Scintillation Counter Study of Gamma Rays from Proton Capture in Sodium*

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The spectrum of the gamma rays produced by the resonant capture of 305-kev protons by sodium has been studied with a single-crystal scintillation spectrometer having a resolution of 21 percent at 6 Mev, and with a three-crystal scintillation pair spectrometer having a resolution of 7 percent at 6 Mev. Gamma rays of energies 10.61±0.05 Mev, 7.9±0.2 Mev, 6.7±0.2 Mev, 4.2±0.1 Mev, and 1.38±0.03 Mev were observed. Cascades were found from coincidence measurements. The energies of the gamma rays and cascades are consistent with transitions between known levels of Mg^{24}.

The alpha decay of the 11.99-Mev Mg^{24} state to the ground state of Ne^{20} has been observed to be much less probable than its gamma decay. The direct gamma transition of this state to the 0^+ ground state of Mg^{24} is absent. The angular distribution of the most energetic gamma ray is anisotropic. These results allow limitations to be placed on the spin and parity of the 11.99-Mev state in Mg^{24}.

INTRODUCTION

THE nuclear energy states of Mg^{24} have been studied in a number of reactions and processes. The energies, spins, and parities of some of the lower states have been determined with certainty, but relatively little is known about states of higher excitation. We have studied the gamma-ray spectrum of the excited Mg^{24} formed by resonant capture of 305-kev protons.

Measurements of the energies of the Mg^{24} gamma rays following the beta decay of Na^{24} give a precise determination of the energies of two of the lower states, at 1.38 and 4.14 Mev. The spins and parities of these states are known from gamma-gamma angular correlation[1] and internal pair conversion[2] measurements to be 2^+ and 4^+, respectively.

Studies of the energies of inelastically scattered proton groups from natural magnesium by Fulbright and Bush[3] were made at bombarding energies of 6.08, 9.64, and 15.30 Mev. They detected the scattered protons with photographic plates, using the magnetic field of the cyclotron for energy analysis. They observed levels at 1.00, 1.33, 1.58, 3.97, 4.17, 5.51, and 7.32 Mev and some others whose origin they question. Most of their data are consistent with previously reported values[4] within their probable error of ±0.2 Mev. Using 9.6-Mev protons, Baker, Dodd, and Simmons[5] measured the ranges of scattered protons with aluminum foils and proportional counters. They found Mg^{24} levels at 1.34, 4.17, and 6.38 Mev. The first two are in good agreement with known levels, and the third agrees with results on inelastic deuteron scattering[6] from separated Mg^{24}. Hausman *et al.*[7] have made the most accurate determination of energy levels in Mg^{24} by this method. They bombarded natural magnesium with 8-Mev protons and magnetically analyzed the scattered protons, obtaining levels at 1.38±0.02, 4.13±0.02, and 4.24±0.02 Mev, which were uniquely assigned to Mg^{24} by a study of the reaction $Al^{27}(p,\alpha)Mg^{24}$.

Mandeville[8] measured the energies of the neutrons from the reaction $Na^{23}(d,n)Mg^{24}$ by the ranges of recoil protons in Ilford C2 emulsions. He found states at 0.83, 1.24, 1.66, 4.16, 7.70, and 8.64 Mev. The energies of the three higher states agree well with previous data, but the lower ones have not been observed in other reactions.

Gamma rays of many different energies result from the reaction $Na^{23}(p,\gamma)Mg^{24}$. Using a single NaI(Tl) crystal, Casson[9] found gamma rays of 10.3±0.3, 7.5 ±0.2, 6.84±0.24, 1.38±0.04 Mev, a probable gamma of 3.6±0.2 Mev, and other unresolved radiation in the region of 2–4.5 Mev.

The evidence for the energies of excited states in Mg^{24} can now be summarized as follows. The most accurate measurements have been made on the gammas following the beta decay of Na^{24} and on natural magnesium by scattering experiments, and some of these levels have been confirmed by work on separated isotopes and by other nuclear reactions. Thus the levels known to belong to Mg^{24} are at 1.38, 4.14, 4.24, 6.38, 7.3, and 8.6 Mev. Other levels have been observed at 1.0, 1.6, and 5.5 Mev, whose isotopic assignment is uncertain. Previous studies of gamma radiation from $Na^{23}(p,\gamma)Mg^{24}$ do not yield enough information to say anything more about the energy level structure. The present work made use of a three-crystal spectrometer to improve the resolution for the higher-energy gamma-ray measurements.

