ISOSPIN-FORBIDDEN DECAY OF THE 0^+, $T=2$ STATE AT 15.43 MeV IN ^{24}Mg †

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The sought, but previously unobserved, isospin-forbidden particle-decay modes of a $T=2$ state in a $T_z=0$ nucleus have been determined by particle-particle coincidence techniques. Proton decays ($\Delta T=1$ or 2) and strong evidence for α-particle decays ($\Delta T=2$) from the $T=2$ state of ^{24}Mg were observed and show $\sum\Gamma_{\text{particle}} \gg \Gamma_\gamma$.

Even though the locations (and very large upper limits on the widths) of many 0^+, $T=2$ states in $T_z=0$ nuclei are known,[1,2] no further information on their properties is available. Since in general no $T=2$ particle-decay channels are open for these $T=2$ states, they are expected to be relatively sharp. Their isospin-forbidden particle decays are of particular interest since they provide a sensitive measure of the isospin impurity admixed into these states by charge-dependent forces (Coulomb plus nuclear). Although attempts to determine the particle-decay properties and total widths of these states through their observation as "twice T-forbidden" compound-nucleus resonances in proton scattering have been made—a technique successfully applied to $T=\frac{3}{2}$ states[3,4]—solely negative results were obtained.[3,5,6]

In order to be certain that a typical $T=2$ state does indeed possess a total particle width comparable with its gamma width ($\sum\Gamma_{\text{particle}} \gtrsim \Gamma_\gamma$), and to establish its decay properties sufficiently to ascertain whether its exploration by compound resonance techniques is feasible, the isospin-forbidden particle decay of the 0^+, $T=2$ state of ^{24}Mg populated in the isospin-allowed reaction $^{26}\text{Mg}(p,t)^{24}\text{Mg}$ has been investigated. This particular $T=2$ state was chosen since previous searches for it in resonance experiments were unsuccessful[3,6] and since its low proton-decay energy makes it accessible to standard electrostatic accelerators.

Figure 1(a) shows all the probable[7] decay modes open to the $T=2$ state of ^{24}Mg. Utiliz-

