Disintegration Scheme of Long-Lived Aluminum-26†

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The disintegration scheme of the long-lived ground-state isomer of Al^{26} has been determined. It is based on the following observations.

The maximum positron energy as determined by absorption measurements is 1.16±0.05 Mev; this agrees with the expected 1.17 Mev. The spectrum appears to be simple.

The scintillation gamma spectrum shows intense positron annihilation radiation, a strong peak at 1.83 ±0.03 Mev, and weak peaks at 1.12±0.03 Mev and 2.96±0.05 Mev, corresponding to transitions from the known Mg^{26} states at 1.82 and 2.97 Mev. A peak at 0.68 Mev is from the addition of two annihilation photons, one being backscattered from the source and surroundings; the gamma of ~0.7-Mev energy reported by others is not present. The peak at 2.97 Mev is shown to result from 2.97-Mev photons as well as from addition of 1.82- and 1.15-Mev photons.

The relative intensities of the annihilation and gamma radiations indicate that Al^{26} undergoes (84.6 ±1.8)% positron emission to the 1.82-Mev state of Mg^{26}; (11.4±1.9)% electron capture to the same state; (3.7±0.3)% electron capture to the 2.97-Mev state followed by emission of 1.15- and 1.82-Mev gamma-rays; and (0.30±0.03)% electron capture to the same state followed by 2.97-Mev radiation. Other energetically possible transitions are apparently negligible in intensity.

Auger electrons and x-rays were observed in a proportional counter spectrometer. Analysis of the spectra yielded K-shell fluorescence yields of 0.008±0.003 for magnesium and 0.008±0.003 for aluminum.

A. INTRODUCTION

IN 1954, a search for the radioactivity of the long-lived ground-state isomer of Al^{26} proved successful.[1] The search had been undertaken as a result of experimental[2–7] and theoretical[8–11] evidence which had indicated that an undetected isomer of the long-known 6.6-second positron-emitting Al^{26} probably existed. Subsequent reaction energy and level studies have now determined that this isomer is the ground state, lying 0.228±0.008 Mev[12–14] below the 6.6-second 0+ state and 4.016±0.018 Mev[14] above the Mg^{26} ground state. Theoretical considerations[8–11] assign to it a configuration with spin-parity 5+. Mg^{26} is known to have excited states at 1.823±0.012 (weighted average of 1.825±0.015[15,16] and 1.820±0.018[17]), 2.972±0.010,[15] and 3.969±0.010[15] Mev. The first undoubtedly has spin-parity of 2+, and the second two can be either 2+ or 3+ according to angular distribution in the $Mg^{25}(d,p)Mg^{26}$ reaction.[18] Al^{26} should then decay predominantly by 1.17-Mev positron emission to the 1.82-Mev Mg^{26} state by a second-forbidden transition with a half-life theoretically estimated[5,11,13] at 10^4–10^6 years, with smaller amounts of electron capture to the 1.82- and 2.97-Mev states.

The initial observations[1] of the radioactivity of Al^{26} showed the presence of 0.5- and ~1.9-Mev photons, from annihilation of positrons and from de-excitation of the 1.82-Mev Mg^{26} state, respectively. Absorption data showed the maximum beta energy to be ~1 Mev, agreeing with the expected value 1.17 Mev. The half-life was estimated from yield considerations to be ~10^6 years. Altogether, the theoretical expectations were remarkably confirmed.

Handley and Lyon,[19] using a more intense source, confirmed that the main disintegration mode involved a 1.30±0.15 Mev positron in coincidence with a 1.82-Mev gamma ray. They also reported gamma rays of 2.91 Mev and 0.717 Mev, the former attributed to single-photon de-excitation of the 2.97-Mev Mg^{26} state and the latter interpreted as indicating a new level in Mg^{26} at about 0.7 Mev. The relative intensities of the

