β decay of proton-rich nucleus ^{23}Al and astrophysical consequences

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We present the first study of the β decay of ^{23}Al undertaken with pure samples. The study was motivated by nuclear astrophysics questions. Pure samples of ^{23}Al were obtained from the momentum achromat recoil separator (MARS) of Texas A&M University, collected on a fast tape-transport system, and moved to a shielded location where β and β-γ coincidence measurements were made. We deduced β branching ratios and log *ft* values for transitions to states in ^{23}Mg, and from them determined unambiguously the spin and parity of the ^{23}Al ground state to be $J^\pi = 5/2^+$. We discuss how this excludes the large increases in the radiative proton capture cross section for the reaction ^{22}Mg$(p,\gamma)^{23}$Al at astrophysical energies, which were implied by claims that the spin and parity is $J^\pi = 1/2^+$. The log *ft* for the Fermi transition to its isobaric analog state (IAS) in ^{23}Mg is also determined for the first time. This IAS and a state 16 keV below it are observed, well separated in the same experiment for the first time. We can now solve a number of inconsistencies in the literature, exclude strong isospin mixing claimed before, and obtain a new determination of the resonance strength. Both states are resonances in the ^{22}Na$(p,\gamma)^{23}$Mg reaction at energies important in novae. The reactions ^{22}Mg$(p,\gamma)^{23}$Al and ^{22}Na$(p,\gamma)^{23}$Mg have both been suggested as possible candidates for diverting some of the flux in oxygen-neon novae explosions from the $A = 22$ into the $A = 23$ mass chain.

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I. INTRODUCTION

Space-based γ-ray telescopes have for some time had the ability to detect γ rays of cosmic origin. They have already provided strong and direct evidence that nucleosynthesis is an ongoing process in our galaxy. γ rays from the decay of long-lived isotopes like ^{26}Al ($t_{1/2} = 7.2 \times 10^5$ yr), ^{44}Ti (60.0 yr), ^{56}Ni (6.1 d), etc., have been detected. Among the expected γ-ray emitters is ^{22}Na ($t_{1/2} = 2.6$ yr), thought to be produced in the thermonuclear runaway and in the high-temperature phase of so-called ONe novae (oxygen-neon novae) through the reaction chain ^{20}Ne$(p,\gamma)^{21}$Na$(p,\gamma)^{22}$Mg$(\beta\gamma)^{22}$Na—the NeNa cycle [1–4]. Measurements, however, have not detected the 1.275 MeV γ ray that follows the decay of ^{22}Na and have only been able to set an upper limit on its production, a limit which is below the theoretical predictions (see, for example, [5,6] and the references therein).

The origin of this discrepancy is not clear, but a poor knowledge of the reaction cross sections employed in the network calculations for the rp-process may be a reason. In particular, it has been proposed that ^{22}Na itself or its precursor ^{22}Mg could be depleted by the radiative proton capture reactions ^{22}Na$(p,\gamma)^{23}$Mg [7] and ^{22}Mg$(p,\gamma)^{23}$Al [8], both leading to a serious reduction of the residual ^{22}Na abundance. The former is the prime candidate for this depletion. With the latter reaction, depletion could happen in the explosive phase, so short and fast that equilibrium with photodissociation is not reached. The reaction is dominated by direct capture to the ground state and by resonant capture through the first excited state in ^{23}Al. There is no direct measurement of the cross section at stellar energies because it is impossible to make a ^{22}Mg ($t_{1/2} = 3.86$ s) target and difficult to obtain an intense ^{22}Mg beam for measurements in inverse kinematics. Therefore, currently, the rate of this reaction is only estimated, based on the resonance energy determined experimentally [9] and on the assumption that the spins and parities in ^{23}Al are the same as in the mirror nucleus ^{23}Ne.

