.*, Phys. Rev. Lett. **91**, 082501 (2003).

[11] J. A. Caggiano *et al.*, Phys. Rev. C **65**, 055801 (2002).

[12] D. W. Bardayan *et al.*, Phys. Rev. C **65**, 032801 (2002).

[13] Y. Parpottas *et al.*, Phys. Rev. C **70**, 065805 (2004).

[14] A. A. Chen *et al.* (E922, proposal accepted by TRIUMF EEC).

[15] G. Savard *et al.*, Nucl. Phys. **A626**, 353 (1997).

[16] J. Clark *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 487 (2003).

[17] J. E. Spencer and H. A. Enge, Nucl. Instrum. Methods **49**, 181 (1967).

[18] G. Savard *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 582 (2003).

[19] G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).

[20] G. Gräff *et al.*, Z. Phys. A **297**, 35 (1980).

[21] G. Savard *et al.*, Phys. Rev. C **70**, 042501 (2004).

[22] M. Mukherjee *et al.*, Phys. Rev. Lett. **93**, 150801 (2004).

[23] D. Seweryniak *et al.*, Phys. Rev. Lett. **94**, 032501 (2005).

[24] A. Parikh *et al.*, Phys. Rev. C **71**, 055804 (2005).

[25] A. Parikh, Ph.D. thesis, Yale University (2006).

[26] J. C. Hardy and I. S. Towner, Phys. Rev. C **71**, 055501 (2005).