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R.J. Tighe, J.C. Batchelder, D.M. Moltz, T.J. Ognibene,
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R.J. Tighe, J.C. Batchelder*, D.M. Moltz, T.J. Ognibene, M.W. Rowe, and Joseph Cerny

Department of Chemistry and Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720, USA

and

B.A. Brown

National Superconducting Cyclotron Laboratory and Department of Physics and
Astronomy, Michigan State University, East Lansing, MI 48824-1321

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OBSERVATION OF STRONG ISOSPIN MIXING IN PROTON EMISSION FROM THE ASTROPHYSICALLY INTERESTING ISOBARIC ANALOG STATE IN ^{23}Mg

R. J. Tighe, J. C. Batchelder*, D. M. Moltz, T. J. Ognibene, M. W. Rowe, and
Joseph Cerny
Department of Chemistry and Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

and

B. A. Brown
National Superconducting Cyclotron Laboratory and
Department of Physics and Astronomy
Michigan State University
East Lansing, MI 48824-1321

Utilizing the ^{24}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 for the first time. The relevant proton group was detected at 223±20 keV with a proton decay branching ratio of 3.5±1.6%. 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±20 meV) has important astrophysical implications.

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Beta-delayed particle decay studies have provided a wealth of spectroscopic information for proton- and neutron-rich nuclei removed from the valley of beta stability [1]. This includes knowledge of level energies, spins, isospins, widths, densities, and beta-decay properties. In addition, the study of delayed-particle decay modes can provide an alternative method in the investigation of astrophysically interesting capture reactions (which often require the use of radioactive targets and/or beams to study directly). 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^π=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. The unique capabilities of our low-energy proton detector ball enabled us to detect the group of interest 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. The proton width of the IAS of ^{23}Mg also has important astrophysical implications concerning the hot NeNa cycle, which is thought to provide an attractive mechanism for understanding anomalous ^{22}Ne isotopic abundances in carbonaceous meteorites [2].

Beta-delayed proton emission from ^{23}Al ($T_{1/2}$=470±30 ms) was first observed using standard Si-Si particle identification telescopes [3]. A proton group with E_{lab} = 830±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 $\Gamma_\gamma/\Gamma_p \geq$ 50 (*i.e.*, $b_p \leq 2\%$) for the competition between the 7.8 MeV M1 gamma decay and the E_{lab} = 206±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. In brief, our targets were located in a chamber pressurized to ~1.3 atm with helium. In the present experiments, a multiple-target, multiple-capillary setup was used (see Ref. [5] for details). Five targets were placed in the helium-jet chamber, with eleven internal capillaries utilized to collect radioactivity. (The eleven capillaries were then combined into a single transport capillary.) Reaction products recoiled out of the targets, were thermalized in the helium, swept out of the chamber (on KCl aerosols suspended in the gas) and transported via a 75 cm long capillary (0.9 mm i.d.) to the counting chamber. Here, they were 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. However, this tape movement makes half-life determinations extremely difficult. Consequently, when half-life measurements are desired, the collection point is stationary and is stepped forward periodically (~ every 30 minutes).

Our low-energy proton detector ball [6] 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 ~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, including the placement of the tape drive, is given in our study of ^{24}Al [7]. This triple telescope design reduces the random beta rate which enters the low-energy proton region by a factor of $>10^6$. In addition, these gas-ΔE, Si-E telescopes have proton detection efficiencies which are energy independent for incident proton energies between ~200 keV to 6000 keV [6].

Preliminary proton energy calibrations were made utilizing the well known beta-delayed proton emitter ^{25}Si [8], produced via the ^{24}Mg(^{3}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 [7]). Proton energy resolutions between ~ 40 keV to 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). This procedure is described in detail in Ref. [7].

