Mass determination near $N = 20$ for Al and Na isotopes

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We report on the mass measurements of ^{31,32}Na and ^{29,34,35}Al, performed with the TITAN Penning trap mass spectrometer at TRIUMF. The mass excesses were found to be 12246(14) and 18638(37) keV for ^{31,32}Na and −18207.77(37), −3000.5(29), and −223.7(73) keV for ^{29,34,35}Al, respectively. Our measurements confirm the observation of a crossover in the two-neutron separation energies of ^{33}Mg and ^{34}Al. We did not observe the recently reported, long-lived, isomeric state of ^{34}Al, but, based on the previously measured half-lives, the mass value of the ground state was determined.

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I. INTRODUCTION

The nuclear shell model has been remarkably successful in describing both the ground state and excited states in nuclei near the valley of stability. However, in 1975, it was discovered in the neutron-rich Na isotopes that the $N = 20$ magic number disappeared [1], in what is now known as the *island of inversion* [2]. The island of inversion is formed through the gain of correlation energy through neutron pairs occupying states in the pf shell across the $N = 20$ shell gap [2,3], causing these so-called intruder states to be lowered in energy, and thus, becoming the ground state. Recently, measurements have suggested that the island of inversion extends through the neutron-rich Mg isotopes from $N = 20$ to $N = 28$ [4,5].

Recently, much effort has been spent investigating the $Z = 13$ shore of the island of inversion. Results from γ-ray spectroscopy [4,6,7], β-decay [8], $2p$ knockout [5], βNMR and βNQR [9–11], and mass measurements [12,13] show that the ground states of ^{33,34}Al are a mixture of intruder and normal configurations. Comparisons of experiment and shell-model predictions [12,14,15] have substantially advanced our interpretation of the gross structure within the island of inversion. Nevertheless, the difficulty for experiments to measure quantities in this region, such as the excitation energy of the recently discovered $J^\pi = 1^+$ isomer in ^{34}Al [8], and the present limited precision of shell-model calculations prevent a complete and nuanced understanding of the inversion mechanism, because the measured excitation energy of the isomer lies ≈450 keV below shell-model predictions [7].

A unique feature revealed by mass measurements at the boundary of the island of inversion is the crossover of the two-neutron separation energies S_{2n} of ^{33}Mg and ^{34}Al, a feature seen nowhere else in the nuclear chart, as first described in Ref. [12]. Large-scale shell-model calculations [12] indicate that the gain in correlation energy peaks at $N = 21$, resulting in a convergence and crossover of the S_{2n} curves. One possible explanation of this crossover would be the presence of a low-lying isomer in ^{34}Al, whose mass was wrongly attributed to the ground state.

Penning trap mass spectrometry is a well-established technique for mass measurements of radioactive nuclides and long-lived isomers [16]. The work presented here applies this technique at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [17] to measure the masses of ^{31,32}Na and ^{29,34,35}Al. During this measurement campaign particular attention was given to searching for the long-lived $J^\pi = 1^+$ isomer in ^{34}Al [8]. A mass measurement of ^{34}Al, including the possible identification of an isomer via mass measurement has also been pursued by the ISOLTRAP experiment at ISOLDE [18]. The isomer has a half-life of 26(1) ms [8] with a recently measured excitation energy of 46.6 keV [7]. The $J^\pi = 4^-$ ground state has a half-life of 56.3(5) ms [6] and is needed to evaluate the two-neutron separation energy.

