First direct mass measurement of the neutron-deficient nucleus ^{24}Al

U. Chowdhury,[1,2] K. G. Leach,[1,3,4,*] C. Andreoiu,[3] A. Bader,[1,5] M. Brodeur,[6] A. Chaudhuri,[1,†] A. T. Gallant,[1,7] A. Grossheim,[1] G. Gwinner,[2] R. Klawitter,[1,8] A. A. Kwiatkowski,[1,‡] A. Lennarz,[1,9] T. D. Macdonald,[1,7] J. Pearkes,[7] B. E. Schultz,[1,§] and J. Dilling[1,7]

[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[2]*Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba R3T 2N2 Canada*
[3]*Department of Chemistry, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*
[4]*Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA*
[5]*École des Mines de Nantes, 4 rue Alfred Kastler, B.P. 20722, F-44307, Nantes, France*
[6]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[7]*Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
[8]*Max-Planck-Institut für Kernphysik, Saupfercheckweg, D-69117 Heidelberg, Germany*
[9]*Institut für Kernphysik, Westfalische Wilhelms-Universität, D-48149 Münster, Germany*

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The first direct mass measurement of the neutron-deficient nucleus ^{24}Al was performed via Penning-Trap Mass Spectrometry (PTMS) using TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN). This measurement was facilitated by the use of TRIUMF's new Ion-Guide Laser Ion Source (IG-LIS), which reduced $A = 24$ isobaric contamination in the delivered beam by nearly six orders of magnitude. The measured mass excess was found to be $\Delta = -48.86(23)$ keV, which is five times more precise than the value quoted in the most recent atomic mass evaluation. When combined with the relevant ^{24}Al excitation energy, and a recent measurement of the ^{23}Mg mass, the astrophysical ^{23}Mg$(p,\gamma)^{24}$Al reaction resonance energy is extracted as $E_r = 480.8(14)$ keV. The presented value shows a 2σ disagreement with the direct measurement of this quantity by the DRAGON recoil spectrometer.

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I. INTRODUCTION

The process of explosive hydrogen burning in stellar environments proceeds through a network of rapid proton-capture reactions (rp process) in high-density and -temperature sites in the universe [1,2]. Initiated at the breakout of the hot Carbon-Nitrogen-Oxygen (hCNO) cycle, the rp process plays a major role in the synthesis of neutron-deficient heavy elements up to ^{105}Te [3]. However, due to the large number of reaction steps, a quantitative understanding of the rp process is more challenging than the reactions in the hCNO cycle. Since the rp-process reaction ^{23}Mg$(p,\gamma)^{24}$Al is believed to be the breakout from the Ne-Na cycle [4,5], an accurate determination of the reaction rate and energy carries particular importance for bypassing the β decay of ^{23}Mg [6].

In the ^{23}Mg$(p,\gamma)^{24}$Al reaction, there are several predicted resonances that are of astrophysical interest, and correspond to states which are above the proton separation energy in ^{24}Al [7]. Of these, the lowest lying resonance (the so-called "473 keV" resonance) is considered to be the dominant contributor to the astrophysical reaction rate at relevant novae temperatures [4,8]. Direct measurements of the reaction rates are difficult due to the very low cross sections, and thus benefit from advanced knowledge of the resonance energies (E_r) to guide and constrain the search region. Typically, E_r is determined indirectly through measurements of the proton separation energy (S_p), and the excitation energy (E_x) of the resonance state:

$$E_r = E_x - S_p. \tag{1}$$

For ^{24}Al, the most precise measurement of the excitation energy of the 473 keV resonance is from a ^{10}B(^{16}O$,2n\gamma$) fusion evaporation reaction with GAMMASPHERE, and yields a value of $E_x = 2345.1(14)$ keV [5]. The proton separation energy is determined from differences in the mass excess values (Δ) for the constituent components in the reaction: ^{1}H, ^{23}Mg, and ^{24}Al.

In the past, the extraction of E_r from the above prescription was limited by the large relative uncertainties in the experimental mass values of ^{23}Mg and ^{24}Al [4]. Currently, the best indirect determination of $E_r = 482.1(20)$ keV is reported in Ref. [9], and results from an updated value for the ^{24}Al mass from (^{3}He$,t$) reactions using the Q3D spectrograph at the Maier-Leibnitz-Laboratorium in Garching, Germany. This single measurement also currently dominates the average for the most recent Atomic Mass Evaluation (AME12) [10]. At the time of its publication in 2010, this measurement reported a 3.2σ shift in the central value of the mass excess from the 2003 Atomic Mass Evaluation [11], which translated to a 9 keV decrease in the measured ^{23}Mg(p,γ) Q value. When combined with the excitation energy in ^{24}Al from Ref. [5], a long-standing discrepancy between the indirect and direct measurement methods was resolved.