Until recently, pure samples of ^{23}Al could not be separated, and only its β-delayed proton branches were known [10,11], which meant that the ground-state spin could not be determined directly. More recently, a study of mass-separated (but not isobar-separated) ^{23}Al identified two γ rays (in addition to β-delayed protons), which were assumed to originate from the decay of the isobaric analog state in ^{23}Mg [12]. There were still no data for β-decay branching ratios to different final states in ^{23}Mg, which would allow one to determine the ground-state spin and parity of ^{23}Al. In the present paper, we report on a study of >99%-pure samples of ^{23}Al, which used β detection and β-γ coincidence techniques to determine the branching ratios and log *ft* values for individual states in the daughter nucleus. This makes possible the unambiguous determination of the spin and parity of the ^{23}Al ground state.

Efforts have been made for a long time to determine the reaction rate for the proton capture reaction ^{22}Na$(p,\gamma)^{23}$Mg, the most credible candidate for depleting ^{22}Na out of the NeNa cycle. Data showed early on that resonance capture plays the overwhelming role. The corresponding resonances are excited states in ^{23}Mg, some of them populated in the β decay of ^{23}Al, including the isobaric analog state of its ground state, which can be identified by its preferential population. However, the reaction rate in stellar environments is still uncertain even after a few direct measurements [13,14] and many spectroscopic studies [11,12,15–17]. The major problem is that at this excitation energy, there is a large density of states that cannot easily be separated and identified. In the present experiment, we separate two important ones and identify the isobaric analog state (IAS).

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II. ASTROPHYSICAL MOTIVATION

The nucleus ^{23}Al is a weakly bound proton-rich nucleus [$S_p = 0.123(19)$ MeV [18]] close to the drip line. It would normally be expected to have a ground-state spin-parity of $5/2^+$ like its mirror ^{23}Ne. Recent measurements of the reaction cross sections for $N = 10$ isotones and $Z = 13$ isotopes around 30 MeV/nucleon on a ^{12}C target found a remarkable enhancement for ^{23}Al, which led the authors to the conclusion that it is one of the rare proton-halo nuclei [19]. They propose this as evidence for a level inversion between the $2s_{1/2}$ and $1d_{5/2}$ orbitals. The inversion was further supported by several microscopic nuclear structure calculations (nonlinear relativistic mean field and Skyrme-Hartree-Fock) that find $J^\pi = 1/2^+$ for the ^{23}Al ground state [20,21]. Some of the existing experimental data seem to support such inversion, such as the systematics of the energies of the first two states in odd-mass Al isotopes; others, such as the isobaric multiplet mass equation (IMME), do not.

If the inversion were correct, it would affect the radiative capture cross section very strongly. Indeed, assuming such an inversion, we recalculate the astrophysical S factor (Fig. 1) and the stellar reaction rate for the ^{22}Mg$(p,\gamma)^{23}$Al reaction and find an increase of 30 to 50 times over the current estimate of the rate for the temperature range of ONe novae; *viz.*,$T_9 = 0.1$–0.5 (see also [22]). This is due to the larger proton penetration for an s-wave capture and the absence of a centrifugal barrier for the last proton in ^{23}Al, which allows the wave function of the barely bound proton in the final state to extend far beyond the nuclear interior, thus increasing its overlap with the wave function of the incoming proton.

With both $5/2^+$ and $1/2^+$ as contenders for the ground-state spin-parity of ^{23}Al, the situation is further confused by the NNDC database, which gives $3/2^+$ for the state [23]. Clearly then, it is important to determine the spin and parity of the low-lying levels in ^{23}Al. It is important both for nuclear structure physics and for its consequences to nuclear astrophysics.

States in ^{23}Mg above the proton separation energy $S_p = 7580.3(13)$ keV [18] are resonances in the reaction ^{22}Na$(p,\gamma)^{23}$Mg and can play roles in the rate of this reaction at astrophysical energies. This problem has already received much attention related to the anomalous Ne isotopic ratio in some meteorites (Ne-E anomaly) [7,24] and the breakout of the NeNa cycle cited above. Some of these states are populated in the β decay of ^{23}Al, and in particular those haviing proton decay branchings contribute to the reaction rate in novae. Confusion still exists about the precise position of resonances and their strengths, leading to uncertainties that may yet be of a few orders of magnitude [17,25].