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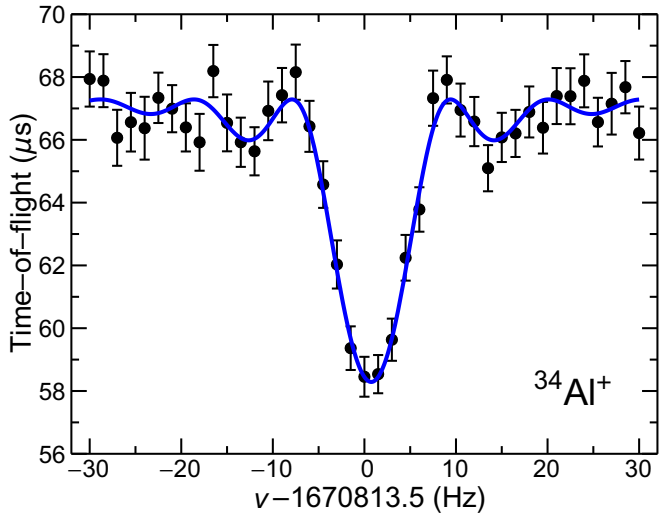

FIG. 1. TOF spectrum of ^{34}Al with an excitation time of 100 ms. The solid curve is an analytic fit [26].

II. EXPERIMENT

The present measurements were performed at the Isotope Separation and Accelerator (ISAC) facility at TRIUMF [19]. The radioactive isotopes were generated via the isotope separator on-line (ISOL) technique [20], in which 10 μA of 480-MeV protons impinged on a UC_x target. The sodium isotopes were surface ionized, while the aluminum isotopes were ionized using the TRIUMF Resonant Ionization Laser Ion Source (TRILIS) [21]. Measured yields ranged from 75 pps for ^{34}Al to 2×10^6 pps for ^{29}Al. The singly charged beam was mass separated via a dipole magnet with a resolving power of $R \approx 2000$ [22] and transported at 20 keV to the TITAN facility where it underwent further beam preparation prior to the mass measurement.

The ions were first sent to the radio-frequency quadrupole (RFQ) cooler and buncher [23], which cools the beam via collisional cooling in a helium buffer gas. The bunched ions were delivered to the measurement Penning trap (MPET) [24], where the ions were trapped via electrostatic and magnetic fields.

The time-of-flight ion-cyclotron-resonance (TOF-ICR) technique [25] was used to determine the cyclotron frequency ν_c, which is related to the ion mass:

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B, \tag{1}$$

where q is the ionic charge, B the magnetic field strength, and m the ion mass. A typical TOF-ICR resonance [26] for ^{34}Al is shown in Fig. 1. In the case of ^{29}Al, a Ramsey scheme [27,28] was employed with two 100-ms excitation pulses separated by a waiting period of 300 ms, which we write as 100-300-100 ms.

III. DATA ANALYSIS

To calibrate the magnetic field, the cyclotron frequency of an ion with a well-known mass is measured before and after the measurement of the ion of interest. The cyclotron frequency of the ion of interest is then linearly interpolated to the measurement time of the ion of interest, and the ratio R of these frequencies is taken,

$$R = \frac{\nu_{c,\mathrm{int}}}{\nu_{c,\mathrm{ref}}} = \frac{q_{\mathrm{int}}}{q_{\mathrm{ref}}}\frac{m_{\mathrm{ref}}}{m_{\mathrm{int}}}, \tag{2}$$

where the subscript identifies quantities belonging to the reference ion and to the ion of interest. Taking the ratio of frequencies effectively cancels most systematic effects, if the masses of the reference ion and the ion of interest are similar [24,29]. Such systematics include relativistic effects, nonlinear fluctuations of the magnetic field, anharmonicities in the trapping potential, and other mass-dependent effects. These systematic uncertainties were investigated [24] and were found to be negligible compared to the present statistical uncertainties. The uncertainty resulting from ion-ion interactions was determined via a count-class analysis [30] whenever sufficient statistics were collected. Moreover, reference measurements of $^{39}K^+$ or $^{23}Na^+$ were alternated with measurements of the ion of interest. These calibration measurements were within one standard deviation of the value in the 2012 Atomic Mass Evaluation (AME2012) [31]. The current results are included in AME2016 [32], thus we only compare to the AME2012.