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[1] Simanton, Rightmire, Long, and Kohman, Phys. Rev. **96**, 1711 (1954).
[2] Swann, Mandeville, and Whitehead, Phys. Rev. **79**, 598 (1950) as interpreted by Stähelin (reference 10). This evidence has subsequently been found to be incorrect.
[3] Montalbetti, Katz, and Goldemberg, Phys. Rev. **91**, 659 (1953).
[4] Haslam, Roberts, and Robb, Can. J. Phys. **32**, 361 (1954).
[5] Kluyver, van der Leun, and Endt, Phys. Rev. **94**, 1795 (1954).
[6] C. P. Browne, Phys. Rev. **95**, 860 (1954).
[7] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).
[8] R. W. King and D. C. Peaslee, Phys. Rev. **90**, 1001 (1953).
[9] P. Stähelin, Phys. Rev. **92**, 1076 (1953).
[10] P. Stähelin, Helv. Phys. Acta **26**, 691 (1953).
[11] S. A Moszkowski and D. C. Peaslee, Phys. Rev. **93**, 455 (1954).
[12] Kluyver, van der Leun, and Endt, Physica **20**, 1287 (1954); Endt, Kluyver, and van der Leun, Physica **20**, 1299 (1954).
[13] Kavanagh, Mills, and Sherr, Phys. Rev. **97**, 248 (1955).
[14] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).
[15] Endt, Haffner, and Van Patter, Phys. Rev. **86**, 518 (1952).
[16] The uncertainty in the 1.825-Mev value is that given by Endt and Kluyver (reference 7) and Endt and Braams (reference 14) rather than in the original publication (reference 15).
[17] R. B. Day, Phys. Rev. **102**, 767 (1956).
[18] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 258 (1953).
[19] T. H. Handley and W. S. Lyon, Phys. Rev. **99**, 755 (1955).

radiations were given as

$$\beta^+:\gamma_{0.717}:\gamma_{1.82}:\gamma_{2.91}=1:0.01:1:0.004.$$

Laubitz[20] studied the positron spectrum with a 2π anthracene scintillation spectrometer and obtained a maximum energy of 1.17±0.05 Mev. The data fitted best the Kurie plot corresponding to a $\Delta J=3$,no (second-forbidden) transition. A gamma of 1.76±0.1 Mev was observed.

An abstract by Johnson and Moffat[21] gives gamma energies of 0.74, 1.10, 1.84, and 2.98 Mev. The second is presumably from the expected 1.15-Mev transition between the 2.97- and 1.82-Mev states. The first was stated to be coincident with positrons, and was regarded as evidence for an intermediate level at 1.84+0.74=2.58 Mev. Using a 4π beta scintillation spectrometer, they confirmed the "unique" second-forbidden ($\Delta J=3$,no) shape of the positron spectrum, and gave the end point as 1.13 Mev.

Recently, Fisher, Hadley, and Speers[22] have found a positron end point of 1.16±0.02 Mev and unique second-forbidden shape, and have confirmed previously reported gamma energies, including components at 0.70 and 1.1 Mev.

In very recently published work Ferguson[23,24] also observed the second-forbidden spectrum shape, with end point 1.160±0.008 Mev, and he found it and a (1.10±0.05)-Mev gamma in coincidence with the (1.84±0.01)-Mev gamma. A peak in the gamma spectrum at ~0.7 Mev was observed, but was identified as an instrumental effect and not a gamma ray.

To facilitate the discussion of our own experiments it will be useful to anticipate the results; these are embodied in the disintegration scheme given in Fig. 1.

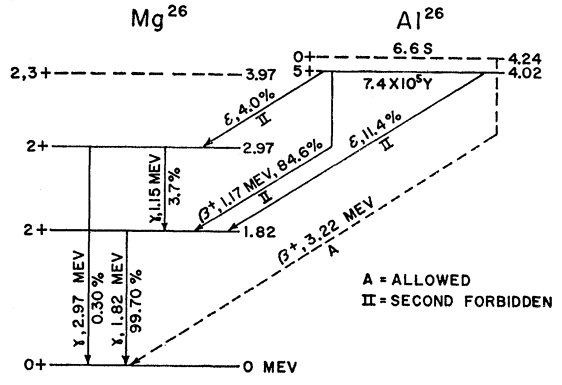

FIG. 1. Disintegration scheme of Al^{26}.

[20] M. J. Laubitz, Proc. Phys. Soc. (London) **A68**, 1033 (1955).
[21] R. G. Johnson and R. D. Moffat, Bull. Am. Phys. Soc. Ser. II, **2**, 230 (1957).
[22] Fisher, Hadley, and Speers, Phil. Mag. **3**, 163 (1958).
[23] J. M. Ferguson, Bull. Am. Phys. Soc. Ser. II, **2**, 395 (1957).
[24] J. M. Ferguson, Phys. Rev. **112**, 1238 (1958).