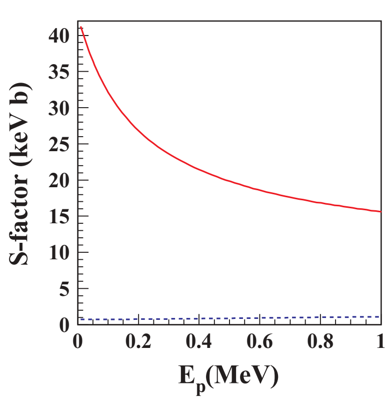

FIG. 1. (Color online) Astrophysical S factor for the ^{22}Mg$(p,\gamma)^{23}$Al reaction, calculated assuming $J^\pi = 5/2^+$ (dashed line), or $J^\pi = 1/2^+$ (orbital inversion, full line) for the g.s. of ^{23}Al.

III. THE EXPERIMENT

We carried out the experiment at the K500 superconducting cyclotron of Texas A&M University, using the momentum achromat recoil separator (MARS) and the fast tape-transport system. Our technique was similar to that used before and described in previous publications [26,27]. A 48-MeV/nucleon ^{24}Mg beam bombarded a H_2 cryogenic gas target, 2.5 mg/cm^2 thick. Recoiling ^{23}Al nuclei from the $p(^{24}\mathrm{Mg},^{23}\mathrm{Al})2n$ reaction were separated in the MARS, which consists of a dipole-quadrupole-dipole momentum achromat, and a mass separator comprising a Wien velocity filter and a final dipole.

Initially, working with a low-current primary beam, we inserted at the focal plane of MARS a 5×5 cm silicon telescope consisting of a 16-strip position-sensitive detector (PSD) 300 μm thick, backed by a 1-mm-thick detector. The telescope was used first for the identification of secondary reaction products, then for the control of the selection and focus of the desired species in the center of the beamline. Selection in MARS is achieved with several pairs of slits, and the focus is realized with two quadrupole doublets situated after the last dipole. A beam of 4.4 mm (full width at half maximum) diameter at the location of the detectors was obtained. At this point it contained 90% pure ^{23}Al.

After the whole tuning procedure, the PSD detector was dropped out of the way and the intensity of the primary beam was increased. The secondary beam then passed through a 50-μm-thick Kapton foil into air, then through a plastic scintillator foil, which counted the ions, through a set of Al attenuators, and finally stopped in the 76-μm-thick aluminized Mylar tape of the tape-transport system. To ensure that the ^{23}Al ions all stopped within the tape, the momentum-selection slits in MARS were closed to ± 1.0 cm, which corresponds to $\sim 1.6\%$ spread in energy. The thickness of the Al attenuators was then empirically adjusted so that $\sim 99\%$ of the ^{23}Al ions were stopped in the tape. Since any impurities passing through MARS had different ranges from ^{23}Al, they did not stop in the tape and the resulting purity of the collected ^{23}Al sample was very close to 100%. With primary ^{24}Mg beam currents from the cyclotron of about 20 pnA, rates of about 4000 ^{23}Al atoms per second were obtained.

The measurement itself was done with the beam from the cyclotron pulsed by the same system that controlled the tape-transport system. After a 1.0 s collection time—approximately two half-lives of 0.47-s ^{23}Al—the beam was switched off, and the collected source was moved 90 cm in 175 ms to a shielded counting station, where its decay was measured for 3.2 s. The counting station consisted of a 1-mm-thick BC404 plastic-scintillator β detector on one side of the tape and a high-purity

(HP) Ge γ-ray detector on the other side. The β detector was situated about 5 mm from the source; the γ-ray detector was 4.9 cm away. β singles were scaled, while β-γ coincidences were recorded event-by-event and stored on disk for off-line analysis. The data recorded for each coincident event included the energy of both detector signals, the time between them, and the time elapsed since the start of the counting period.

