

Observation of strong isospin mixing in proton emission from the astrophysically interesting isobaric analog state in ^{23}Mg

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Utilizing the $^{24}\text{Mg}(p,2n)$ reaction and unique particle telescopes, beta-delayed proton emission from ^{23}Al proceeding via its isobaric analog state in ^{23}Mg has been observed. The relevant proton group was detected at 223 ± 20 keV with a proton decay branching ratio of $3.5 \pm 1.9\%$. The proton width determined for this state is approximately an order of magnitude larger than that predicted by a full-basis $1s-0d$ shell model calculation which includes the expected isospin mixing. In addition, the resulting resonance strength (45 ± 25 meV) has important astrophysical implications.

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There has been considerable astrophysical interest recently in breakout nuclear reactions from both the hot CNO cycle and the rapid proton capture (rp) process. Most of the important information for the relevant reactions involves difficult measurements of cross sections at subbarrier energies and may require radioactive targets. Additionally, many capture reactions [e.g., (p, γ)] must proceed via high-lying nuclear states for which little information is known. As we discuss below, advances in detector development permit the observation of low-energy protons (≥ 180 keV) in a very high beta particle background. This allows us to use the well-known technique of beta-delayed proton emission [1] in a new way in studying a reaction of astrophysical interest, namely the destruction of ^{22}Na in the hot NeNa cycle via proton capture to ^{23}Mg [2].

We wish to report our observation of beta-delayed proton emission from ^{23}Al proceeding via its isobaric analog state (IAS) in ^{23}Mg ($E^* = 7.795$ MeV, $J^\pi = 5/2^+$, $T = 3/2$). Aluminum-23 is the lightest nucleon-stable member of the $A = 4n + 3$, $T_z = -3/2$ mass series, and the only member of this series in which delayed proton emission from the IAS is potentially observable. We detected this group at a laboratory energy (E_{lab}) of 223 ± 20 keV, representing the lowest-energy identified proton group observed to date. Proton decay from the IAS does not conserve isospin, and can therefore only occur due to isospin mixing. A comparison between the proton width (Γ_p) of the ^{23}Mg IAS determined in the present work and the prediction of a full $1s-0d$ configuration shell model calculation which includes isospin mixing of the IAS indicates the observed isospin mixing is stronger by a factor of ~ 10 than predicted.

Beta-delayed proton emission from ^{23}Al ($T_{1/2} = 470 \pm 30$ ms) was first observed using standard Si-Si particle identification telescopes [3]. A proton group with $E_{\text{lab}} = 830 \pm 30$ keV was assigned to emission from an excited state in ^{23}Mg

658 keV above the IAS. A search for proton emission from the IAS led to a "crude" estimate of $\Gamma_p/\Gamma_\gamma \geq 50$ (i.e., $b_p \leq 2\%$) for the competition between the 7.8 MeV M1 gamma decay and the $E_{\text{lab}} = 206 \pm 6$ keV proton decay of this state [3].

In the present study, a helium-jet system [4] was utilized to collect and transport reaction products to a low-background counting area. The activity was deposited onto a collection tape in the center of our low-energy proton detector ball. The tape can be moved continuously to reduce the beta background from long-lived activities. Our low-energy proton detector ball [5] is capable of detecting identified protons with energies down to ~ 180 keV (see below) on essentially an event-by-event basis. It consists of six individual gas- ΔE , gas- ΔE , Si- E triple telescopes, although in helium-jet studies only four of the telescopes are used. Relative to the collection point, each of these four telescopes subtends a solid angle of $\sim 4\%$ of 4π . A cross-sectional view of one such triple telescope as well as a schematic cross-sectional view of the detector ball showing the relative placement of the six telescopes and the tape drive, is given in our study of ^{24}Al [6]. This triple telescope design reduces the random beta rate which enters the low-energy proton region by a factor of $> 10^6$ [5].