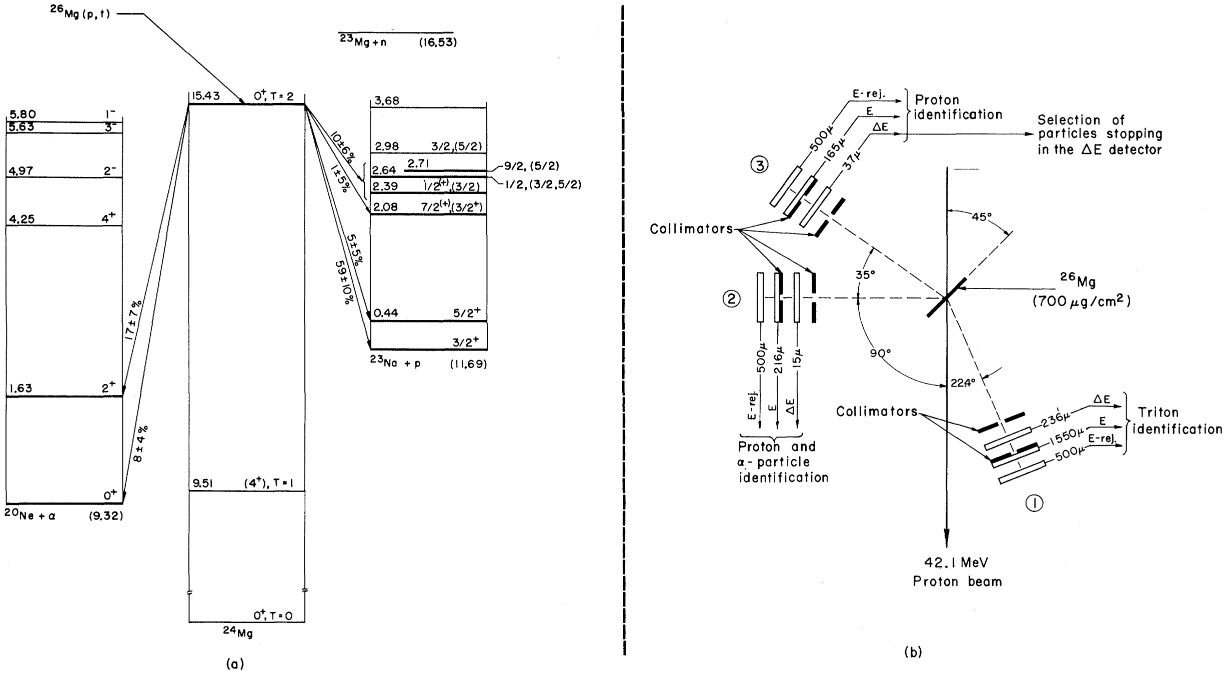

FIG. 1. (a) Level diagram showing the 0^+, $T=2$ state at 15.43 MeV in ^{24}Mg and its possible particle-decay modes. Observed transitions are indicated with arrows, along with their percentage branching ratios. (b) Schematic representation of the experimental setup showing the arrangement of the three telescopes and target with respect to the incident beam. Thicknesses of the phosphorous-diffused or lithium-drifted silicon detectors are indicated.

ing the 42.1-MeV proton beam of the Berkeley 88-inch cyclotron, we have measured coincidences between tritons forming this state at 15.43 ± 0.07-MeV excitation and decay protons [$E_{\max}$(lab) = 3.9 MeV] or α particles [$E_{\max}$(lab) = 6.1 MeV] leading to the ^{23}Na or ^{20}Ne levels indicated by heavy lines in the figure. Figure 1(b) presents the layout of the three three-counter telescopes which were employed; E-reject detectors were used to reduce background. Tritons leading to the $T = 2$ state were identified[8] in system 1 placed at the $L = 0$ peak angle of 22.4 deg (lab). Fast and slow coincidences were required between tritons and (A) identified protons in system 2 or 3 or identified α particles in system 2 (solid angles of 3.5×10^{-3} sr) or (B) particles stopping in the ΔE detector of system 3 (solid angle of 8.0×10^{-3} sr). Because of the small solid angles of systems 2 and 3 arising from the need for particle identification, the low cross section for tritons populating the $T = 2$ state ($d\sigma/d\Omega \approx 100$ μb/sr), and a counting-rate limitation of 30 000 cps in the system-1 E detector, an average of only two coincidence events per hour in both systems from the decay of this state was obtainable. 40 hours of coincidence data were recorded in four 512×512 arrays on magnetic tape utilizing an on-line PDP-5 computer while the cumulative triton singles data were stored in a 1024-channel pulse-height analyzer. The spin-zero property of the $T = 2$ state ($\Gamma \leq 35$ keV[9]) guaranteed an isotropic decay with respect to the ^{24}Mg c.m. system—thus detailed angular-correlation measurements were not required to extract decay widths.

Data from several coincidence arrays are presented in Fig. 2. Figure 2(a) shows the triton coincidences with particles stopping in the ΔE detector of system 3; coincident particles which lost more than 1.8 MeV in this detector were required by kinematics to be α particles. Alpha decays leading to the ^{20}Ne ground and first excited states lie inside the two bands on the figure. These bands are established from the curve given by three-body kinematics adjusted for finite counter geometry, energy losses in the target, and electronic resolution. (Events corresponding to energy losses of less than 1.8 MeV in the ΔE detector are probably due to triton-proton coincidences.) Figure 2(b) shows the array arising from triton coincidences with identified protons in system 3. The bands encompass decays to the ground and first