THREE-CRYSTAL SCINTILLATION SPECTROMETER

A gamma ray of energy two Mev or greater may interact in a number of different ways with a scintil-

* Supported in part by the U. S. Atomic Energy Commission.
[1] E. L. Brady and M. Deutsch, Phys. Rev. **78**, 558 (1950).
[2] S. Bloom, Phys. Rev. **88**, 312 (1952).
[3] H. W. Fulbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948).
[4] T. R. Wilkins, Phys. Rev. **60**, 365 (1941); R. H. Dicke and J. Marshall, Phys. Rev. **63**, 86 (1943).
[5] Baker, Dodd, and Simmons, Phys. Rev. **85**, 1051 (1952).
[6] Massachusetts Institute of Technology Progress Report, July, 1950 (unpublished), p. 174.
[7] Hausman, Allen, Arthur, Bender, and McDole, Phys. Rev. **88**, 1296 (1952).
[8] C. E. Mandeville, Phys. Rev. **76**, 436 (1949).
[9] H. Casson, Phys. Rev. **89**, 809 (1953).

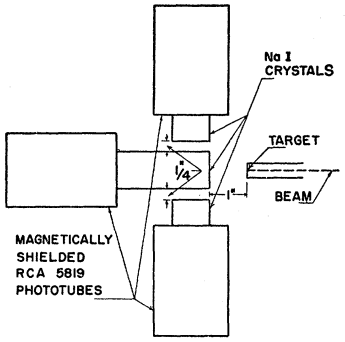

FIG. 1. Physical arrangement of three NaI crystals forming the three-crystal scintillation pair spectrometer.

lating crystal. The broad distribution of the Compton recoil electrons has a high-energy edge at about $E_\gamma - 0.5$ Mev, where E_γ is the gamma-ray energy. From the pair process, in general, one may obtain peaks at E_γ, $E_\gamma - 0.51$ Mev, or $E_\gamma - 1.02$ Mev, as none, one, or both of the annihilation quanta escape from the crystal. The resulting confusion may be alleviated at the sacrifice of the counting rate by the use of a three-crystal pair spectrometer.[10] The annihilation radiation is detected in two crystals placed on opposite sides of a center crystal, on which the gamma ray is incident. A triple coincidence between the three crystals corresponds to an energy loss of $E_\gamma - 1.02$ Mev in the center crystal, and an analysis of the coincident pulses from the center counter yields a spectrum which is much easier to analyze than the single-crystal distribution.

A three-crystal spectrometer was arranged as in Fig. 1 in order to study the Mg^{24} gamma radiation. Commercially potted NaI(Tl) crystals[11] $1\frac{1}{2}$ in. in diameter, 1 in. thick, were used for the annihilation radiation detectors; the center crystal was $1\frac{1}{2}$ in. in diameter and either 2 in. or 4 in. long. The RCA 5819 photomultipliers were operated at 1000 volts. The block diagram of the electronic circuits for the detection of triple coincidences and pulse-height analysis is given in Fig. 2. The pulses from the annihilation radiation crystals were limited[12] in height, their maximum height being equal to that produced by a 750-kev gamma ray, in order to detect the annihilation radiation in the presence of radiation of energy extending up to 10 Mev without overloading the amplifier, and to expand the voltage scale in the region of interest. The pulses from the three crystals were amplified by Atomic Instrument Company Model 204B amplifiers, and triple coincidences were detected by an Atomic Instrument Company Model 502, 0.5-microsecond resolving time, coincidence circuit. The spectrum of the pulses from the center crystal was analyzed with a 10-channel pulse-height analyzer,[13] which was gated by the 3-fold coincidence pulse. The pulses from the center crystal were delay-line clipped so that they were fairly flat on top for 0.5 microsecond, and then delayed by 1 microsecond before amplification in order to allow time for the gating triple coincidence pulse to open the 2-microsecond gate of the analyzer. The counting rate in the side crystal was usually several thousand per second, and about one thousand per second in the center crystal. The insertion of a 4-microsecond delay in one of the coincidence channels showed that the number of accidental triple coincidences was negligible.