Preliminary proton energy calibrations were made utilizing the well known beta-delayed proton emitter ^{25}Si [7], produced via the $^{24}\text{Mg}(^3\text{He}, 2n)$ reaction. The resulting proton spectra demonstrate that the random beta rate is completely suppressed between the known 386.1 keV and 905.7 keV proton lines from ^{25}Si , allowing even the weak ^{25}Si proton peak at 534 keV to be clearly resolved (see Fig. 3 in Ref. [6]). Proton energy resolutions between ~ 40 keV and 50 keV (FWHM) have been routinely obtained. To acquire an energy calibration which reaches the lower limit of our detectors, it has been necessary to develop a reliable extrapolation technique at energies less than the lowest proton line from ^{25}Si (i.e., $E < 386$ keV).

Two independent experiments were performed in our study of ^{23}Al . In each case the $^{24}\text{Mg}(p, 2n)$ reaction was

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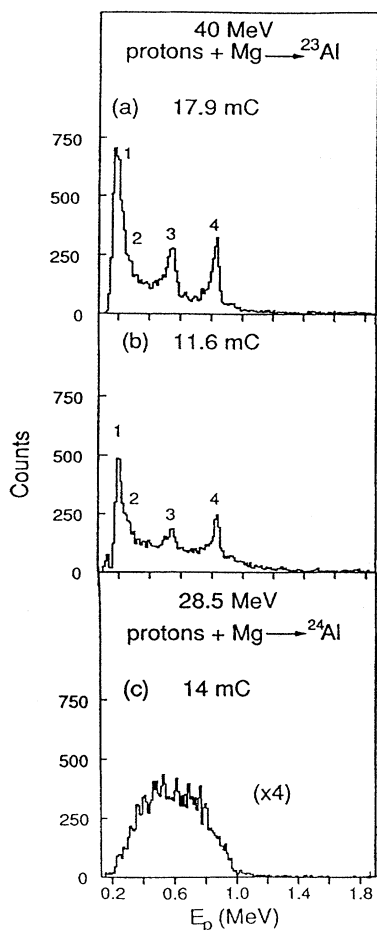


FIG. 1. Proton spectra for (a) a telescope with a continuously moving tape drive; (b) the same telescope as in (a) but for stopped tape collection; and (c) ^{24}Al .

used to produce ^{23}Al recoils. The 40 MeV proton beams produced by the 88-Inch Cyclotron at Lawrence Berkeley Laboratory, which had intensities up to $\sim 2 \mu\text{A}$, were pulsed to eliminate neutron induced background events. In each case, the cycle consisted of a 500 ms bombarding period followed by an 800 ms (beam off) counting period. In the first experiment the targets were all $\sim 1 \text{ mg/cm}^2 \text{ natMg}$. During this 17.9 mC bombardment [Fig. 1(a)], the tape drive system was moved continuously to remove longer-lived activities. The second, stopped tape, experiment utilized $\sim 1 \text{ mg/cm}^2 \text{ }^{24}\text{Mg}$ targets (99.8% enriched); this 11.6 mC bom-

bardment was performed with an on-target beam intensity (dc) of $\sim 400 \text{ nA}$ [Fig. 1(b)]. In Figs. 1(a)–1(c), the resulting projected proton spectra are shown when events are required to fall within *both* proton gates (one each in a separate gate ΔE -Si E 2D plot) of a telescope.

In both experiments an apparent continuum of low-energy protons was observed from low energies to $\sim 1100 \text{ keV}$ (see Fig. 1). Relative to the discrete proton lines observed, this continuum was enhanced in the second experiment (where a stationary collection point was used), implying the source of the proton continuum has a relatively long half-life. For this reaction and bombarding energy, the only potential beta-delayed proton emitters are ^{20}Na , ^{23}Al , and ^{24}Al . Thresholds for the $^{24}\text{Mg}(p, \alpha n)^{20}\text{Na}$, $^{24}\text{Mg}(p, 2n)^{23}\text{Al}$, and $^{24}\text{Mg}(p, n)^{24}\text{Al}$ reactions are 25.0, 30.8, and 15.3 MeV (lab beam energies), respectively. Subsequent experiments [6] have unambiguously assigned this proton continuum to delayed emission from ^{24}Al ($T_{1/2} = 2.053 \text{ s}$). Figure 1(c) shows the ^{24}Al beta-delayed proton spectrum.