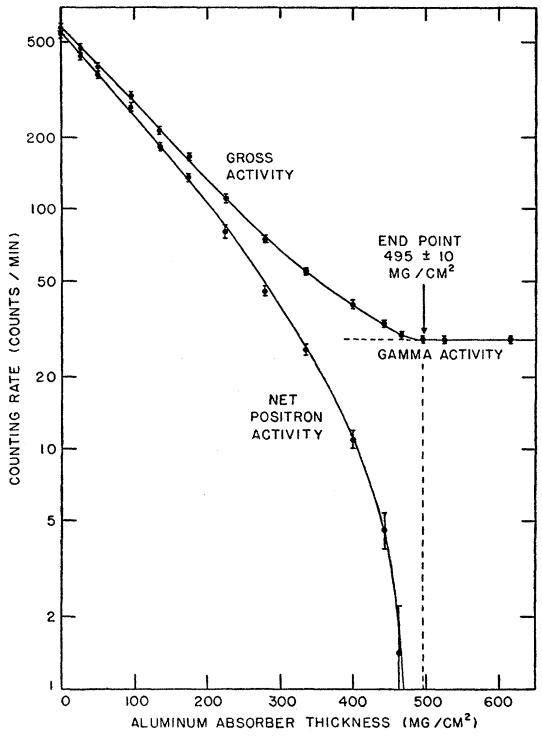

FIG. 2. Al^{26} absorption curve.

B. MAXIMUM POSITRON ENERGY

An aluminum absorption curve was taken with a sample of Al^{26} of moderately high specific activity isolated from a magnesium target bombarded for 10 hours at 180 μa with 15-Mev deuterons in the University of Pittsburgh cyclotron. 50 mg of aluminum carrier were added to the target solution, isolated, and recycled to constant specific activity.[1] The end point at 495±10 mg/cm² in Fig. 2 corresponds[25] to a maximum positron energy of 1.16±0.05 Mev. The indicated uncertainty includes an estimated uncertainty in the range-energy relationship. This is in excellent agreement with the value predicted from the most precise reaction data, (4.016±0.018)−(1.823±0.012)−1.022 = 1.171±0.022 Mev. The spectrum appears simple, with no indication of a beta transition to any other state in Mg^{26} than that at 1.82 Mev.

C. SCINTILLATION SPECTRUM AND GAMMA ENERGIES

1. Experimental Results from Simple Spectrum

Using an intense Al^{26} source of low specific activity, which was a portion of that used by Handley and Lyon,[19] we recorded the scintillation gamma spectrum with a NaI(Tl) crystal 1.5 inches in diameter and 1 inch thick. The arrangement was calibrated with the

[25] L. Katz and A. S. Penfold, Revs. Modern Phys. **24**, 28 (1952).

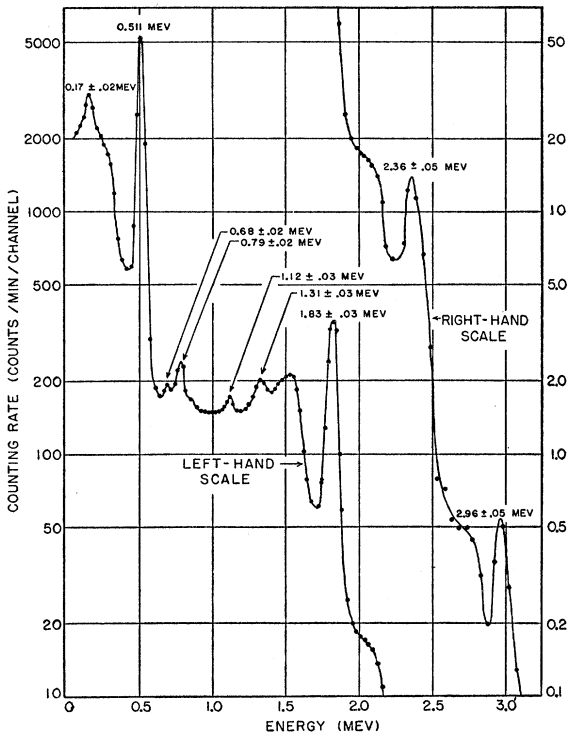

FIG. 3. Al^{26} scintillation spectrum.

