critical point.

Several other related examples will be reported in a separate paper[6] with detailed arguments on the above models. [As should be the case, spin correlations obtained exactly in the model (1) satisfy Griffiths-Kelly-Sherman inequalities[7] for $J_k \geq 0$ and $J_k' \geq 0$.]

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β-Delayed Proton Emission of ^{23}Al†

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The weak β-delayed proton emitter ^{23}Al, with a half-life of 470 ± 30 msec, was produced by the reaction ^{24}Mg$(p, 2n)^{23}$Al. We observed delayed protons with a center-of-mass energy of 870 ± 30 keV and a maximum production cross section ≈ 220 nb.

Recent mass measurements[1] have shown ^{23}Al to be the lightest, nucleon-stable member of the mass series $A = 4n + 3$, $T_z = \frac{1}{2}(N - Z) = -\frac{3}{2}$; however, no technique capable of characterizing the decay properties of these nuclides has been demonstrated. Using the ^{24}Mg$(p, 2n)$ reaction we have observed ^{23}Al through its β-delayed proton emission. Extension of this approach to heavier $T_z = 0$ target nuclei should, in principle, permit the observation of several heavier members of this mass series which are predicted[2] to be nucleon stable (^{27}P through ^{35}K).

The external proton beam of the Berkeley 88-in. cyclotron was used to induce the reaction ^{24}Mg$(p, 2n)^{23}$Al on 99.96%-enriched ^{24}Mg targets. Two independent experimental approaches were used. In the first of these, delayed protons from activity in the target were detected in a counter telescope mounted downstream from the target behind a slotted, rotating wheel. This wheel controlled the duration of the beam pulse and shielded the detectors during the beam-on intervals. Beam pulsing was achieved by modulating the cyclotron dee voltage; we utilized beam intensities of up to 8 μA on target. In these experiments a detector telescope, consisting of an 8-μm ΔE detector, fed a Goulding-Landis particle identifier. Any long-range particles were eliminated by a 50-μm reject detector. In order to observe low-energy protons (and α particles), singles spectra were recorded from the 8-μm detector as well as from an additional 14-μm detector. All detectors (except the ΔE) were cooled to -25°C. Accurate energy scales were obtained in this setup by scattering, from a thin Au foil, H_2^+ beams of 0.63 and 1.15 MeV/nucleon as measured in an analyzing magnet (a 4-μm ΔE detector was used for this calibration).

The second experimental configuration employed a helium-jet system[3] which swept nuclei recoiling from the target through a 0.48-mm-diam, 80-cm-long capillary and deposited them on a 550-μg/cm^2 Ni collector foil. At 1.2-sec intervals this foil was quickly (~ 25 msec) moved by a solenoidal stepping motor from the collection position to a position in front of a counter telescope. The telescope and its associated electronics were identical to those in the first setup except that it employed a 6-μm ΔE detector. In these experiments we utilized a continuous proton beam of up to 8 μA on target. By comparing the yields obtained in both experimental configurations (corrected for recoil-range effects), the absolute efficiency of the helium-jet technique for collecting ^{23}Al was determined to be ~10%. This disadvantage was offset by the higher attain-

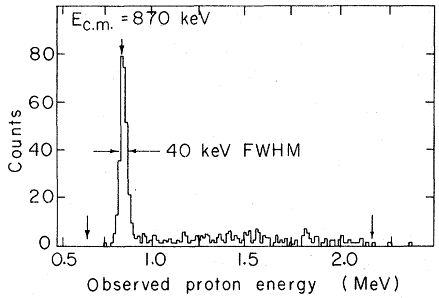

FIG. 1. An identified proton spectrum arising from the bombardment of ^{24}Mg by 40-MeV protons using the helium-jet technique. The vertical arrows designate the energy region over which protons could be observed.

able geometry as well as by the improved energy resolution which was a result of the very thin layer of collected activity.

Figure 1 shows an identified-proton energy spectrum arising from the bombardment of ^{24}Mg with 40-MeV protons using the helium-jet technique. Essentially no background is present arising from β-particle pile-up. The dominant group in the spectrum has an energy of 870 ± 30 keV in the c.m. system. Higher-energy events (from 0.95 to 2.2 MeV lab) were observed in both experimental configurations. Although these events had a half-life consistent with that of the dominant group at 870 keV, their low yield precluded the assignment of other distinct transitions. The 870-keV group was observed to have a half-life of 470 ± 30 msec and was produced with a maximum cross section ≈ 220 nb. This half-life is consistent with the upper limit of 560 msec obtained from simple calculations using a $\log ft = 3.3$ for the superallowed decay[4] of ^{23}Al and known $\log ft$ values for the first three allowed decays of its mirror nucleus ^{23}Ne.

Figure 2 shows excitation-function data (acquired with the slotted-wheel technique) which establish ^{23}Al as the only possible source of this new activity. Figure 2(a) presents an excitation function for the 870-keV proton group in which the experimental threshold is consistent with the expected value of 30.78 ± 0.08 MeV for the reaction ^{24}Mg$(p, 2n)^{23}$Al. However, the threshold for the reaction ^{24}Mg$(p,\alpha n)^{20}$Na is only 24.99 ± 0.01 MeV and, though ^{20}Na is a well-known β-delayed α emitter,[5] it is possible for it to emit β-delayed protons $\lesssim 1$ MeV. Furthermore, its known half-life of 445.7 ± 3.1 msec[6] is uncomfortably similar to the observed ^{23}Al half-life of 470 ± 30 msec.