Three proton groups from ^{23}Al are clearly evident in Fig. 1 (labeled 1, 3, and 4), including the previously known group (4) corresponding to an E_{lab} of 839 keV [3]. The laboratory energies and intensities (relative to the 839 keV line) of these groups are presented in Table I. In addition to these lines, there is evidence in each of the spectra for a high-energy shoulder (labeled 2) on the lowest-energy group. This has been assigned as a fourth ^{23}Al proton line and is included in Table I. It was observed in several proton spectra (not presented here) that proton peak 1 was slightly cut off on the low-energy side of the peak. Taking into account the expected FWHM of the group, the energy calibration, and the observed cutoff, a proton energy threshold of $180 \pm 10 \text{ keV}$ was determined for our triple telescopes. This calibration and energy cutoff were confirmed by a separate series of measurements which degraded the 386 keV proton group from ^{25}Si decay down to energies as low as 219 keV. Also included in Table I are the excitation energies in ^{23}Mg corresponding to the four proton groups observed. It can be seen in each case that there is good correspondence with a known level in ^{23}Mg [8]. Figure 2 presents a proposed partial decay scheme of ^{23}Al , in which the origin of each of the four observed proton lines is indicated. The assignment of the three newly observed proton groups to beta-delayed emission from ^{23}Al was based on both excitation function and half-life arguments (stopped tape). A subsequent bombardment at 28.5 MeV (below the ^{23}Al threshold but still above the ^{24}Al and ^{20}Na thresholds, see above) showed no evidence for these proton lines.

TABLE I. Summary of results for observed proton lines. Averages determined from experiments with continuously moving and stopped collection.

Peak No.	$E_{p, \text{lab}}$ (keV)	E^* in ^{23}Mg (keV)		
		This work	Ref. [8]	Rel. intensity
1	223 ± 20^a	7813 ± 20	7795 ± 6	2.2 ± 0.5
2	285 ± 20^a	7877 ± 20	7852 ± 6	0.9 ± 0.3
3	560 ± 5	8164 ± 6	8155 ± 6	0.7 ± 0.1
4	839 ± 5	8456 ± 6	8453 ± 5	1.0

^aLarger error bars apply to peaks below 387 keV due to systematic errors in the extrapolation.

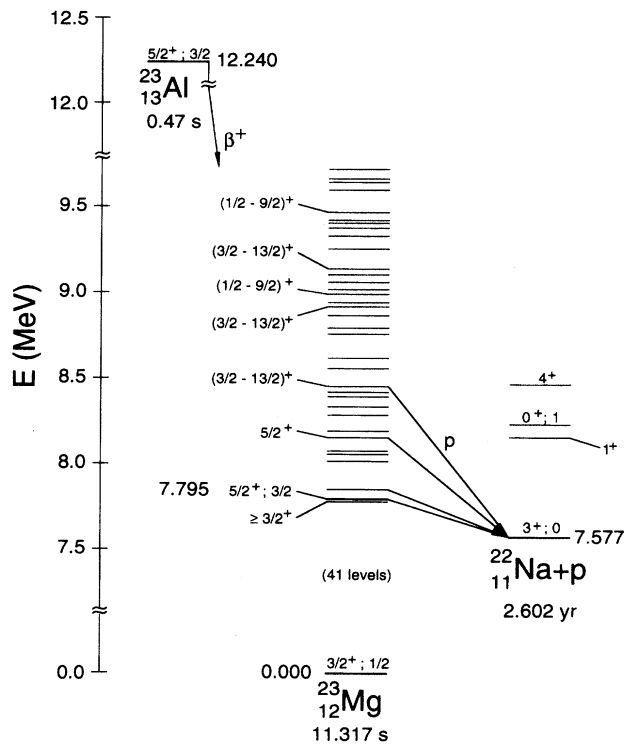


FIG. 2. Proposed partial decay scheme for ^{23}Al , indicating the four beta-delayed proton decays observed. Where the spin, parity, and/or isospin of a level are known, the values are given in the order $J^\pi; T$.