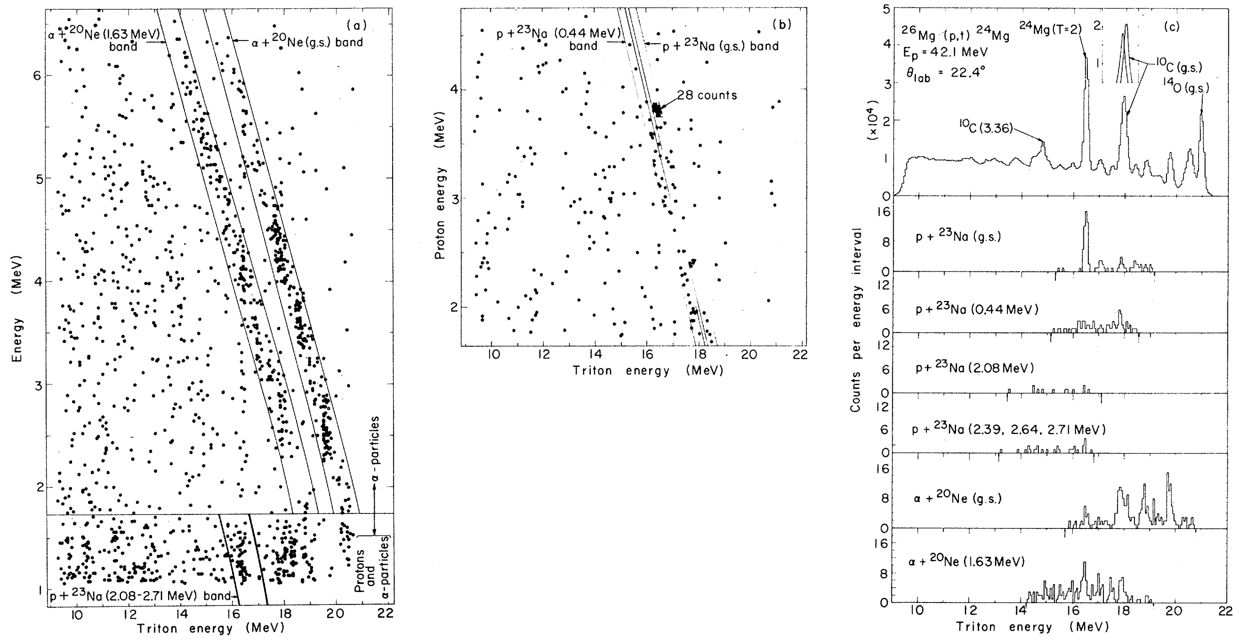

FIG. 2. (a) A two-dimensional spectrum of individual events of tritons from system 1 in coincidence with particles stopping in the ΔE detector of system 3. (b) A two-dimensional spectrum of individual events of tritons from system 1 in coincidence with protons from system 3. The pronounced peak corresponds to decays from the $T = 2$ state of ^{24}Mg to the ^{23}Na(g.s.). (c) The upper spectrum presents the triton singles data. The lower spectra are projections of the bands in the coincidence data onto the triton axis; the arrows in these spectra indicate the energy cutoffs required by kinematics.

excited states of ^{23}Na.

A triton singles spectrum is shown at the top of Fig. 2(c); the resolution (full width at half-maximum) of the $T=2$ peak is about 180 keV. Below this spectrum are displayed projections of bands from three of the coincidence arrays onto the triton axis. The ^{23}Na ground-state and 0.44-MeV state projections contain data from systems 2 and 3; data for the other ^{23}Na levels come only from system 2. The ^{20}Ne + α data are obtained from system 3.[10]

Counts attributed to the decay of the $T=2$ state were obtained by summing the projected spectra over the appropriate triton energies and subtracting (A) the chance background and (B) the "real" continuum background. The continuum was assumed smooth and was calculated by interpolating the projected count level averaged over 15 channels on both sides of the $T=2$ peak. Fractional decay widths for each observable decay mode were obtained by comparing its net coincidence counts with the number predicted from the triton singles data after transforming[11] the isotropic decay of the $T=2$ state in the ^{24}Mg c.m. system to the laboratory system, assuming 100% decay via that particular mode.