The resolution of the three-crystal spectrometer has been studied with gamma rays at 4.43, 6.13, and 11.67

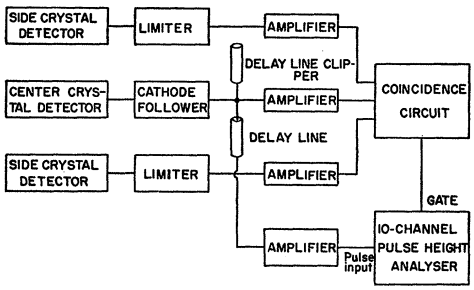

FIG. 2. Block diagram of the electronic circuits for the detection of triple coincidences in the three-crystal spectrometer and pulse-height analysis of the coincident pulses from the central crystal.

Mev, from the $B^{11}(p,\gamma)C^{12}$ and $F^{19}(p,\alpha\gamma)O^{16}$ reactions. The single-crystal and three-crystal spectra of the 6.13-Mev gamma ray detected with a 2-in. long crystal are given in Fig. 3. The requirement of a triple coincidence rejects the two higher-energy peaks, leaving the single pair peak at (6.13−1.02) Mev. The width at half-maximum of the "pair" peak has been reduced from 21 percent to 7 percent and the Compton background suppressed. At 11.67 Mev and with a 4-in. long center crystal, the three-crystal pair peak is 11 percent wide at half-maximum. The width of the three-crystal pair peak is due to photomultiplier statistics, difficulties in light collection, escape of electrons and positrons from the crystal, and bremsstrahlung produced in the crystal by the positron-electron pair. The width due to photomultiplier statistics and poor light collection should decrease for higher-energy gamma rays. The escape of the positron, electron, and bremsstrahlung would tend to broaden the peak and could account for the long tail on the low-energy side. Campbell and Boyle[14] have performed "Monte Carlo" calculations to determine the distribution in pulse height obtained with a single NaI crystal, of nearly the same size as we have used, for incident gamma-ray energies of

[10] J. K. Bair and F. C. Maienschein, Rev. Sci. Instr. **22**, 343 (1951); S. A. E. Johansson, Nature **166**, 794 (1950); Phil. Mag. **43**, 249 (1952).
[11] Harshaw Chemical Company, Cleveland, Ohio.
[12] W. C. Elmore, Rev. Sci. Instr. **20**, 963 (1949).
[13] W. C. Johnstone, Nucleonics **11**, No. 1, 36 (1953).
[14] J. G. Campbell and A. J. F. Boyle, Australian J. Phys. **6**, 171 (1953).

6 Mev, 12 Mev, and 18 Mev. They find that, for gamma-ray energies greater than 10 Mev, a significant fraction of the incident gamma-ray energy escapes from the crystal and that the fraction fluctuates. This limitation on the resolution of a single-crystal spectrometer is also present in the three-crystal spectrometer. We have observed a considerable increase in the asymmetry of the peak toward the low-energy side as E_γ increases from 6 Mev to 12 Mev.

Accidental coincidences among the three crystals of the spectrometer have not been important at the counting rates used in our experiments. The existence of triple-gamma cascades has been established in the Mg^{24} decay, and these spurious true coincidences contribute to the background. When the side counters were moved away from the center crystal so that the annihilation radiation would not contribute to triple coincidences, and the counter-target distance kept constant, the threefold coincidence rate decreased to less than 20 percent of the original value for lower-energy gamma rays and was negligible for higher-energy gamma rays. The spurious rate can be made small by moving the three crystals farther from the source, and it was this