IV. RESULTS

After measuring the frequency ratio R as defined in Eq. (2), the atomic mass of the ion of interest m_{int} can be calculated relative to the atomic mass of the reference m_{ref}:

$$m_{\mathrm{int}} = \frac{1}{R}(m_{\mathrm{ref}} + B_{\mathrm{ref}} - m_e) - B_{\mathrm{int}} + m_e, \tag{3}$$

where B are the electron binding energies of the reference ion and the ion of interest, and m_e is the mass of the electron. The electron binding energies of $\approx$6 eV were negligible for the singly charged ions when compared to the statistical uncertainty, and are not included in the analysis. The resulting mass excess (ME) values are presented in Table I alongside the literature values.

The mass excesses of ^{31}Na and ^{32}Na were found to be 12246(14) keV and 18638(37) keV, respectively. The uncertainties of these new measurements are at least halved compared to the AME2012 values. The present measurement of ^{31}Na agrees with the AME2012, to within 0.7σ, and to within 1.4σ for ^{32}Na. Figure 2 shows the evolution of the mass excesses for ^{32}Na. The measurements of ^{29,34}Al agree with our prior values [12], to within 1σ for ^{29}Al and to within 1.4σ for the weighted average of ^{34}Al. The mass excess value of ^{35}Al agrees with AME2012 [31]; however, it features an order of magnitude increase in precision.

During the experiment and the data analysis, special attention was paid to the possible presence of a long-lived isomer of ^{34}Al [7,8]. The evidence presented in Lică *et al.* supports the 26(1)-ms state as the isomer and the 56.3(5) ms as the ground state. The isomer could have been produced in the ISAC production target and delivered simultaneously with the ground state. To identify the constituent species in the beam, the laser ionization of ^{34}Al was turned on and off. Note that due to Doppler broadening in the ionization region,

TABLE I. Measured ions alongside the ion that was used as a reference, the excitation time in MPET T_{ex}, the ratio R [see Eq. (2)], mass excesses (ME) from this work and the literature, as well as the two-neutron separation energy S_{2n}. For ^{31,32}Na and ^{35}Al we compare to AME2012 [31] and for ^{29,34}Al to the more recent values in Ref. [12]. All species presented in this experiment were singly charged. In the case of ^{29}Al, a 100-300-100-ms Ramsey excitation [27] was used. This table also presents the combined results of the 50, 71, 100 ms excitation time measurements of ^{34}Al.

Species	Reference ion	T_{ex} (ms)	R	ME_{TITAN} (keV)	ME_{Lit} (keV)	S_{2n} (keV)
^{31}Na	$^{39}K^+$	20	1.25636549(62)	12246(14)	12261(23)	6576(16)
^{32}Na	$^{39}K^+$	20	1.2168586(15)	18638(37)	18810(120)	5979(38)
^{29}Al	$^{23}Na^+$	100-300-100	0.793281449(10)	−18207.77(37)	−18209.0(19)	17153.51(37)
^{34}Al	$^{39}K^+$	50	1.14610225(44)	–2999(12)	−2990.0(72)	8042(15)
^{34}Al	$^{39}K^+$	71	1.14610245(24)	−3004.4(67)	−2990.0(72)	8048(11)
^{34}Al	$^{39}K^+$	100	1.14610227(12)	−2999.5(34)	−2990.0(72)	8042.8(93)
^{34}Al	$^{39}K^+$	50,71,100	1.14610230(11)	−3000.5(29)	−2990.0(72)	8043.7(92)
^{35}Al	$^{39}K^+$	50	1.11325817(25)	−223.7(73)	–220(70)	7869(10)

both the ground state and isomer of ^{34}Al can be ionized with the same laser-excitation scheme. Further, the stable molecule $^{31}PH_3^+$ was identified in MPET via its cyclotron frequency, which accounted for ≈75% of the surface-ionized beam. Still, more than 90% of the beam delivered to TITAN could be assigned to ^{34}Al when the laser-ionization scheme was active.