Cs^{137} 0.667-Mev gamma, the Na^{22} 0.511-Mev annihilation radiation and 1.28-Mev gamma, and the Na^{24} 1.38- and 2.76-Mev gammas. The Al^{26} in 18 g of Al_2O_3 was contained in a glass bottle having an inside diameter of ~3 cm and filled to a height of ~2 cm, placed against the scintillator cover.

Figure 3 shows the gamma spectrum. The strongest peak is that at 0.51 Mev, due to positron annihilation. The peaks at 1.83±0.03 and 1.12±0.03 Mev we ascribe to primary gamma radiation from Mg^{26}, since the energies correspond closely to the values 1.82 and 1.15 Mev expected from the well-known first and second excited states of Mg^{26}. The peak at 2.96±0.05 Mev corresponds to the peak of about the same energy reported by others[19,21,22] and attributed in all cases to a gamma of that energy. The peak at 2.36±0.05 Mev is undoubtedly due to the addition of the 1.82-Mev gamma and the 0.51-Mev annihilation radiations.[19] Compton edges are seen at ~2.8, ~1.6, ~0.86, and ~0.30 Mev. The shoulder at ~2.1 Mev can be ascribed to the addition of the annihilation peak to the 1.6-Mev edge. The peaks at 1.31±0.03 and 0.79±0.02 Mev are close to one and two electron masses below the 1.82-Mev peak, and hence are interpreted as secondary "escape" peaks. The peak at 0.17±0.02 Mev corresponds to Compton backscattered annihilation radiation.[26] The 0.68±0.02 Mev peak may be identified with the 0.717-Mev peak of Handley and Lyon,[19] the 0.74-Mev peak of Johnson and Moffat,[21] and the 0.70-Mev peak of Fisher *et al.*,[22] regarded by all of these observers as indicating a gamma ray of that energy. No peak was observed at 3.97 Mev, the energy of the third excited Mg^{26} state.

[26] B. Crasemann and H. Easterday, Nucleonics 14, No. 6, 63 (1956).

2. Investigation of 0.68-Mev Peak

To test whether the 0.68-Mev peak was primary or secondary in origin, we took spectra with the source at varying distances from the scintillator. The counting rate in a peak due to a single gamma ray is proportional approximately to the inverse square of the distance from source to detector, whereas the intensity of an addition peak whould be proportional approximately to the inverse fourth power. Spectra in the region from 0.6 to 1.2 Mev, taken with the source mounted at ~1 inch and ~1.5 inches from the center of the scintillation crystal to the center of the source, are shown in Fig. 4. The peaks at 0.78 Mev and 1.12 Mev decreased in intensity by a factor of ~2, confirming that each is due to a single gamma ray. The peak at 0.68 Mev decreased by a factor of ~4, indicating that it is an addition peak, presumably of the 0.51- and 0.17-Mev photons. The latter is the experimentally observed average energy of large-angle Compton-backscattered photons having initial energies of 0.51 Mev.[26] We have also observed the 0.17- and 0.68-Mev peaks with the positron-emitter Na^{22} mounted under the same conditions as the Al^{26} source.

Thus there is no ~0.7-Mev gamma ray in the Al^{26} radiations. The supposed gamma ray of about this energy reported by others[19,21,22] can probably be attributed to this addition peak. In private com-

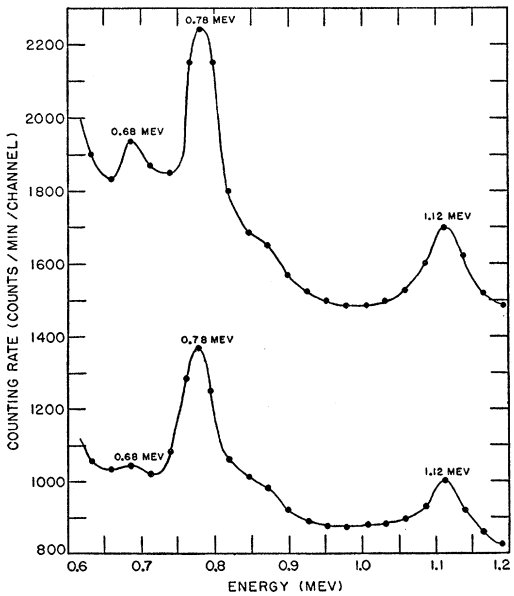

FIG. 4. Investigation of the 0.68-Mev peak.