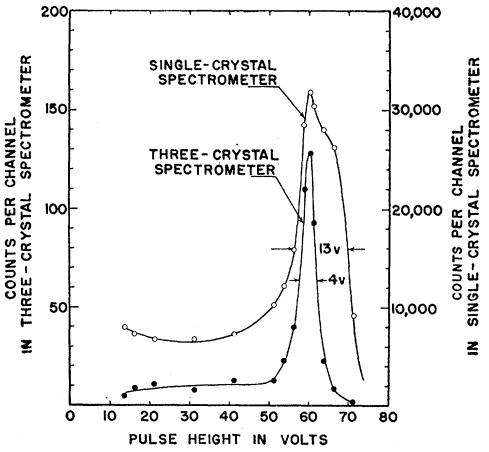

FIG. 3. Single-crystal spectrometer and three-crystal pair spectrometer measurements of the 6.13-Mev gamma ray produced in the $F^{19}(p,\alpha\gamma)O^{16}$ reaction. The 3:1 improvement in resolution and 3:1 improvement in peak-to-valley ratio are attained at a sacrifice of 250:1 in peak counting rate.

difficulty which determined the choice of distances shown in Fig. 1.

From the data shown in Fig. 3 it can be seen that the ratio of the peak counting rate of the three-crystal spectrometer to that of the single-crystal spectrometer is as 1 to 250 at 6.13 Mev. The differential pulse-height analyzer window width was 2.5 volts. Another way to express the efficiency of the three-crystal spectrometer is to give the number of counts observed in the peak per gamma ray emitted. The yield of fluorine gamma rays from a thick target is 0.1 rutherford per μa of protons. About 2.5×10^{-6} count is obtained in our apparatus in the triple-coincidence peak for every 6.13-Mev gamma ray emitted. Gamma rays of energy less than about 3.0 Mev cannot be detected in our experiment because of the decrease in pair-production cross section with decreasing energy.

PROCEDURE AND RESULTS

Protons from an rf ion source[15] were accelerated by a 500-kv Cockcroft-Walton accelerator.[16] The beam was analyzed and its energy determined by a 90° deflection magnet. The magnet was calibrated using the $B^{11}(p,\gamma)C^{12}$ reaction at 163 kev and the $F^{19}(p,\alpha\gamma)O^{16}$ reaction at 340 kev.

1. Energy of Gamma Radiation

Thick targets of Na_3PO_4 were pressed mechanically into the ends of thin-walled brass tubes and bombarded by beam currents of approximately 200 μa. The yield curve shows resonances at 225 kev and at 305 kev in agreement with Tangen.[17] The 305-kev resonance is about 100 times stronger than the 225-kev resonance, and all the gamma radiation observed was attributed to it. Particular care was taken to avoid fluorine contamination as it exhibits the strong $F^{19}(p,\alpha\gamma)O^{16}$ reaction at 340 kev. The lowest resonance in phosphorus is at 355 kev.[18] The only gamma ray produced in the $O^{16}(p,\gamma)F^{17}$ reaction has an energy less than 1 Mev.

The results of a typical run with the three-crystal spectrometer are shown in Fig. 4. The slow counting rate makes it impractical to use it for energies below about 3 Mev in this reaction. The three-crystal spectrum was obtained in about 3 hours. The width of the channels of the 10-channel analyzer, 2 volts, was checked with pulses from a mercury relay pulse generator.[19] The stability of the entire electronic system was checked frequently by increasing the signal level 8-fold by an input attenuator which precedes the amplifier,

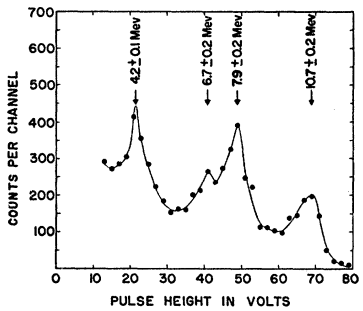

FIG. 4. Results of a three-crystal spectrometer study of gamma rays from the 11.99-Mev state of Mg^{24}.

[15] Moak, Reese, and Good, Nucleonics **9**, No. 3, 18 (1951).
[16] W. R. Arnold, Rev. Sci. Instr. **21**, 796 (1950).
[17] R. Tangen, Kgl. Norske Videnskab. Selskabs Skrifter, No. 1 (1946).
[18] D. E. Alburger and E. M. Hafner, Revs. Modern Phys. **22**, 373 (1950).
[19] W. C. Johnstone (private communication).