The γ rays observed following the β decay of ^{23}Al have a wide range of energies extending up to 8 MeV. We thus required an efficiency calibration at these high energies. For this purpose, we used the γ rays from the known decay of ^{24}Al, sources of which we produced in a separate experiment that followed the ^{23}Al measurement. We used the same beam, bombarding energy, and target, but tuned MARS to separate ^{24}Al rather than ^{23}Al. We then measured the decay γ rays with the same experimental setup. As the cross section for the production of ^{24}Al is much higher than that for ^{23}Al, we could produce about 200 000 atoms per second of separated ^{24}Al at the focal plane of MARS. We made measurements first with the HPGe detector at the same distance (4.9 cm) from the collected source that we had used previously for ^{23}Al, then at the 15-cm distance, at which the efficiency of our detector had been calibrated to better than 0.4% over the energy range from 70 keV to 3.5 MeV [28]. We adjusted the intensity of the primary beam in each case to obtain a reasonable counting rate in the detector. The measurement cycle for ^{24}Al was a 4.0-s collection time, 175-ms transport time, and 4.0-s measurement time.

IV. RESULTS

The γ-ray spectrum measured in coincidence with β's is presented in Fig. 2. The upper spectrum appears in log scale over the energy range 0–4 MeV; below it, in linear scale, is the rest of the spectrum up to 9 MeV. Transitions to and from 13 distinct excited levels in ^{23}Mg are observed. We clearly see γ-ray transitions depopulating the lowest lying states in ^{23}Mg: the $5/2_1^+$ state at $E_x = 450.7$ keV and the $7/2_1^+$ state at $E_x = 2051$ keV (corresponding γ-ray lines at $E_\gamma = 1600$ and 2051 keV). We also see a large number of γ rays depopulating higher excited states up to $E_x = 7803$ keV.

Twenty γ-ray peaks in all were identified as originating from the decay of ^{23}Al. To determine their absolute intensities, we required first an accurate knowledge of the absolute efficiency of our HPGe detector. At a source-to-detector distance of 15 cm, this is already well known and documented [28] in the energy range between 50 and 3500 keV, where a combination of Monte Carlo calculations and experimental measurements achieved a precision of 0.4% or better over the whole range. At higher energies, we first extended the Monte Carlo calculations using the same geometric dimensions established in our earlier work, and then compared those calculations to the ^{24}Al data obtained in this work. The two agreed to within 3.5%. Next, with these efficiencies adjusted to the 4.9-cm source-to-detector distance used for ^{23}Al, we obtained absolute intensities for the observed γ rays and, from those results, constructed a decay scheme that includes 14 β-decay branches to states in ^{23}Mg, including the ground