Two independent experiments were performed in our study of ^{23}Al. In each case the ^{24}Mg(p,2n) reaction was 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 ~2 μA, were pulsed to eliminate neutron induced background events and to facilitate half-life determinations. 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 ~1 mg/cm^2 ^{nat}Mg. During this 17.9 mC bombardment, the tape drive system was moved continuously to remove longer-lived activities. The second experiment utilized ~1mg/cm^2 ^{24}Mg targets (99.8 % enriched); this 11.6 mC bombardment was performed with an on-target beam intensity (dc) of ~400 nA. In this experiment the collection point was kept stationary to permit half-life measurements (see below). Results from the first bombardment are presented in Figures 1 and 2. In Figure 1, two-dimensional plots of both gas-ΔE signals ("trigger" and "filter") versus the Si-E signal are shown for one telescope. These represent "back-projected" two-dimensional spectra generated by requiring that events fall within the gated proton region of the other gas-ΔE versus Si-E plot (in principle, the gated events could fall anywhere in these "back-projected" spectra). Three distinct proton groups are evident in the proton regions shown in Figure 1. (The proton gates employed in the analysis were set utilizing the groups from ^{25}Si, and extrapolated to energies below 386 keV (see Ref. [7]).) In Figures 2a-c, the resulting projected proton spectra for three of the telescopes are shown when events are required to fall within both of the proton gates of a telescope. Similar proton spectra were obtained in the second bombardment (see difference noted below).

In both experiments an apparent underlying continuum of low-energy protons was observed from low energies to ~ 1100 keV (see Figure 2). 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}Mg(p,αn)^{20}Na, ^{24}Mg(p,2n)^{23}Al, and ^{24}Mg(p,n)^{24}Al reactions are 25.0, 30.8, and 15.3 MeV (lab beam energies), respectively. Subsequent experiments [7] have unambiguously assigned this proton continuum to delayed emission from ^{24}Al ($T_{1/2}$ = 2.053 s).

Three proton groups from ^{23}Al are clearly evident in Figure 2 (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 cut-off, a proton energy threshold of 180±10 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 [9]. Figure 3 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.

The proton group at 839 keV was previously determined to be produced with a maximum cross section of ~220 nb [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 μb (as predicted by the statistical evaporation code ALICE [10]), 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), a proton branching ratio (b_p) of 3.5±1.6% [11] from the IAS can be determined [12]. (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±1.6%.)

In the past several years, full 1s-0d shell wave functions based on a single, smoothly mass dependent Hamiltonian have been realized [13]. 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^π=5/2$^+$, T=1/2 states or through isospin mixing in the proton daughter final state. (However, no significant mixing of the ^{22}Na (J^π=3$^+$) ground state is expected.)

Calculations based on isospin-mixed 1s-0d-shell wave functions obtained by adding the isospin-nonconserving (INC) interaction of Ormand and Brown [14] 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 [15]. 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 mirror state in ^{23}Na is measured to be 3.0 eV [9]. The sd shell model calculation for the width of this state [13] is in agreement with experiment; the calculated gamma width for the IAS in ^{23}Mg is also 3.0 eV. Utilizing the value for b_p determined above, this implies the proton width of the IAS ($\Gamma_{p,exp}$) is 0.11±0.05 eV. Interestingly, a quite recent and (as yet) unpublished measurement of the proton width of the IAS obtained using the ^{22}Na(^{3}He,d)^{23}Mg reaction [16], which is again an isospin forbidden transition, yields a proton width of $0.05^{+.02}_{-.04}$ eV for the IAS [17].

Using a Woods-Saxon potential with the depth adjusted to give the experimental decay energy, the unrestricted single-particle proton width for the IAS ($\Gamma_{p,sp}$) has been calculated to be 0.65 eV. Taking into account the uncertainty [9] in the proton decay energy (±6 keV) and a modest deformation (ε~0.15) as previously observed in this mass region, one obtains a value for $\Gamma_{p,sp}$ of $0.91^{+.34}_{-.25}$ eV. This single-particle proton width, along with the proton width inferred above, then yields a spectroscopic factor (S_{exp}) of $0.12^{+.06}_{-.07}$. The shell model calculations utilizing the INC interaction result in the much lower spectroscopic factor (S_{INC}) of 2.4x10^{-3}.