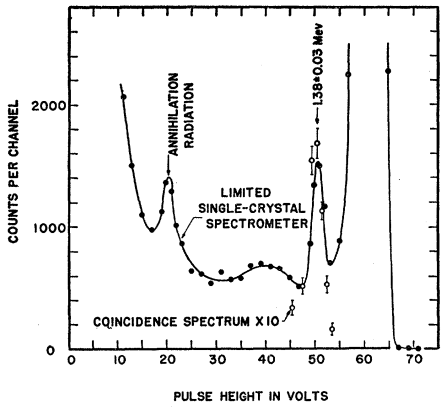

FIG. 5. The full circles show the results of a single-crystal spectrometer study of the low-energy part of the Mg^{24} gamma spectrum when the pulses have been limited in height. The open circles show the results of the measurement of the energy of the low-energy gamma ray in twofold coincidence with the highest energy gamma ray of the Mg^{24} spectrum.

and measuring the photopeak of the Cs^{137} (663 kev) gamma ray. Shifts of the photopeak were not more than 2 percent during any of the runs. The three-crystal spectrometer was calibrated at 4.43 Mev, 6.13 Mev, and 11.67 Mev and was linear within the accuracy of measurement of the calibration points. The reaction was monitored by an integral discriminator on the center crystal of the spectrometer.

A careful search was made for the gamma radiation which would result from the direct transition to the ground state of Mg^{24}, at an energy of 11.99 Mev.[20] The single-crystal and three-crystal spectrometers were calibrated with the 11.67-Mev radiation from $B^{11}(p,\gamma)C^{12}$. The direct transition to the ground state was not observed, and it is estimated that its intensity is less than 2 percent of the 10.7 ± 0.2 Mev radiation.

A single-crystal spectrometer was used to study the lower-energy part of the spectrum in detail. The pulses were limited in height so that the entire voltage range of the analyzer could be used to study the spectrum from 0 to 1.5 Mev. The results are shown in Fig. 5. The energy calibration of the pulse analyzer was established with the 663-kev Cs^{137} and 1.33-Mev Co^{60} gamma rays.

These measurements indicate gamma rays of 10.7 ± 0.2, 7.9 ± 0.2, 6.7 ± 0.2, 4.2 ± 0.1, and 1.38 ± 0.03 Mev. The peak corresponding to the 6.7-Mev gamma ray appeared consistently in each of several runs. The energy region from about 1.5 Mev to about 3.5 Mev was not surveyed.

2. Coincidence Counting

The number and energies of the gamma rays emitted in Mg^{24} suggest a number of cascades. Some of these were studied by coincidence counting. Two single-crystal NaI detectors and single-channel differential pulse-height analyzers (Atomic Instrument Company, Model 510) were used to show that the 10.7 ± 0.2 and 1.38 ± 0.03 Mev gamma rays are emitted in cascade. One scintillator-analyzer detected the 10.7 ± 0.2 Mev peak and the other scanned the low-energy region. The pulses from the low-energy detector were limited in height to those equivalent to 1.75 Mev, permitting greater accuracy in scanning this part of the spectrum. The number of coincidence counts as a function of the analyzer setting is given in Fig. 5. A more precise determination than from the pair spectrometer of the energy of the highest-energy gamma ray can be obtained knowing that it is in cascade with the 1.38 ± 0.03 Mev gamma rays and the energy of excitation of Mg^{24}. The result is 10.61 ± 0.05 Mev.

The same arrangement, minus the limiter, was used to show that the 7.9 ± 0.2 Mev gamma radiation is in cascade with 4.2 ± 0.2 Mev gamma radiation. One scintillator-analyzer detected the 7.9 ± 0.2 Mev peak and the other scanned the spectrum. The number of coincidence counts as a function of analyzer setting has the same shape as the single-crystal pulse-height distribution up to pulse heights corresponding to 4.2 ± 0.2 Mev gamma-ray energy. Beyond this point, no coincidences were found.