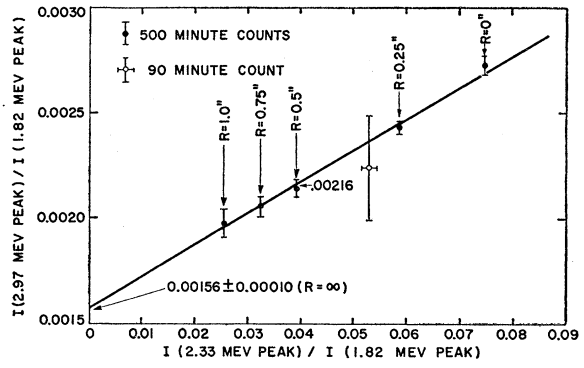

FIG. 5. Investigation of the 2.97-Mev peak.

munication, Dr. Johnson states that he and Moffat have independently come to the conclusion that the 0.7-Mev peak was an instrumental effect, by experiments similar to ours. The similar conclusion of Ferguson[23,24] was reached by absorption experiments, which showed that the 0.7-Mev peak was attenuated much more rapidly than are photons of that energy.

3. Investigation of 2.97-Mev Peak

Pulses at 2.97 Mev could result either from addition of coincident 1.82- and 1.15-Mev gamma rays or from single-photon de-excitation of the 2.97-Mev Mg^{26} state; accordingly, the previous work[19,21,22] does not prove the occurrence of gamma rays of the latter energy. To determine the fraction of the 2.97-Mev peak resulting from single gamma rays, spectra in the region from 1.5 to 3.0 Mev were taken with the lower edge of the source mounted at 0, 0.25, 0.5, 0.75, and 1.0 inches from the scintillator cover.

Neglecting minor effects, the ratio of intensities of 2.97-Mev gamma pulses to 1.82-Mev gamma pulses should remain constant at all distances of source from detector; likewise, the ratio of the intensities of the addition component of the 2.97-Mev peak to the 2.33-Mev addition peak should remain nearly constant. Hence, the observed 2.97-Mev peak intensity for the source placed at any distance from the detector should be given by:

$$I_{2.97}{}^{\text{obs}}=C_1I_{1.82}+C_2I_{2.33},$$

where $I_{2.97}{}^{\text{obs}}$ = observed 2.97-Mev peak intensity, $I_{1.82}$ = observed 1.82-Mev peak intensity, $I_{2.33}$ = observed 2.33-Mev peak intensity, and C_1,C_2 = coefficients for the particular experimental arrangement. Dividing both sides of this equation by $I_{1.82}$ yields

$$I_{2.97}{}^{\text{obs}}/I_{1.82}=C_1+C_2I_{2.33}/I_{1.82}.$$

Figure 5 is a plot of $I_{2.97}{}^{\text{obs}}/I_{1.82}$ as a function of $I_{2.33}/I_{1.82}$. The straight line obtained was extrapolated back to $I_{2.33}/I_{1.82}=0$, giving 0.00156 ± 0.00010 for the constant C_1, which is the ratio of the single-photon part of the 2.97-Mev peak to the 1.82-Mev gamma peak. The point obtained from the initial spectrum is also included in Fig. 5; although the disposition of the source relative to the scintillator was somewhat different, the point lies quite close to the line. Thus C_1 and C_2 are probably not very sensitive to geometry modifications.

To test the validity of these results, a lead absorption curve was taken with the lower edge of the source mounted at 0.5 inch from the scintillator cover. With an absorber between source and detector, the observed intensity of the 2.97-Mev peak is given by

$$I_{2.97}{}^{\text{obs}}(T)=I_{2.97}{}^{\text{sin}}(0)\exp(-\mu_{2.97}T)+I_{2.97}{}^{\text{add}}(0)\exp(-\mu_{1.15}T-\mu_{1.82}T),$$