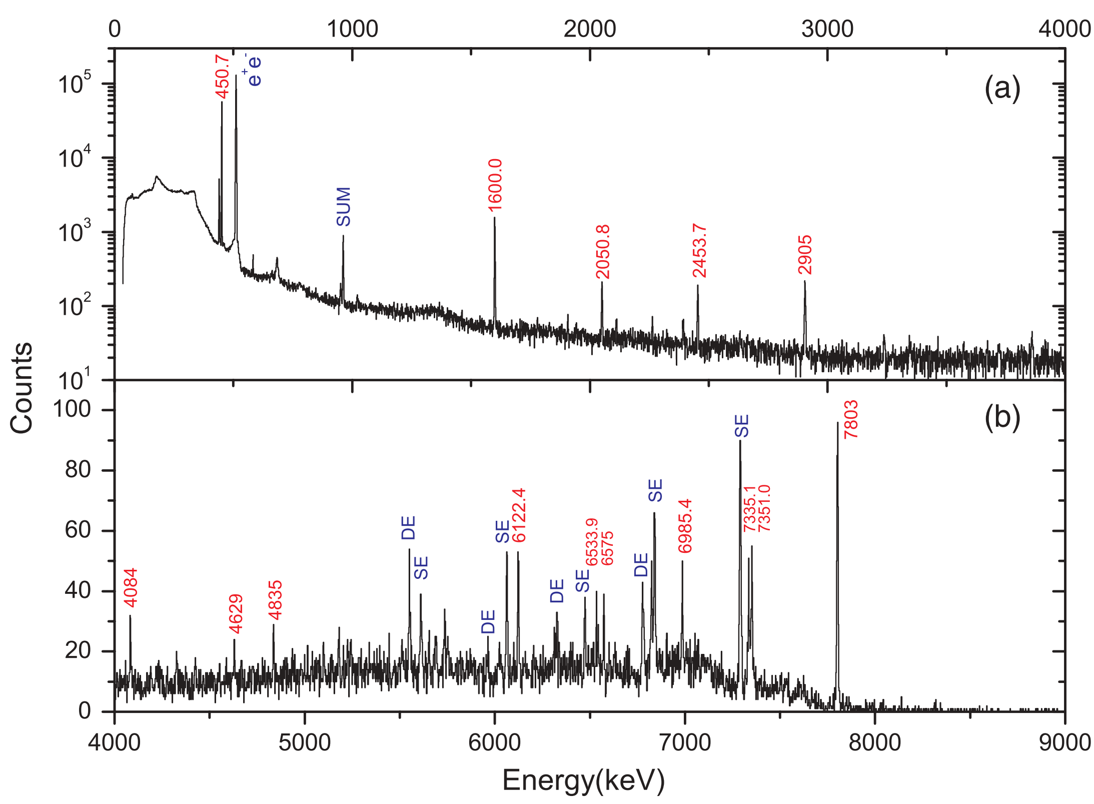

FIG. 2. (Color online) The gamma-ray spectrum in coincidence with betas from ^{23}Al decay. (a) The energy range $E_\gamma = 0$–4 MeV (notice the log scale). (b) The energy range $E_\gamma = 4$–9 MeV (linear scale). SE and DE denote single-escape and double-escape, respectively.

TABLE I. The properties of the observed decay of ^{23}Al to final states in ^{23}Mg. Spins and parities listed for the ground state and first three excited states were known previously [30]. Those for the last two states are deduced from the present measurement.

E_x (keV)	Branching ratio (%)	log *ft*	J^π
0	36.3(16)	5.30(2)	$3/2^+$
450.7	26.2(5)	5.36(1)	$5/2^+$
2051	5.91(10)	5.67(1)	$7/2^+$
2359	<0.1	>7.4	$1/2^+$
7787(2)	4.89(25)	3.76(2)	$(7/2)^+$
7803(2)	13.4(7)	3.31(3)	$5/2^+$(IAS)

state. Finally, we derived the β-decay branching ratios by assuming detailed balance between the total feeding and decay for each level. Because the density of states is relatively low in a light nucleus like ^{23}Al, the effect of unobserved γ rays on the branching ratios (the pandemonium effect [29]) should be small enough to be absorbed within our other uncertainties.

To derive log *ft* values for each measured β transition, we also required a reliable half-life for the parent nucleus; unfortunately, the currently accepted value, 470(30) ms [30], is rather imprecise. However, since all of our coincident events were tagged with their time of arrival, we could use our own data to determine the half-life associated with each observed γ-ray peak. Using the strongest peaks in the spectrum—the ones at 450.7 and 1600.0 keV—we determined the half-life of ^{23}Al to be 446(6) ms. With this value, we then derived log *ft* values for all observed decay branches.

A detailed description of the efficiency-calibration and analysis procedures, including the extraction of branching ratios and the decay lifetime, will be given elsewhere [31]. In this paper we shall concentrate only on the findings with consequences in nuclear astrophysics. These results are summarized in Table I and in the partial decay scheme shown in Fig. 3.

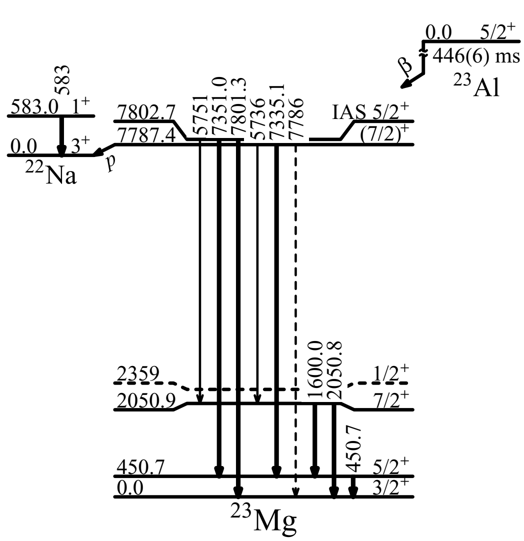

FIG. 3. The relevant part of the decay scheme of ^{23}Al.