*kleach@triumf.ca
†Present address: Institute for Basic Science, RISP, 70 Yuseong-daero 1689-gil, Yuseong-gu, Daejeon 305-811, Korea.
‡Present address: Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA.
§Present address: Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA.

TABLE I. A list of the most recent experimental ^{23}Mg$(p,\gamma)^{24}$Al resonance energies from direct and indirect experimental methods. The method for indirect extraction of E_r is explained in the text.

Method	Experiment	Ref.	E_r (keV)
Direct (DRAGON)	^{23}Mg$(p,\gamma)^{24}$Al	[4]	$485.7^{+1.3}_{-1.8}$
Indirect (Q3D)	^{24}Mg$(^3$He$,t)^{24}$Al	[9]	482.1(20)
Indirect (TITAN)	PTMS	This work	480.8(14)

The only direct measurement of this reaction was performed using the DRAGON recoil spectrometer at TRIUMF, and yields a value for the resonance energy of $E_r = 485.7^{+1.3}_{-1.8}$ keV [4]. This value is in agreement with the indirect determination presented in Ref. [9], and is listed in Table I. To confirm the revised ^{23}Mg(p,γ) Q value in Ref. [9], this article presents the first direct measurement of the ^{24}Al mass and reports a new indirect determination of E_r.

II. EXPERIMENT

The experiment was conducted at TRIUMF's Isotope Separator and Accelerator (ISAC) facility [12], in Vancouver, Canada. The rare-isotope beam was produced via spallation reactions from a 40 μA, 480-MeV proton beam incident on a SiC target. Nonionized reaction products were subsequently released into the newly commissioned Ion-Guide Laser Ion Source (IG-LIS), which selectively ionized aluminum. The use of IG-LIS provided a suppression of surface-ionized contaminants by nearly six orders of magnitude [13], without which this measurement would not have been possible due to high levels of ^{24}Na. The IG-LIS concept was recently implemented and used online for the first time at TRIUMF-ISAC to facilitate measurements of the neutron-deficient nuclei ^{20,21}Mg [14]. Following ionization and mass selection, the continuous 20 keV beam, consisting of roughly 10^2 ions/s for each of ^{24}Al$^+$, ^{24}Mg$^+$, and ^{24}Na$^+$, was delivered to TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [15]. A short-lived isomeric state in ^{24}Al also exists ($E_x = 425$ keV, $T_{1/2} = 130$ ms) but was not observed at the ISAC yield station, and was not delivered to TITAN.

The TITAN facility consists of three ion traps: (i) A Radio-Frequency Quadrupole (RFQ) linear Paul trap [16,17], (ii) an Electron-Beam Ion Trap (EBIT) for generating Highly Charged Ions (HCIs) [18,19] and performing decay spectroscopy [20,21], and (iii) a 3.7 T, high-precision mass Measurement PEnning Trap (MPET) [22]. Following the delivery of the continuous $A = 24$ ISAC beam to TITAN, ions were injected into the RFQ trap where they were cooled using a He buffer gas. The resulting ion bunches were then transported with a kinetic energy of 2 keV to the Penning trap, where individual singly charged ions were captured for study. Since HCIs were not needed for this particular measurement, the TITAN EBIT was bypassed.

In MPET, the mass of a single ion is determined by measuring its characteristic cyclotron frequency using the Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR) technique [23,24]. This is the standard measurement method employed by most on-line Penning trap systems [25]. ^{23}Na$^+$ from the TITAN stable ion source was used as a reference ion for the extraction of the absolute mass excess due to its similar mass, relative availability, and small mass uncertainty. A small mass-dependent frequency shift of $-0.5(4)$ ppb was therefore accounted for between ^{24}Al$^+$ and ^{23}Na$^+$ using the prescription reported in Ref. [26]. Reference measurements were taken both before and after each ^{24}Al$^+$ run to reduce any additional systematic effects. Additionally, the time between measurements was kept between 30 and 45 minutes to reduce any effects due to time-dependent magnetic field fluctuations. The magnetic field decay of the MPET solenoid is <1 ppb per hour [26], and is therefore negligible at the level of precision presented here.