Comparing this result with reaction studies, the isospin allowed ^{25}Mg(p,t)^{23}Mg reaction strongly populates the IAS (as well as lower-lying T=1/2 states). The (p,t) reaction [18] indicates no significant splitting of the IAS strength over possible nearby levels within 100 keV. 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 [19], 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 3 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 $S_{INC} = 0.006$ (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.

A further understanding of rp-process nucleosynthesis in the Ne-Na-Mg region, particularly with regard to the hot NeNa cycle, has recently been the source of considerable interest. Specifically, reaction rates for determining ^{22}Na abundances are important since the decay of ^{22}Na ($T_{1/2}$ = 2.6 y) provides an attractive mechanism for producing ^{22}Ne isotopic anomalies (NeE), which have been observed in meteoritic inclusions [20]. 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}Na(p,γ)^{23}Mg reaction (Q=7.577 MeV). Hence, the resonant proton capture width to the IAS of ^{23}Mg is critical. The value of $\Gamma_{p,exp}$ determined in the present work implies a resonance strength ($\omega\gamma$) of 45±20 meV for the IAS (see Ref. [2] for the definition of $\omega\gamma$). This strength and resonance energy will dominate the predicted reaction rate [21] by a factor of ~10 to 1000 in the range $0.1 \geq T_9 \geq 0.5$ (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 [21]. There have been reports of two recent experiments utilizing radioactive ^{22}Na targets to search for ^{22}Na(p,γ)^{23}Mg resonances. In the first experiment [22], the proton bombarding energies were too high to sample the IAS. In the second experiment [21], 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_{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 $\omega\gamma$ determined in the ^{22}Na(^{3}He,d) measurement (20^{+10}_{-20} meV) is in approximate agreement with our result [16]. 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 [23] that these abundances may be attributed to ^{22}Ne produced directly in the core of intermediate mass stars.

Using the ^{24}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 $\Gamma_{p,exp}$ which implies extremely strong isospin mixing of the IAS in ^{23}Mg. This partial width also has potentially important astrophysical implications related to the destruction of ^{22}Na in the hot NeNa cycle.

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*Present address: Oak Ridge National Laboratory, Building 6008, MS 6374, Oak Ridge, TN 37831-6374.

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Figure Captions

Figure 1. Two-dimensional spectra for both the "trigger" and "filter" gas-ΔE signals versus the Si-E signal obtained by "back projecting" (see text). A threshold of 10 counts has been used in the figure.

Figure 2. Proton spectra for three independent telescopes with a contiuously moving tape drive.