It can clearly be seen from the table that the β decay from ^{23}Al populates the $3/2^+$ ground state of ^{23}Mg as well as $5/2^+$ and $7/2^+$ excited states at 450.7 and 2051 keV, respectively, with log *ft* values characteristic of allowed Gamow-Teller transitions. Furthermore, we do not observe the direct population of the $1/2^+$ excited state at 2359 keV; the lower limit we set on its log *ft* value is 7.4, a value which does not absolutely rule out allowed decay but makes it rather unlikely. Given the $\Delta J = 0, 1$ ($\Delta\pi$ no) selection rule for allowed β decays, the observed strong population of $3/2^+, 5/2^+$, and $7/2^+$ final states is sufficient evidence in itself to restrict the ground-state spin of ^{23}Al to be $5/2^+$. The absence of any observed transition strength to a $1/2^+$ state simply adds confirmation of that conclusion. This spin is also consistent with the expected mirror symmetry between ^{23}Al (with $T_z = -3/2$) and ^{23}Ne ($T_z = +3/2$), since the latter's ground state is already known to be $5/2^+$ [30].

Another important result evident from Table I is the log *ft* value we obtain for the transition to the 7803-keV state. The result, log *ft* = 3.31(3), is in agreement with the value expected for a predominantly Fermi transition between $T = 3/2$ analog states: *viz.*, log $ft \leqslant 3.31$. This positively identifies the state as being the isobaric analog of the ^{23}Al ground state. Although the state has been seen before [12] and correctly assumed to be the IAS, its log *ft* value has never been measured before. The log *ft* values reported here are calculated using the Q_{EC} value resulting from the IMME for $A = 23$ isobars with the energy of the IAS found above, $Q_{EC} = 12218(6)$ keV, as found also in Ref. [12]. Using the value from the latest mass tables [18]$Q_{EC} = 12243(19)$ keV leads to variations smaller than our statistical error bars.

Although our experiment was only sensitive to γ rays emitted in the decay of ^{23}Al, that nucleus is known to emit β-delayed protons as well. In fact, as can be seen from Fig. 3, any states populated in ^{23}Mg above ~7.8 MeV are open to subsequent decay by proton emission to ^{22}Na. Two detailed studies of β-delayed protons from the decay of ^{23}Al have been published [11,12], reporting a number of proton peaks with energies between 200 and 1930 keV. The relative intensities of the peaks seen above ~300 keV are similar in the two experiments, but they differ sharply from one another at lower energies, exactly in the region of the protons emitted from the analog state. These are very low-energy protons to identify and observe efficiently in a $\Delta E - E$ particle telescope, even with a gas ΔE detector as used in both references, and a very plausible explanation for this discrepancy is that the proton spectrum in Ref. [12] has been partially cut off by experimental thresholds. One might then choose justifiably to rely entirely on Ref. [11] except that only in Ref. [12] are both protons and γ rays measured and the ratio between them determined for the decay that the authors attribute to the analog state. Thus, we have taken this ratio from Ref. [12], corrected it for the evident losses in that reference's low-energy proton spectrum (as determined by comparison with the proton spectrum in Ref. [11]) and obtained an estimate, 1.1(3)%, for the summed intensity of all proton decay branches. This estimate is reasonably consistent with the value 3.5(19)% proposed by Tighe *et al.* [11], which they base on a calculated production cross section combined with their measured proton intensities. Our value has already been incorporated into the branching ratios presented in Table I.

It is also interesting to note that we observe a 583-keV peak in our γ-ray spectrum, which is likely due to the decay of the first excited state in ^{22}Na. Since we took extra precautions to ensure that no ^{22}Mg impurity was present in our collected sample, we must conclude that this γ ray signals the presence of β-delayed proton decay channels from ^{23}Al that populate the first excited state of ^{22}Na in addition to its ground state. Neither published study of delayed protons from ^{23}Al [11,12] attributed any of their peaks to an excited-state channel, but they did not eliminate the possibility either. In any case, we conclude from the measured intensity of our 583-keV γ-ray peak that the contribution of the β-delayed proton decay branch to the first state of ^{22}Na is about 0.25%. Its effect on the results in Table I is thus negligible.