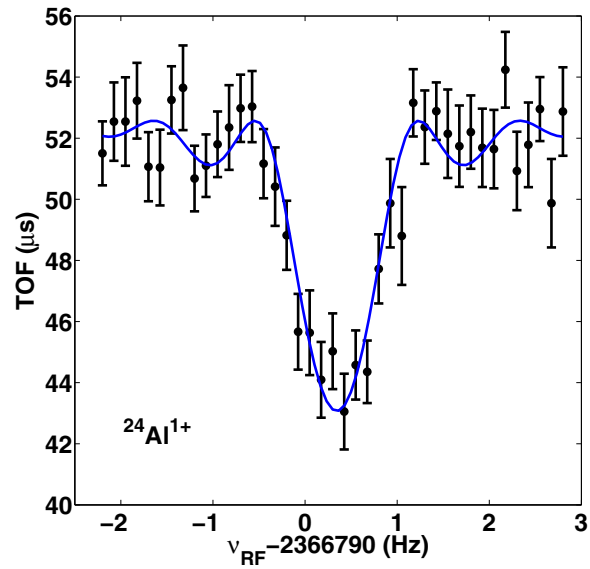

FIG. 1. (Color online) A typical time-of-flight quadrupole-excitation resonance spectrum for ^{24}Al$^+$ ions. The blue line is a statistical fit to the experimental data, performed using an analytic function designed to reproduce the result of a ToF-ICR spectrum resulting from a quadrupole excitation in MPET [24].

Penning trap RF excitation times of 975 ms were used for both ^{24}Al$^+$ and ^{23}Na$^+$. A typical quadrupole excitation resonance from an ^{24}Al$^+$ run is shown in Fig. 1. During the ^{24}Al measurement, an average of 1.5 ions were detected during each extraction. Accounting for the ion detection efficiency of $\sim$60%, this implies that an average of roughly 2.5 ions were present in the trap during a given measurement. To remove any effects of ion-ion interactions in the Penning trap during RF excitation, a count-class analysis [27] was also performed. With an absolute value of 100 eV, this was the largest systematic uncertainty in the measurement. The uncertainties were summed in quadrature with a statistical uncertainty of 205 eV to obtain the total measurement error. The extracted frequency ratio ν_{Al}/ν_{Na} is listed in Table II along with the determined Δ and S_p values for ^{24}Al.

TABLE II. The measured average frequency ratio ($\overline{R}$) for $^{24}Al^{+}$ is relative to the reference ion $^{23}Na^{+}$, and results from five measurements. The mass excess (Δ) is extracted from the frequency ratio, and is in agreement with the Atomic Mass Evaluation (AME12) [10], but is more than five times as precise. The proton separation energy (S_p) in ^{24}Al is also extracted using the value for ^{1}H in Ref. [10].

$\overline{R} = \nu/\nu_{\text{ref}}$	Δ (keV)		S_p (keV)	
	TITAN	AME12	TITAN	AME12
0.957 908 185(10)	−48.86(23)	−47.6(11)	1864.32(28)	1863.3(13)

III. RESULTS AND DISCUSSION

As a result of the significant improvement in precision for both the ^{24}Al (this work) and ^{23}Mg (Ref. [28]) masses, a new indirect determination of the ^{23}Mg(p,γ) resonance energy is extracted as $E_r = 480.8(14)$ keV. This value agrees with other previous indirect extractions of E_r, but deviates from the direct measurement by more than 2σ. The agreement in S_p between this work and the AME12 implies that this difference results from either a discrepancy in the direct measurement or the excitation-energy measurement in Ref. [5]. A comparison of the extracted resonance energies through the different measurements and methods is shown in Fig. 2(b), along with measured proton separation energies for ^{24}Al in Fig. 2(a).

The indirect extractions of E_r presented in Fig. 2(b) all require the ^{24}Al excitation energy measurement from Ref. [5] for the extraction of E_r. Therefore, a discrepancy in this single measurement could lead to the observed difference with the direct measurement. The absolute difference in the central value of E_r between this work and DRAGON is nearly 5 keV, and represents the shift in the excitation energy from Ref. [5] that would have to be present for exact agreement between the two methods. The improvement in uncertainty on the atomic masses from this work and Ref. [28] therefore provide an increased motivation for confirmation of the 2345 keV state energy in ^{24}Al.