where $I_{2.97}{}^{\text{sin}}(0)$ = intensity of the single-photon part of the 2.97-Mev peak with no absorber present, $I_{2.97}{}^{\text{add}}(0)$ = intensity of the 2.97-Mev addition contribution with no absorber present, T = thickness of lead absorber (g cm^{-2}), $\mu_{2.97}$ = mass absorption coefficient of the 2.97-Mev gamma-ray = 0.0422 cm^2 g^{-1}, $\mu_{1.82}$ = mass absorption coefficient of the 1.82-Mev gamma-ray = 0.0473 cm^2 g^{-1}, and $\mu_{1.15}$ = mass absorption coefficient of the 1.15-Mev gamma-ray = 0.0604 cm^2 g^{-1}. The mass absorption coefficients were obtained by graphical interpolation from the tables of Grodstein.[27] From Fig. 5 it is deduced that at 0.5 inch the fractional composition of the 2.97-Mev peak is

$$I_{2.97}{}^{\text{sin}}(0)/I_{2.97}{}^{\text{obs}}(0)=0.00156/0.00216=0.72,$$
$$I_{2.97}{}^{\text{add}}(0)/I_{2.97}{}^{\text{obs}}(0)=(0.00216-0.00156)/0.00216=0.28,$$

where $I_{2.97}{}^{\text{obs}}(0)$ is the observed intensity with no absorbers present. The absorption curve should then be given by

$$I_{2.97}{}^{\text{obs}}(T)=[0.72\exp(-0.0422T)+0.28\exp(-0.1077T)]I_{2.97}{}^{\text{obs}}(0).$$

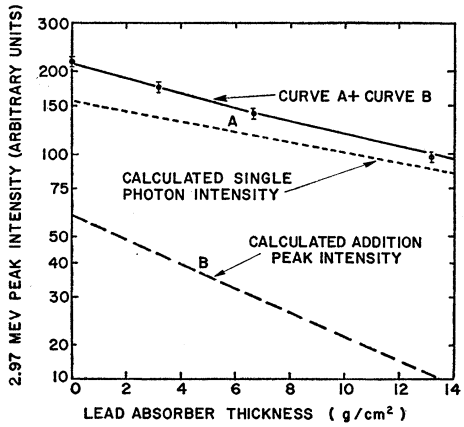

FIG. 6. Absorption curve of the 2.97-Mev peak.

[27] G. W. Grodstein, *X-Ray Attenuation Coefficients From 10 kev to 100 Mev*, National Bureau of Standards Circular No. 583 (U. S. Government Printing Office, Washington, D. C., 1957).

TABLE I. Energetic photons from Al^{26}.

Measured photon energy (Mev)	Actual photon energy (Mev)	Net counting rate (min^{-1})	Relative crystal efficiency	Relative photon emission rate	Absolute photon emission rate
0.51[a]	0.511	7620±18	1	7620±18	1.692 ±0.036
1.12±0.02	1.15	53.2±4.0	0.320±0.004	166±13	0.037 ±0.003
1.83±0.03	1.82	727±8	0.162±0.003	4490±96	0.9970±0.0003
2.96±0.05	2.97	1.13±0.08[b]	0.083±0.003	13.6±1.1	0.0030±0.0003
	(3.97)	<0.02	~0.06	<0.32	<0.00007

[a] Energy standard.
[b] This is the rate ascribable to 2.97-Mev photons, obtained by multiplying the 1.82-Mev peak rate by 0.00156±0.00010. The total net counting rate in the 2.97-Mev peak was 1.67 min^{-1}.

Figure 6 shows the fitting of this equation to the experimentally observed absorption curve. The excellent agreement indicates that the procedure is valid and allows us to obtain an accurate value for the intensity of the 2.97-Mev gamma.

4. Coincidences

The existence of the 0.68-Mev addition peak indicates that the two 0.51-Mev photons are produced simultaneously, and are therefore positron annihilation photons. The 2.33-Mev addition peak indicates that positrons are emitted in coincidence with the 1.82-Mev gamma radiations.[19] The existence of some addition character to the 2.97-Mev peak indicates that the 1.15- and 1.82-Mev gamma-rays are emitted in coincidence, as has also been shown by two-detector coincidence studies.[23,24]