The sum of all fractional widths for decay to the six lowest ^{23}Na levels and the two lowest levels of ^{20}Ne is $1.3_0 \pm 0.2_0$. This sum should be ≤ 1.0; although the discrepancy is outside one standard deviation, it is considered to be statistical. There is, of course, no way to be certain that a small state does not lie underneath the $T=2$ state[12] and, perhaps, decay anisotropically. Further, from the nature of the projected data in Fig. 2(c), such a state would more probably undergo α decay. However, since the major peaks in the projected spectra associated with the $T=2$ decays center precisely about the relevant triton energy, and since the triton singles peak shape coupled with an absolute comparison of the $^{26}\mathrm{Mg}(p,t)^{24}\mathrm{Mg}(T=2)$ with the $^{26}\mathrm{Mg}(p,{}^3\mathrm{He})^{24}\mathrm{Na}(T=2)$ angular distribution data[13] implies <10% "contamination," we consider a significant contribution from such a small state to be improbable. In any event, no such problem could affect the conclusion that the major decay mode of the $T=2$ state of ^{24}Mg is via proton decay to ^{23}Na(g.s.). Figure 1(a) presents the observed data on the decay of the $T=2$ state.

Since the sum of the observed fractional particle-decay widths for the $T=2$ state in ^{24}Mg is equal to $1.3_0 \pm 0.2_0$, the isospin-allowed gamma width must be relatively quite small. After correcting for penetrabilities,[14] the dimensionless α-particle reduced width for decay to the ^{20}Ne 1.63-MeV state, requiring $\Delta T=2$, is about half the width for the decay to proton + ^{23}Na(g.s.) ($\Delta T=1$ or 2). Alpha-particle widths are expected to be particularly interesting from the point of view of isospin mixing because in first order only the isotensor part of the charge-dependent perturbation can mix $T=0$ amplitude into the $T=2$ states of $T_z=0$ nuclei (compare, MacDonald[15]). By contrast, isospin-forbidden decays of $T=\frac{3}{2}$ states may result from both the isovector and the isotensor part of the charge-dependent interaction.

The present experiment does not yield information on the absolute width of this $T=2$ state of ^{24}Mg; further, some uncertainty in the relative widths results from the continuum underneath the state. However, since the width for the decay to proton + ^{23}Na(g.s.) width is approximately 60% of the total width, it should in fact be possible for compound resonance experiments to provide more detailed data on the properties of this $T=2$ state.[16]

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[1] G. T. Garvey, J. Cerny, and R. H. Pehl, Phys. Rev. Letters 12, 726 (1964).

[2] J. Cerny, R. H. Pehl, and G. T. Garvey, Phys. Letters 12, 234 (1964); J. Cerny and G. T. Garvey, in Isobaric Spin in Nuclear Physics, edited by J. D. Fox and D. Robson (Academic Press, Inc., New York, 1966), pp. 514 and 517; and C. A. Barnes, in Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee, 1966 (to be published).

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[4] G. M. Temmer and R. Van Bree, in Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee, 1966 (to be published); and F. S. Dietrich, M. Suffert, S. S. Hanna, and A. V. Nero, ibid.

[5] G. M. Temmer, in Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee, 1966 (to be published).

[6] B. Titleman, G. T. Garvey, and G. M. Temmer, private communication.

[7] The only other open decay mode, ^{12}C + ^{12}C + 1.5 MeV, would be strongly inhibited by the Coulomb barrier. The ^{23}Na level scheme is taken from A. R. Poletti and

D. F. H. Start, Phys. Rev. 147, 800 (1966), and references therein; the ^{20}Ne data come from T. Lauritsen and F. Ajzenberg-Selove, in Nuclear Data Sheets, compiled by K. Way et al. (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.).