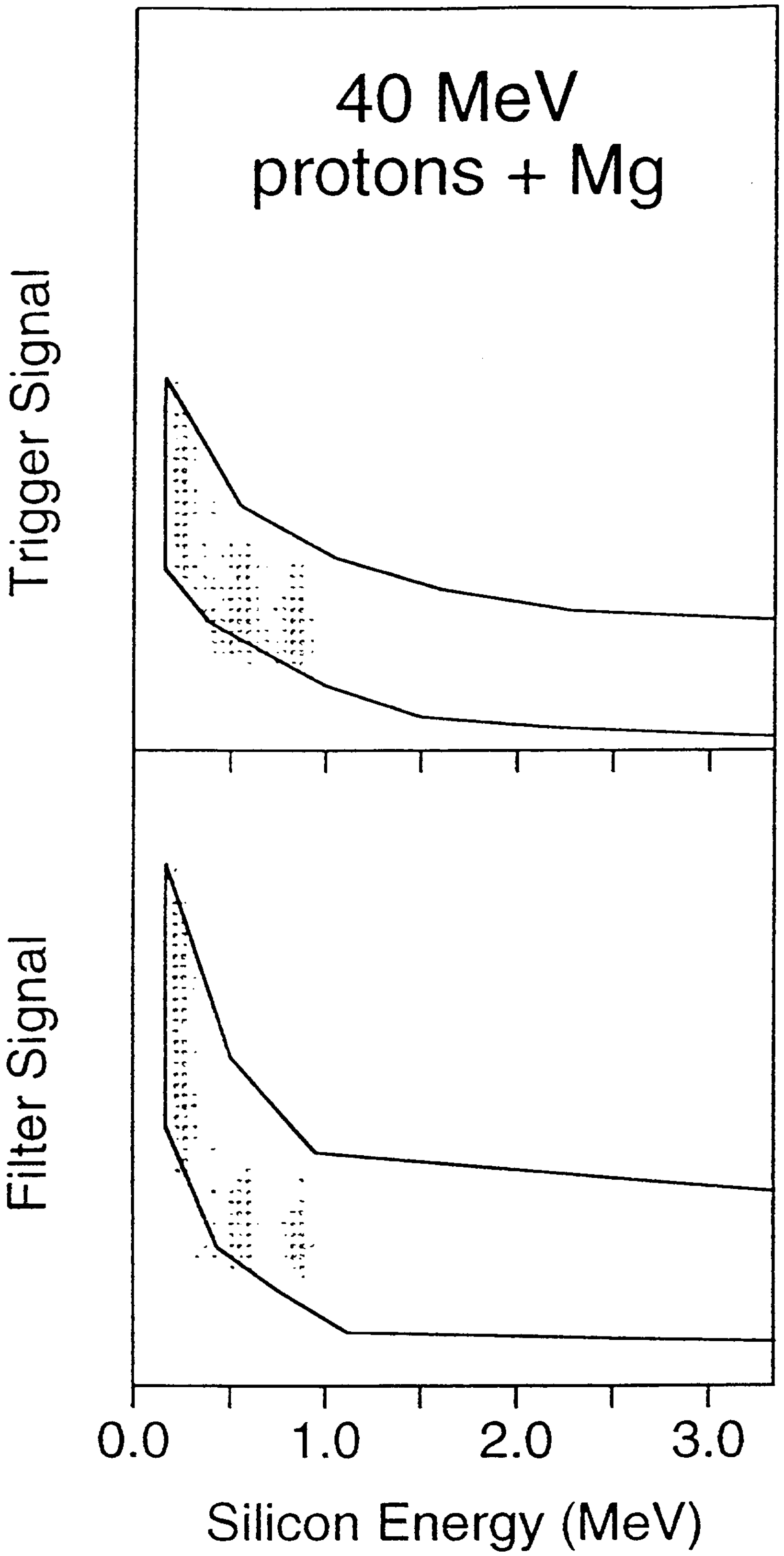
Figure 3. Proposed partial decay scheme for ^{23}Al, indicating the four beta-delayed proton decays observed. Where the spin, parity, and/or isospin of a level are known, the values are given in the order J^{π};T.

TABLE I. Summary of results for observed proton lines [a].

		E* in ^{23}Mg (keV)		
Peak No.	$E_{p,lab}$ (keV)	This work	Ref. [9]	Rel. Intensity
1	223±20[b]	7813±20	7795±6	2.2±0.5
2	285±20[b]	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

[a] Averages determined from experiments with continuously moving and stopped collection.