Three scintillation spectrometers have been used to detect triple-gamma cascades. The three counters were located symmetrically about the target chamber. The integral discriminators of the amplifiers for two of the counters, A and B, were set so that pulses produced by gamma rays of energy less than 1.4 Mev could not be detected. The discriminator of the amplifier for counter C was set to require pulses greater than those produced by a 0.7-Mev gamma. The threefold-coincidence pulse gated the 10-channel pulse-height analyzer and the spectrum of the pulses in the counter C obtained. The insertion of a 4-microsecond delay in one channel demonstrated that the accidental coincidences were negligible. The pulses from counter C were limited in height, being less than those produced by a 2.3-Mev gamma ray. The triple-coincidence peak for counter C agrees exactly with that of the 1.38-Mev gamma obtained in the single-crystal spectrometer and demonstrates that at least one triple cascade occurs via the 1.38-Mev level in Mg^{24}. The bias on counter C was increased so that only gamma rays of energy greater than 1.38 Mev could be counted in any counter and a significant number of triple coincidences detected.

3. Angular Distribution of 10.6-Mev Gamma Ray

The angular distribution with respect to the proton beam of the highest-energy gamma ray, at 10.61 Mev, was measured by discriminating against pulses from the 2-in. NaI counter produced by gamma rays of lower energy. A thick $NaAlO_2$ target on a 0.01-in. tantalum backing was bombarded with a 60-μa beam. A yield curve showed only the sodium resonance and

[20] C. W. Li, Phys. Rev. 88, 1038 (1952).

the pulse-height distribution of the gamma rays was the same as previously obtained from the Na_3PO_4 targets. The target disk was placed at 45° to the beam. There was a small asymmetry in the system which could be corrected by comparison with the apparent asymmetry in the angular distribution of the gamma radiation from $F^{19}(p,\alpha\gamma)O^{16}$, which is known to be isotropic.[21] The function $W=1+A\cos^2\theta$ fits the data reasonably well for measurements in the forward quadrant. The most precise result of the measurement is the anisotropy, $W(0°)/W(90°)=0.76\pm0.05$.

4. Alpha Decay of Mg^{24}

A resonance in the reaction $Na^{23}(p,\alpha)Ne^{20}$ was sought in the neighborhood of 305-kev proton energy. The alpha-particle energy would be 2.24 Mev. The target was $NaAlO_2$ on a thick brass backing at right angles to the beam, and the alpha counter was a NaI(Tl) flake on the end of a Lucite light pipe placed at an angle of 105° to the beam. The brass backing could be rotated to give target spots of $NaAlO_2$, CaF_2, and graphite with the same geometry in order to compare alpha and gamma yields from sodium and fluorine and to measure the background. Scattered protons were stopped by 50 microinches of nickel foil in front of the counter. Polonium alpha particles whose energy had been reduced by aluminium foils were used to calibrate the detector.

We measured A: the ratio of the alpha yield to gamma yield from sodium with a 20-μa beam, and B: the corresponding ratio for fluorine with a 3-μa beam. Let f be the fraction of disintegrations of Mg^{24} which proceed by alpha decay to the ground state of Ne^{20}, ϵ_1 be the efficiency of detection of the Mg^{24} alpha particles, η_1 be the efficiency of detection of the Mg^{24} gamma rays, and N_1 be the number of disintegrations per second. For the fluorine reaction, we use the same symbols with a subscript 2. Then

$$A=N_1f\epsilon_1/[N_1(1-f)\eta_1],$$
$$B=N_2\epsilon_2/N_2\eta_2.$$

Consequently,

$$f/(1-f)=(A/B)(\eta_1/\eta_2)(\epsilon_2/\epsilon_1).$$

The ratio ϵ_2/ϵ_1 is about 0.5 and the ratio η_1/η_2 of the gamma efficiencies is about one. The yield of alpha particles in the Mg^{24} decay did not show a resonance at 305 kev which was significantly larger than the background, while the gamma yield showed a clear resonance. After subtracting the background, our values for A and B are

$$A=0\pm0.03,\quad B=0.063\pm0.002,$$

from which we conclude that f is at most equal to $\frac{1}{5}$.

[21] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 24, 321 (1952).

DISCUSSION OF RESULTS

1. Gamma Radiation

The number and energies of the gamma rays observed in this study are in general agreement with the results of Casson.[9] The pair spectrometer is not suited to a study of this radiation in the 1–3 Mev region, and the single-crystal spectrum is so complex and poorly resolved that one cannot be certain of the energy of the radiation in this region. The results of a Compton spectrometer are also confused because of the large number of pulses from gamma rays of higher energy and cascade gammas of higher energy. The uncertainty in the energy measurements with the three-crystal spectrometer arises about equally from the instability of the electronic apparatus, the width of the pair peak, and the lack of adequate calibration points in the 6–10 Mev region.