The proton group at 839 keV was produced with a cross section of ~ 220 nb at 40 MeV [3]. Then, using a calculated value of $\log ft = 3.28$ (see description of shell model calculations below) for the superallowed beta decay of ^{23}Al to the IAS of ^{23}Mg , a total ^{23}Al production cross section of $100 \mu\text{b}$ (as predicted by the statistical evaporation code ALICE [9]), and the weighted average of the relative yield between the 223 keV and 839 keV proton groups from the independent results of the various telescopes (2.2 ± 0.5 —this error encompasses all eight independently determined values utilized in the average), a proton branching ratio (b_p) of $3.5 \pm 1.9\%$ from the IAS can be determined [10]. The error in this branching ratio has been calculated by adding the statistical error to assumed errors from the two cross sections [11]. (It is also possible to determine b_p independently of cross sections by utilizing the calculated beta-decay branching ratios to the states corresponding to the 560 keV and 839 keV proton groups and their relative ratios to the 223 keV group. In each of these cases the value of b_p also agrees with $3.5 \pm 1.9\%$.)

In the past several years, full $1s-0d$ shell wave functions based on a single, smoothly mass dependent Hamiltonian have been realized [12]. The eigenvalues obtained from diagonalizing the “universal sd ” interaction of Wildenthal in the complete sd -shell space agree quite well with experimentally determined levels for all nuclei in the shell. In addition, the eigenfunctions yield matrix elements which reproduce various experimental observables. Since proton emission

from the IAS does not conserve isospin, it should proceed primarily through isospin mixing of the IAS with $J^\pi = 5/2^+$, $T = 1/2$ states or through isospin mixing in the proton daughter final state. Calculations based on isospin-mixed $1s-0d$ -shell wave functions obtained by adding the isospin-nonconserving (INC) interaction of Ormand and Brown [13] onto Wildenthal’s isospin-conserving interaction have successfully reproduced previous experimental results concerning isospin forbidden proton emission for proton-rich nuclei in the $A = 4n + 1$, $T_z = -3/2$ series [14]. These calculations essentially use a first order perturbation theory expansion to determine the contribution made by the various states which mix with the IAS to estimate the allowed spectroscopic amplitude for proton emission from the IAS. The gamma width of the lowest $T = 3/2$ (mirror) state in ^{23}Na is measured to be 3.0 eV [8]. The sd shell-model calculation for the width of this state [12] is in agreement with experiment; the calculated gamma width for the IAS in ^{23}Mg is also 3.0 eV. Utilizing the value of b_p determined above, this implies the proton width of the IAS ($\Gamma_{p,\text{exp}}$) is 0.11 ± 0.06 eV.

Using a Woods-Saxon potential with the depth adjusted to give the experimental decay energy, the unrestricted single-particle proton width for the IAS ($\Gamma_{p,\text{sp}}$) has been calculated to be 0.65 eV. Taking into account the uncertainty [8] in the proton decay energy (± 6 keV) and a modest deformation ($\epsilon \sim 0.15$) as previously observed in this mass region, one obtains a value for $\Gamma_{p,\text{sp}}$ of $0.91^{+0.34}_{-0.25}$ eV. This single-particle proton width, along with the proton width inferred above, then yields a spectroscopic factor (S_{exp}) of $0.12^{+0.07}_{-0.08}$. The shell-model calculations utilizing the INC interaction result in the much lower spectroscopic factor (S_{INC}) of 2.4×10^{-3} .