[b] Larger error bars apply to peaks below 387 keV due to systematic errors in the extrapolation.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Trigger Signal
Filter Signal
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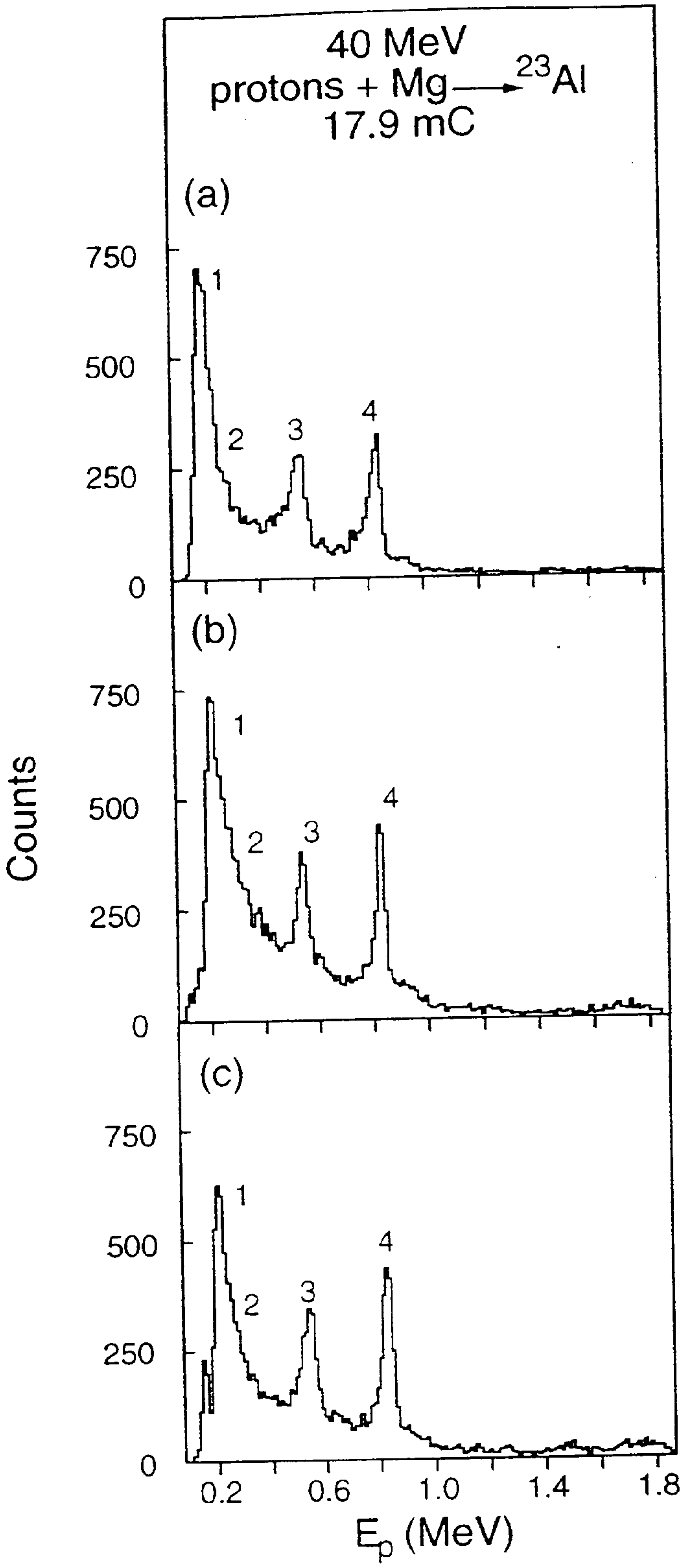
1.0
2.0
3.0
Silicon Energy (MeV)