The observed gamma rays may be fit into a decay scheme involving the known levels in Mg^{24} as shown in Fig. 6, but the lack of precision in the knowledge of the energy of the higher states and in the gamma-ray measurements make a unique fit of all the radiation impossible. The 10.61 ± 0.05 Mev and 1.38 ± 0.03 Mev gammas are in cascade. Since the energy of the 1.38-Mev gamma ray corresponds so closely to that of the 1.38-Mev level, it appears that the decay proceeds by way of the well-known 1.38-Mev state which has spin and parity of 2^+. The 4.2 ± 0.1 Mev gamma probably does not arise from a direct transition from the 4^+ state at 4.14 Mev as the crossover transition is not observed in the gamma radiation following the Na^{24} beta decay.[22] The discovery of the level at 4.24 Mev which is not reached in the beta decay provides a convenient explanation for the observed 4.2-Mev radiation. The 7.9 ± 0.2 Mev radiation may result from a transition from the capture state to the 4.24-Mev state, since it is in cascade with the 4.2-Mev gamma ray.

The triple cascade involving the 1.38-Mev gamma ray is energetically consistent with a cascade by way

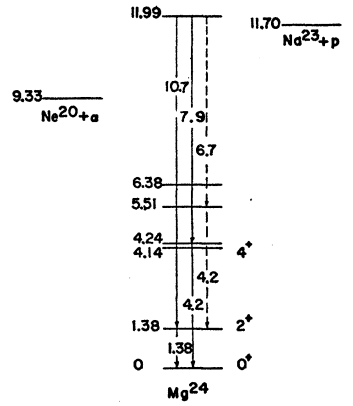

FIG. 6. The horizontal lines indicate known energy levels of Mg^{24} and related nuclear configurations with their energies on the left in Mev and their spins and parities on the right. The transitions indicated are consistent with the measured gamma-ray energies and coincidences.

[22] Bishop, Wilson, and Halban, Phys. Rev. 77, 416 (1950).

of the 5.51-Mev and 1.38-Mev levels. The triple cascades involving higher than 1.38-Mev gammas may proceed in a number of different ways which have not been identified.

2. Proton Capture State

The ground state of Na^{23} has[23] spin $\frac{3}{2}$ and even parity.[24] For *s*-wave proton capture this limits the 11.99-Mev level in Mg^{24} to 1^+, 2^+; for *p*-wave, to 0^-, 1^-, 2^-, 3^-; for *d* wave, to 0^+, 1^+, 2^+, 3^+, 4^+. From the observed anisotropy of the 10.6-Mev gamma ray, we can conclude that the spin is not zero and pure *s*-wave capture does not occur. Spin values of 1 are also ruled out by the failure to observe a gamma transition to the 0^+ ground state of Mg^{24}. Isotopic spin selection rules would not replace the angular momentum selection rules in this argument since it is not expected that pure isotopic spin states would be found at 11.99-Mev excitation.[25] Spin values of 3^+ and 4^+ would require pure *d*-wave capture which is unlikely at these bombarding energies. This leaves us with the possibilities 2^+, 2^-, 3^-. Goldberg *et al.* have observed a 2^+ level at 11.985-Mev excitation in Mg^{24} in alpha scattering experiments[26] on Ne^{20}. Since the 11.99-Mev level in Mg^{24} has a width of less than 0.5 kev and is separated by about 50 kev from nearby levels,[17] it is reasonable to identify the level studied here with that studied in the alpha-scattering experiments. This requires that both *s*- and *d*-wave protons contribute to the capture. The failure to observe alpha particles implies that the penetrability is sufficiently low for alpha particles to allow gamma radiation to compete successfully.

[23] I. I. Rabi and V. W. Cohen, Phys. Rev. **46**, 707 (1934).
[24] P. Shapiro, Phys. Rev. **93**, 290 (1954).
[25] L. Radicati, Phys. Rev. **87**, 521 (1952).
[26] Goldberg, Haeberli, Galonsky, and Douglas, Phys. Rev. **93**, 799 (1954).