In an effort to clarify which nuclear state of ^{34}Al was being measured, excitation times of 50, 71, and 100 ms were used, as the half-lives of the isomer and ground state differ by a factor of 2. In Fig. 3 we show the effect of varying isomer to ground state ratios on the expected resonance line shapes for an excitation time of 100 ms. With an excitation energy of 46.6 keV, the ground-state and isomer cyclotron frequencies would be separated by ≈2.46 Hz, which can only be fully resolved at TITAN with an excitation time of 1 s. Because of variations in the ISAC yields, it was not possible to normalize the count rates between the various measurements of ^{34}Al and to determine the amount of isomer present in the measurement. However, as the shortest measurement cycle was more than twice the half-life of the isomer, a maximum of 25% of those delivered to the measurement trap would have survived long enough to be observed. This drop in the number of detected short-lived isomers would be even more apparent with the longer excitation time of 100 ms, and therefore we conclude that the measured mass value corresponds to the longer-lived 56.3(5)-ms ground state.

The weighted average mass excess of ^{34}Al of −3000.5(29) keV agrees with the previous TITAN measurement of −2990.0(72) keV [12], where the overlap of the S_{2n} of ^{33}Mg and ^{34}Al had first been reported. The two-neutron separation energy tabulated in Table I is defined as

$$S_{2n}(N,Z) = -m(N,Z) + m(N-2,Z) + 2m_n. \quad (4)$$

Thus, in the present experiment, the two-neutron separation energy crossover of ^{33}Mg and ^{34}Al at $N = 21$ is confirmed with an overlap of 15(10) keV.

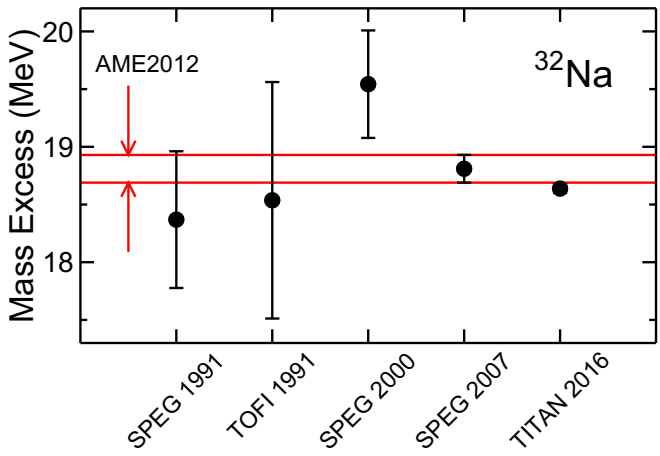

FIG. 2. Mass measurements of ^{32}Na with the horizontal lines centered around the AME2012 data indicating the 1σ confidence level. The TITAN value is 1.4σ below the AME2012 value. Values taken from [33–36].

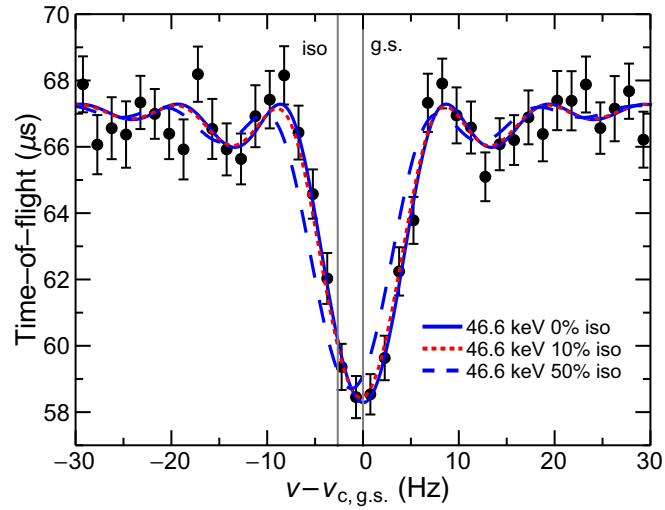

FIG. 3. A typical measured resonance and expected TOF resonances for $^{34}Al^+$ with isomer to ground-state ratios of 0, 10, and 50%, for an excitation time of 100 ms. The left vertical line represents the ν_c of the 46.6-keV isomer, while the right vertical line represents the ν_c of the ground state. An excitation energy of 46.6 keV corresponds to a frequency difference of 2.46 Hz.