Comparing this result with reaction studies, the isospin allowed $^{25}\text{Mg}(p,t)^{23}\text{Mg}$ reaction strongly populates the IAS (as well as lower-lying $T = 1/2$ states). The (p,t) reaction [15] indicates no significant splitting of the IAS strength over possible nearby levels within 100 keV. Our calculations show that the nearest states which could be important for splitting are at 7.15 MeV and below and at 8.16 MeV. If there were any significant mixing with the 8.16 MeV state, the beta-decay branching to this state would be much larger than is observed. In analogy with the case of ^{24}Mg [16], we may postulate mixing of the IAS with an anti-analog state (AAS) about 800 keV below the IAS with an INC matrix element of ~ 150 keV (this is about three times larger than the typical Ormand-Brown INC matrix elements). This would give a 3.5% mixing [a strength which is not inconsistent with the (p,t) data] and $S_{\text{INC}} = 0.006$ (assuming the allowed AAS value of $S = 0.17$ from the shell-model calculations). This provides closer agreement within probable error, given our experimental results, the above analysis, and the many uncertainties involved in the calculation of the emission of such low-energy, isospin forbidden protons.

Recently there has been considerable interest in further understanding the rp-nucleosynthesis process in the Ne-Na-Mg region, particularly with regard to the hot NeNa cycle. Specifically, reaction rates for determining ^{22}Na abundances are important since the decay of ^{22}Na ($T_{1/2} = 2.6$ yr) provides an attractive mechanism for producing ^{22}Ne isotopic anomalies (NeE), which have been observed in meteoritic inclusions [17]. The proton capture reactions producing

^{22}Na are well understood. However, the abundance of ^{22}Na also depends critically on the rates of possible depletion reactions, the most important being the $^{22}\text{Na}(p, \gamma)^{23}\text{Mg}$ reaction ($Q=7.577$ MeV). Hence, the resonant proton capture width to the IAS of ^{23}Mg is critical. The value of $\Gamma_{p,\text{exp}}$ determined in the present work implies a resonance strength ($\omega\gamma$) of 45 ± 25 meV for the IAS (see Ref. [2] for the definition of $\omega\gamma$). This strength and resonance energy will dominate the predicted reaction rate [18] by a factor of ~ 10 to 1000 in the range $0.1 \leq T_9 \leq 0.5$ (where T_9 is the temperature in billions of degrees K), potentially the most interesting range of temperatures for hydrogen burning in the NeNa cycle for astrophysical sites (i.e., novae) thought to be important in understanding NeE abundances [18]. There have been reports of two recent experiments utilizing radioactive ^{22}Na targets to search for $^{22}\text{Na}(p, \gamma)^{23}\text{Mg}$ resonances. In the first experiment [19], the proton bombarding energies were too high to sample the IAS. In the second experiment [18], proton energies of 170–1290 keV were used. Although no resonance was observed corresponding to capture to the 7.795 keV state in ^{23}Mg ($E_{\text{lab}}=227$ keV), limits of $\omega\gamma \leq 1.3$

meV and $\omega\gamma \leq 10$ meV were quoted for two separate detection methods. However, the quite recent value of $\omega\gamma$ [20] determined in the $^{22}\text{Na}(^3\text{He}, d)$ measurement ($0.05 \leq \omega\gamma \leq 33$ meV) overlaps both our result and that of Ref. [18]. Although the value of $\omega\gamma$ for the IAS determined in the present work indicates the hydrogen burning environment on the surface of novae is a less attractive mechanism for producing NeE anomalies, there has been a recent suggestion [21] that these abundances may be attributed to ^{22}Ne produced directly in the core of intermediate mass stars.

Using the $^{24}\text{Mg}(p, 2n)$ reaction and low-energy proton particle telescopes we have observed beta-delayed proton emission from ^{23}Al through its IAS in ^{23}Mg . The value of b_p determined yields a $\Gamma_{p,\text{exp}}$ which implies extremely strong isospin mixing of the IAS in ^{23}Mg .

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