In addition to the IAS, we also find another state strongly populated ($\log ft = 3.76$) only 16 keV below it, at $E_x = 7787(2)$ keV. We find γ-decay branching to the ground/first-excited (451 keV)/second-excited (2051 keV) states to be 100/45(5)/5.5(21) and 3.8(25)/100/20(5) for the IAS and 7787-keV state, respectively. A state at (roughly) this energy has been seen before [14,17], also observed to decay predominantly to the 451-keV level, and assigned to be $(7/2^+)$ [17]. Observation of its production in allowed β decay now makes its positive parity unambiguous. Our experiment is the first to positively identify the IAS at $E_x = 7803(2)$ keV; it is also the first to see both the IAS and this $(7/2)^+$ state populated and resolved from one another in the same experiment.

None of this information was available at the time of the two β-delayed proton experiments [11,12]. Very likely it explains one of their puzzling observations. The strong low-energy proton peak observed by Tighe *et al.* [11] was attributed to decay of the IAS, which has isospin $T = 3/2$. The proton decay of this state to $T = 0$ states in ^{22}Na is isospin forbidden except through $T = 1/2$ admixtures present in its wave function, yet the observed proton peak was about 50 times larger than would have been expected from calculations with commonly accepted isospin nonconserving interactions [32]. The authors concluded that they had found evidence for "extremely strong isospin mixing" [11]. Now that we know there is a $T = 1/2$ state that is open to isospin-allowed proton decay and also strongly populated in β decay and lying only 16 keV below the IAS, we can conclude that with 40-keV resolution, the proton peak observed by Tighe *et al.* must contain a component of, and is probably dominated by, the decay of this level. This would explain the proton data without any need for extraordinary isospin mixing.

The isobaric analog state and its neighbors in ^{23}Mg must play an important role in the radiative proton capture reaction ^{22}Na$(p,\gamma)^{23}$Mg in an astrophysical environment. The states above the proton binding energy in ^{23}Mg [$S_p = 7580.3(14)$ keV [18]] become resonances in the capture process; therefore, their precise E_x, J^π, and decay widths are all needed to evaluate the resonant part of this reaction rate. With our more precise γ-ray energy determination and using the latest proton binding energy [18], we find the energy of the IAS resonance to be $E_{\rm res}({\rm IAS}) = 223(2)$ keV (energy in the center of mass of the system). Unfortunately, we cannot make a new determination of the strength for this resonance from the presently available data without inferring values from calculations that involve unchecked assumptions, so the uncertainties must remain as large as in [25].

Having clearly identified the 7787-keV state [$E_{\rm res} = 207(2)$ keV] as a key player, we can now estimate its resonance strength based on the assumption that the proton peak observed by Tighe *et al.* [11] is predominantly due to the decay of this state. We take from this reference the proton branching relative to higher energy proton peaks and then use the proton-to-γ-ray branching determined in Ref. [12], obtaining $\Gamma_p/\Gamma_\gamma = 0.08(2)$. From this result and the lifetime of the state as recently measured in a GAMMASPHERE experiment [17], $\tau = 10(3)$ fs, we derive the resonance strength $\omega\gamma = 2.6(9)$ meV. This value agrees with the one obtained from the direct measurement, $\omega\gamma = 1.4(3)$ meV [14]. However, this latter experiment was a difficult one involving a radioactive ^{22}Na target, and only the main γ-decay branch to the first excited state in ^{23}Mg was observed, an upper limit of 0.4 meV being set on each other possible γ-decay branch. The authors only included the single observed transition in their determination of $\omega\gamma$. Presumably to incorporate the possibility of other branches, the NACRE compilation [25] value, which was based on the same measurement, was $\omega\gamma = 1.8(7)$ meV—closer to what we find—and it was this value that was adopted in the nucleosynthesis calculation of Ref. [17].

The only other state in this energy region is the one seen at $E = 7769$ keV by Jenkins *et al.* [17]. We see no evidence of this state being populated in β decay, which is consistent with the 9/2 spin assumed by those authors.