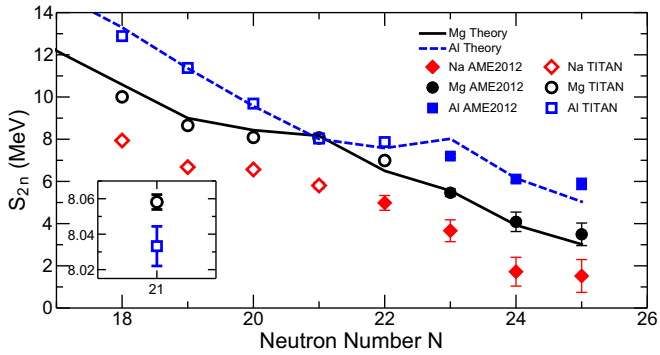

FIG. 4. Two-neutron separation energies for the Na, Mg, and Al isotopic chains. Filled symbols indicate S_{2n} values that include at least one AME2012 value, while open symbols indicate values based solely on TITAN measurements. Lines show theoretical values [12] for Mg and Al. The inset shows the overlap of the S_{2n} between ^{33}Mg and ^{34}Al at $N = 21$.

The importance of knowing the aluminum masses derives from the transitional nature of the Al isotopes as they border the island of inversion. In addition to agreeing with previous measured mass values, the ^{29,34,35}Al values presented here support large-scale nuclear shell-model calculations [12] in which ^{34,35,36}Al have mixed *sd* and *pf* orbitals. The relative gains in correlation energy peak at $N = 21,22$ for the aluminum isotopes, which can be seen in the change in slope of the two-neutron separation energy from ^{34}Al to ^{36}Al in the shell-model calculation. Figure 4 shows this for Al and Mg for the $N = 19$–21 region, and also shows crossover at $N = 21$. The present TITAN measurements confirm this change in slope of the ^{34,35}Al two-neutron separation energies; however, mass measurements of even higher mass Al isotopes are needed to confirm the shell-model prediction.

V. SUMMARY AND OUTLOOK

We presented results of mass measurements near the island of inversion by determining the masses of ^{31,32}Na as well as ^{29,34,35}Al. The TITAN mass measurements in the island of inversion now span $^{29–32}$Na, $^{29–34}$Mg, and $^{29–35}$Al. The observed disappearance of the $N = 20$ shell gap supports the predictions of large correlation energy gains in ^{34,35}Al [12]. The long-lived 46.6 keV, 1^+ isomer in ^{34}Al was not observed; however, through the use of in-trap decay recoil capture of ^{34}Mg, it may be possible to directly measure this state in the future. The present measurement of ^{34}Al supports the claim that the two-neutron separation energies of the Mg and Al isotopic chains cross at $N = 21$, with an overlap of 15(10) keV, assuming that the longer-lived 56.3(5)-ms $J^\pi = 4^-$ is the ground state.

The abundance of experimental [4–13] and theoretical [12,14,15] effort represents a tour de force by the international community to understand the high-Z shore of the island of inversion. The recent measurement of the excitation energy of the low-lying 1^+ isomer places ^{34}Al at the intersection between normal and intruder configurations at the edge of the island of inversion [7]. The reconfirmed cross-over of the ^{33}Mg and ^{34}Al two-neutron separation energies, and the low excitation energy of ^{34}Al, will provide important benchmarks to future shell-model calculations. Further mass measurements in the Al isotopic chain beyond $N = 21$ will continue to shed light on the shore of the island of inversion.

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