XBL 948-539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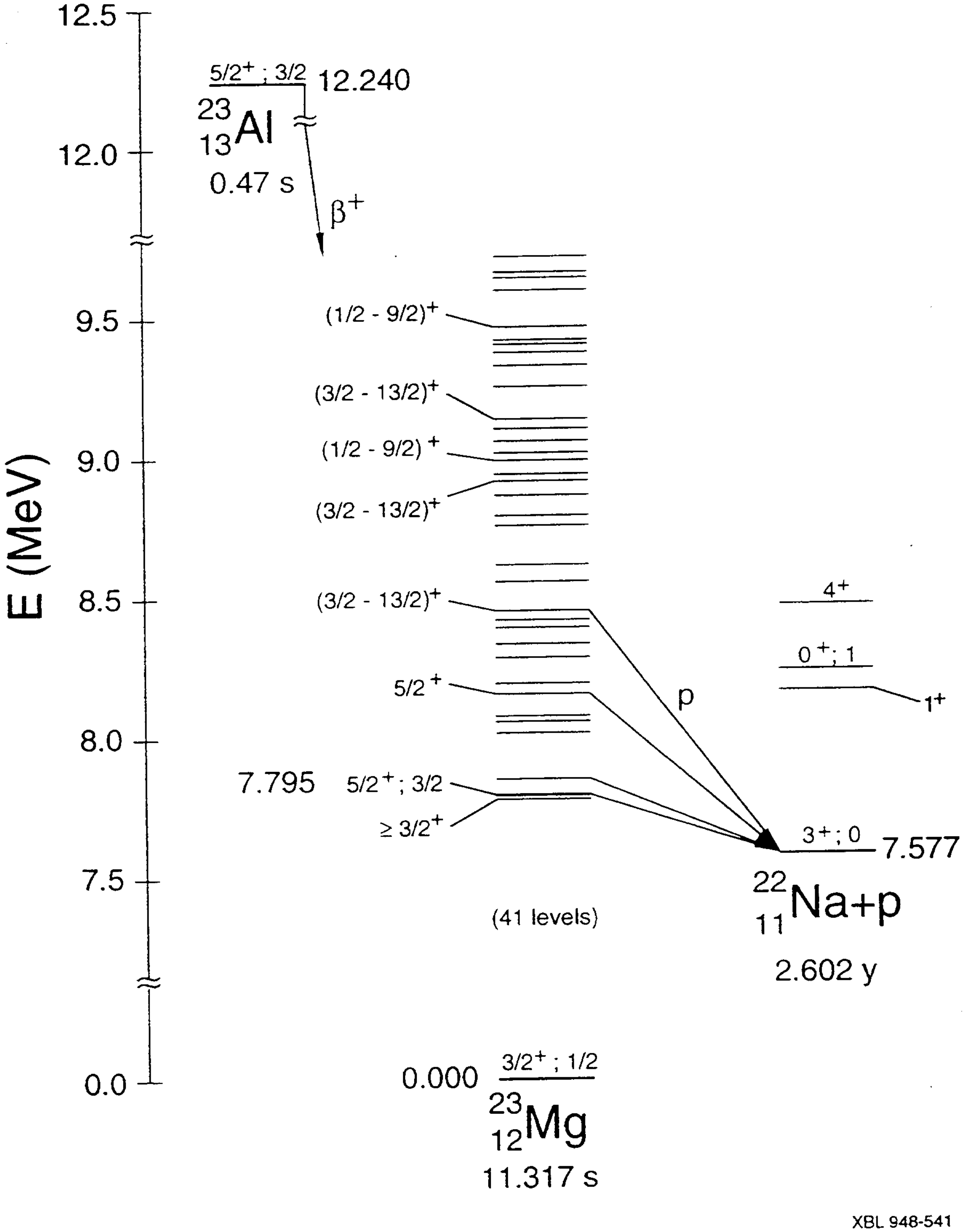
protons + Mg ⟶ ^{23}Al
17.9 mC
(a)
(b)
(c)
750
500
250
0
1
2
3
4
Counts
0.2
0.6
1.0
1.4
1.8
E_p (MeV)

XBL 948-540


E (MeV)
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12.0
9.5
9.0
8.5
8.0
7.5
0.0
5/2+ ; 3/2
12.240
23 13 Al
0.47 s
β+
(1/2 - 9/2)+
(3/2 - 13/2)+
(1/2 - 9/2)+
(3/2 - 13/2)+
(3/2 - 13/2)+
5/2+
7.795
5/2+; 3/2
≥ 3/2+
(41 levels)
p
4+
0+; 1
1+
3+; 0
7.577
22 11 Na+p
2.602 y
0.000
3/2+ ; 1/2
23 12 Mg
11.317 s
XBL 948-541