Our newly determined strength for $E_{\rm res} = 207$ keV shows this to be the resonance that contributes most to the reaction rate for the important temperature range for ONe novae, $T_9 = 0.1$–0.4. This value, though more reliable, is not very different from those used in previous nucleosynthesis calculations, and it does not significantly change the reaction rates. The depletion of ^{22}Na via radiative proton capture, ^{22}Na$(p,\gamma)^{23}$Mg, is about 40% larger and will further diminish the detectability distances for the 1.275-MeV γ line from ^{22}Na decay in space-based telescopes. The estimates of the maximum detectability distances depend not only on the reaction rates obtained from nuclear data, but also on the novae models adopted. To recalculate them here is beyond the scope of this paper. As our rates are slightly higher than those obtained in Ref. [17] we can only conclude that these new data will further reduce the detection distance below the limit of 0.6 kpc found in that work for the INTEGRAL spectrometer SPI.

V. CONCLUSIONS

We have presented here the results of an experimental study of the β decay of pure samples of ^{23}Al. β singles and β-γ coincidences allowed us to determine the absolute branching ratios and *ft*-values for transitions to final states in the daughter nucleus ^{23}Mg, including some with already known spins and parities. From the latter we unambiguously determined $J^\pi = 5/2^+$ for the ^{23}Al ground state. This contradicts the earlier suggestion that $J^\pi = 1/2^+$, based on reaction cross section measurements [19] and relativistic mean field calculations

[20,21]; moreover, in our opinion, it also sheds serious doubt on the claim that ^{23}Al is a proton-halo nucleus. The large centrifugal barrier for a $d_{5/2}$ orbital and the already large Coulomb barrier should easily contain the wave function of the last proton inside the nuclear potential well, in spite of its low binding energy. This higher spin for the ^{23}Al ground state also has as a consequence that the direct component of the reaction rate for the radiative proton capture on ^{22}Mg is not very large. It decreases the possibility of a simple explanation for the nonobservation of the 1.275 MeV line from ^{22}Na decay in spectra taken by space-based γ-ray telescopes. There is no evidence that its precursor, ^{22}Mg, can be depleted in ONe novae explosions by the reaction ^{22}Mg$(p,\gamma)^{23}$Al.

In a recent conference communication [33], a RIKEN group reported measuring the magnetic moment of ^{23}Al and finding its value to be consistent with the normal shell model prediction for $J^{\pi} = 5/2^{+}$. Their results were published [34] after this paper was submitted for publication. It should be noted that assignments of spin-parities from magnetic moments are model dependent, while those from β-decay systematics are considered definitive [35]. Fortunately, in this case, both methods give the same result. The ground-state spin-parity of ^{23}Al is settled.

Currently, experimental studies of Coulomb dissociation of ^{23}Al are being carried out at RIKEN to determine the γ-ray width of its first excited state. The preliminary result in Ref. [36], $\Gamma_{\gamma} = 7.2 \pm 1.4 \times 10^{-7}$ eV, agrees with the value we estimated using single-particle wave functions for the $E2$ transition, $\Gamma_{\gamma} = 6 \times 10^{-7}$ eV, and was used in the calculation of the resonant term shown in Fig. 3b of Ref. [22] for the capture reaction rate ^{22}Mg$(p,\gamma)^{23}$Al.

We have also found two states in ^{23}Mg with small ft values at 7803(2) and 7787(2) keV and identified them to be the isobaric analog state of the ^{23}Al ground state and a $J^{\pi} = (7/2)^{+}$ state, which likely dominates the proton-decay spectrum. Both are resonances contributing to the depletion reaction, ^{22}Na$(p,\gamma)^{23}$Mg. For the latter resonance at $E_{\mathrm{res}} =$ 207(2) keV, we find its resonance strength to be $\omega\gamma =$ 2.6(9) meV, making it the dominant contributor to the reaction rate at the temperatures of explosive H burning in ONe novae. To further improve our knowledge about this reaction rate, a high-resolution remeasurement of the β-delayed proton decay of these ^{23}Mg states is desirable.

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