[8] F. S. Goulding, D. A. Landis, J. Cerny, and R. H. Pehl, Nucl. Instr. Methods 31, 1 (1964).

[9] A. B. McDonald, E. G. Adelberger, and C. A. Barnes, private communication.

[10] Only α particles corresponding to transitions to the ^{20}Ne(g.s.) were cleanly observed in system 2 because of the ΔE counter thickness. The fewer coincidence counts resulting from the smaller solid angle of this system were in agreement with the data from system 3, but were not incorporated.

[11] Č. Zupančič, Nuklearni Institut Jozef Stefan Report No. R-429, 1964 (unpublished).

[12] It is of some interest to note that the reaction ^{22}Ne(^{3}He,n)^{24}Mg near this excitation populates only the $T=2$ state at 15.43 MeV and an additional level at 15.54 MeV (unobserved in these results) with a full width at half-maximum of about 380 keV (Ref. 9).

[13] J. Cerny and G. T. Garvey, unpublished data.

[14] W. T. Sharp, H. E. Gove, and E. B. Paul, Atomic Energy of Canada Limited Report No. 268, 1955 (unpublished).

[15] W. M. MacDonald, Phys. Rev. 100, 51 (1955); and in Nuclear Spectroscopy, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960), Pt. B, p. 932.

[16] Although angular-momentum statistical factors significantly aid the observation of a $T=\frac{3}{2}$ state in a $|T_z| = \frac{1}{2}$ nucleus compared with the lowest $T=2$ state in a $T_z=0$ nucleus, it is interesting to note that, in general, resonance studies of the latter require lower proton energies, which may encourage their investigation.

STRUCTURE-DEPENDENT ASYMMETRY IN SEQUENTIAL BREAKUP FROM THE REACTION Li^6(He^3,$p\alpha$)He^4 [†]

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A cylindrical asymmetry about the direction of motion of Li^5 has been seen in the breakup of the ground state of this nucleus as an intermediate state in the reaction Li^6(He^3,$p\alpha$)He^4. It is shown that this asymmetry in the secondary decay of the sequential break-up process can arise from the memory retained by the intermediate state of its structure during the primary reaction in which a neutron is transferred from Li^6 to He^3. As confirmation of this idea it is found that the strength of the asymmetry is sharply dependent upon the duration of the final-state interaction. The effect described is a new tool for examining the ground-state wave function of the target nucleus and the wave functions of short-lived intermediate states.

The three-body breakup of the p, α, α system has previously been observed using two-dimensional analysis, with the conclusion that sequential processes predominate.[1] No detailed examination of individual break-up channels was reported. The mechanism of sequential breakup yielding multiparticle final states has been discussed by Phillips[2] in terms of a compound-nucleus-cluster model. In low-energy processes leading to three-particle final states, sequential breakup can be described as a two-particle final-state interaction simulating an intermediate nucleus with strong two-body cluster parentage. This decays to the final state with a time delay typically an order of magnitude longer than the duration of direct interactions. We find that the behavior of the intermediate-system wave function during this delay strongly influences the manner in which the system breaks up.

Experimental spectra were obtained by bombarding an isotopically enriched LiF target (95.6% Li^6) evaporated on a thin carbon backing[3] with 1.25-MeV He^{3+} ions from the University of British Columbia Van de Graaff accelerator. The reaction products were observed by surface barrier detectors operated in triple coincidence with a resolving time of 50 nsec. This arrangement represents an overdetermination of the kinematics, but is convenient for unambiguous particle identification and reduces the random coincidence rate to less than 5%. None of the random counts observed in a test run appeared in the region of interest. Two-dimensional coincidence spectra of the energies of the first alpha particle and the proton were accumulated in a 64×64 array using an ND 160 dual-parameter pulse-height analyzer gated by the triple-coincidence pulse. Events corresponding to the sequential breakup through the ground state of Li^5 populate a segment of