Figure 2(b) shows the ratio of relative yields of ^{23}Al protons to α particles from the decay of ^{20}Na;

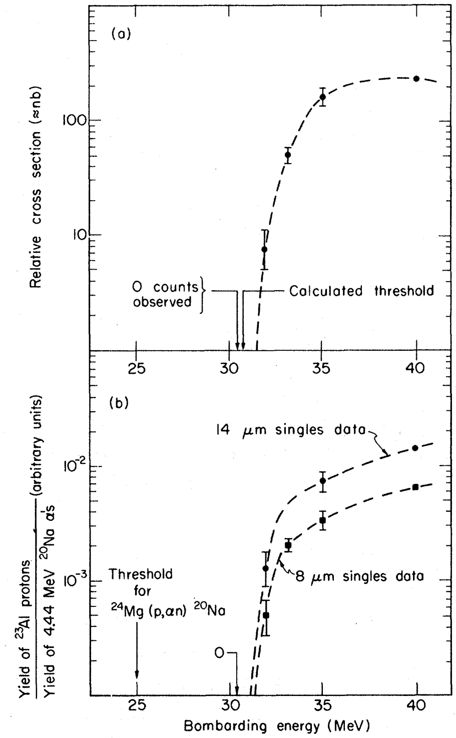

FIG. 2. (a) An excitation function of identified protons arising from the reaction ^{24}Mg$(p,2n)^{23}$Al. Where error bars are not shown, they are smaller than the data points. (b) The yield ratio of ^{23}Al identified protons to ^{20}Na α particles on an arbitrary scale as a function of bombarding energy.

both yields were measured simultaneously. The ^{20}Na yield was determined from its 4.44-MeV α group, detected via its ΔE loss, in two independent singles detectors of 8 and 14 μm thicknesses. The yield ratio is seen to vary by a factor of approximately 10 over an 8-MeV range of bombarding energy. This variation eliminates ^{20}Na as a possible source of the 870-keV protons. All other proton-induced reactions on ^{24}Mg which can lead to β-delayed proton emitters have thresholds much higher than that observed. Furthermore there are no reasonable target contaminants which could account for this activity; ^{23}Al remains the only possible source of the delayed protons.

A preliminary decay scheme for ^{23}Al is presented in Fig. 3. The assumed ground-state spin of $\frac{5}{2}^+$ is based on its mirror ^{23}Ne; other data in the figure are from Hardy *et al.*[7] and Haun and Robertson.[8] For simplicity we have shown the 870-keV group decaying to the ground state of ^{22}Na. The protons, then, would originate from a heretofore unknown state at 8.45 MeV in ^{23}Mg which, if

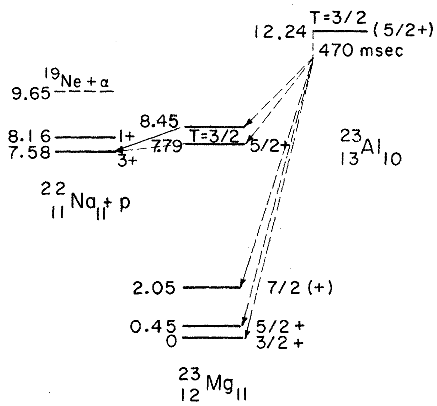

FIG. 3. A preliminary decay scheme for ^{23}Al. Energies are given in MeV. Decays which have not been directly observed are shown as dashed lines.

populated by allowed β decay, is restricted to $J^\pi = \frac{3}{2}^+,\ \frac{5}{2}^+$, or $\frac{7}{2}^+$.

The superallowed β decay of nuclides in the mass series $A = 4n+3$, $T_z = -\frac{3}{2}$ leads to levels in their daughters which are very close to the proton separation energy. The superallowed decay of ^{23}Al feeds the lowest $T = \frac{3}{2}$ state in ^{23}Mg at 7.788 ± 0.025 MeV[7]; proton emission from this state would be isospin forbidden and of low energy (209 ± 25 keV c.m.). Penetrability calculations alone show the width for this proton emission to be of the same order of magnitude as a typical 7.8-MeV $M1$ γ ray in this mass region.[9] Although the possibility of observing these protons was, at best, marginal, an attempt was made using the helium-jet method. The experiment was conducted with a 40-MeV proton beam. The low-energy proton group was searched for in the spectrum from the 6-μm ΔE counter of the usual detector telescope (located on the same side of the collector foil as the deposited activity). In order to minimize the background of low-energy ^{16}O recoils formed in the decay of ^{20}Na (which was always present as a reaction by-product), an additional high-geometry (3.3 sr) counter, located behind the collector foil, was placed in anticoincidence with the 6-μm detector. No experimental evidence for a 209-keV (c.m.) proton group was found; these results permit a very crude estimate[10] that $\Gamma_\gamma/\Gamma_p \gtrsim 50$ for the isospin-forbidden decay of the 7.79-MeV ($T = \frac{3}{2}$) state of ^{23}Mg.

Heavier members of the mass series $A = 4n+3$, $T_z = -\frac{3}{2}$ are also expected to emit β-delayed protons of low energy and can, in principle, be observed using the techniques described in this work.

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