For the direct measurement, possible systematic effects in the DRAGON setup have been well studied, and are presented in Ref. [29]. Although the uncertainties quoted in Ref. [4] are relatively large, DRAGON has been calibrated to a variety of well known proton-capture resonances over the course of several years. A systematic reduction of 0.15% in the value used for their magnet constant was, however, recently suggested [29]. This shift would lead to a decrease in the recommended resonance energy from the direct ^{23}Mg(p,γ) measurement in Ref. [4]. When this prescription is applied, the slightly revised value of $E_r = 485.0^{+1.3}_{-1.8}$ keV from the direct DRAGON measurement moves closer to agreement with the result presented here, but still presents a discrepancy. Although this adjustment is a good estimate of the revised value, it is slightly misleading since Ref. [4] gives a probability distribution function for the resonance strength, which is directly tied to the extraction of E_r. Therefore, the result presented here also increases the motivation for a new direct measurement of the ^{23}Mg$(p,\gamma)^{24}$Al reaction.

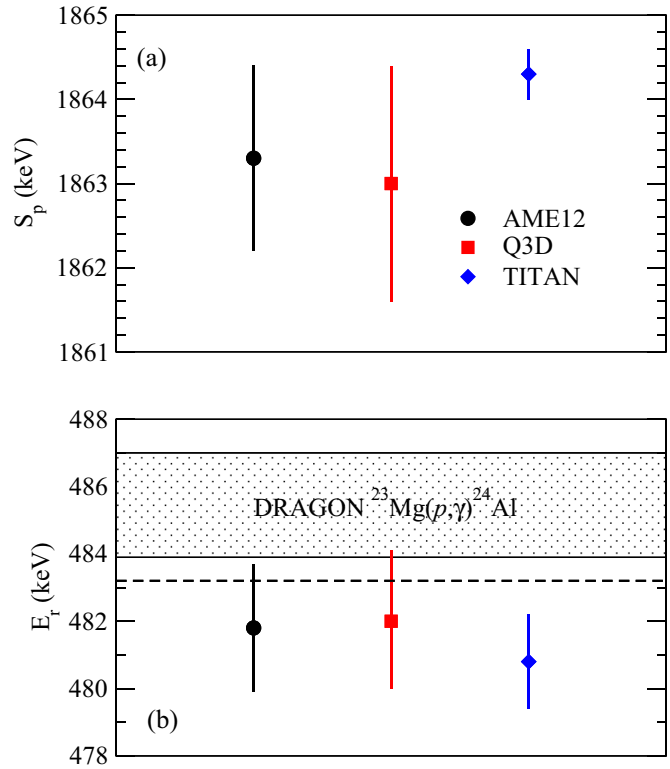

FIG. 2. (Color online) (a) The extracted proton separation energies for ^{24}Al from the AME12 evaluated data [10], reaction Q-value measurements (Q3D) [9], and the TITAN work presented here. (b) A comparison of the ^{23}Mg(p,γ) resonance energy from the direct DRAGON measurement to the three indirect extractions. The dashed line represents the lower limit of the direct measurement accounting for a 0.15% decrease in the DRAGON magnet constant, as discussed in the text. The high precision TITAN result shows a disagreement of E_r with the direct measurement.

IV. CONCLUSIONS

In summary, the first direct measurement of the ^{24}Al mass excess was performed using the TITAN facility at TRIUMF. This measurement was made possible for the first time through the use of TRIUMF's new ion-guide laser ion source for isobaric purification of the delivered ion beam. The measured mass excess was found to be in agreement with the most recent atomic mass evaluation, but five times more precise. When combined with the excitation energy of the "473 keV resonance" state in ^{24}Al, the astrophysical ^{23}Mg$(p,\gamma)^{24}$Al reaction resonance energy is extracted as $E_r = 480.8(14)$ keV. This disagrees with the only direct measurement using the DRAGON recoil spectrometer at TRIUMF. This difference could result from either a discrepancy in the ^{24}Al excitation-energy measurement of the resonance state or the direct ^{23}Mg$(p,\gamma)^{24}$Al measurement. As these values both result from single measurements, a confirmation of each would be beneficial. With a reconciliation of the two methods, a direct measurement of the resonance strength ($\omega\gamma$) would benefit greatly from the advanced knowledge of E_r, but still remains the limiting factor for improving the uncertainty on nova-produced ^{26}Al and ^{22}Na.

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