D. GAMMA INTENSITIES AND BRANCHING FRACTIONS

1. Calibration of Scintillation Spectrometer

To determine the relative intensities of the various gamma radiations, spectra from Na^{22} and Na^{24} sources were taken to calibrate the crystal for efficiency as a function of photon energy. The Na^{22} source was prepared by absorbing a small amount of active Na^{22} solution in 18 g of inactive Al_2O_3 and mounting in a polyethylene bottle having the same dimensions as that used for the Al^{26} source. The Na^{24} source was prepared by placing ~20 g of Na_2CO_3 in the same-sized polyethylene bottle, which was then irradiated for a short time with neutrons from the University of Pittsburgh cyclotron. From the most accurate literature values of the electron-capture branching fraction in Na^{22}, 0.099±0.006,[28] 0.110±0.009,[29] and 0.109±0.009,[30] we select the unweighted average 0.106±0.006 as the best value; accordingly 89.4% of the disintegrations yield positrons, each producing two 0.51-Mev photons. A 1.28-Mev gamma is emitted in 99.95% of the disintegrations.[31] In Na^{24} equal numbers of 1.38- and 2.76-Mev gamma rays are emitted.

[28] R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954).
[29] W. E. Kreger, Phys. Rev. **96**, 1554 (1954).
[30] Allen, Burcham, Chackett, Munday, and Reasbeck, Proc. Phys. Soc. (London) **A68**, 681 (1955).
[31] B. T. Wright, Phys. Rev. **90**, 159 (1953).

In the Na^{22} spectrum, the ratio of the areas under the 1.28- and 0.51-Mev peaks was 0.1494. Dividing this by the emission ratio of 1.28- and 0.51-Mev photons, 0.559, gives 0.267 as the ratio of crystal efficiencies at 1.28 and 0.51 Mev. The ratio of efficiencies at 2.76 and 1.38 Mev was given directly by the ratio of areas under the two peaks in the Na^{24} spectrum, which was 0.381. A fairly unique adjustment of the relative efficiencies at 1.38 and 1.28 Mev could be made, so as to yield a smooth curve fitting all four points. The resulting relative efficiencies are: 0.51 Mev, unity; 1.28 Mev, 0.267; 1.38 Mev, 0.241; 2.76 Mev, 0.0918. The calibration curve was similar to that calculated by Bell *et al.*[32] for an identical crystal and point source mounted at 1.5 cm, the average distance from our sources to the crystal. This simple method of efficiency calibration using only Na^{22} and Na^{24} should be quite generally useful, since Na^{24} can be produced readily with quite modest sources of neutrons, and Na^{22} is long-lived and commercially available, and can also be obtained in the form of absolute standards.

2. Relative and Absolute Photon Emission Rates

The areas under the 0.51-, 1.15-, and 1.82-Mev peaks of the Al^{26} spectrum were measured, and the relative photon emission rates were obtained by dividing the counting rate in each peak by the corresponding relative crystal efficiency as read off of the calibration curve. The relative emission rate of the 2.97-Mev photon was obtained by multiplying the measured 1.82-Mev peak by the ratio of intensities of the 2.97-Mev primary gamma to the 1.82-Mev gamma, obtained from Fig. 5, and dividing by the relative crystal efficiency at 2.97-Mev. An upper limit on the emission rate of a 3.97-Mev gamma ray is given as twice the standard deviation of the background counting rate in this region divided by the approximate relative crystal efficiency. The details of this analysis are given in Table I.

The relative photon emission rates can be converted to absolute numbers of photons per disintegration by making the following assumptions: (1) None of the Al^{26} transitions go directly to the Mg^{26} ground state

[32] P. R. Bell, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, and Interscience Publishers, Inc., New York, 1955), p. 154.

(justified below); (2) none of the transitions go to Mg^{26} states higher than 2.97 Mev (justified experimentally from the scintillation spectrum and theoretically below); (3) internal conversion is negligible (since the energies are large and multipole orders low). It follows that the Mg^{26} ground state can be reached only by 1.82- or 2.97-Mev gamma emission. Hence, the total disintegration rate, on the same scale as that of the relative photon emission rates, is equal to the sum of the rates for the 1.82- and 2.97-Mev gamma-rays. The absolute photon emission rates given in Table I were obtained by dividing the relative rates by this sum.

3. Branching Fractions and Disintegration Scheme

The positron branching fraction is one-half of the absolute intensity of 0.51-Mev annihilation photons, or $(84.6\pm1.8)\%$. The beta absorption curve (above) and theoretical considerations (below) indicate that all of the positrons are in the spectrum with 1.17-Mev end point exciting the 1.82-Mev Mg^{26} level.

The remainder, $(15.4\pm1.8)\%$, is the electron-capture branching fraction. The branching fraction of electron capture to the 2.97-Mev Mg^{26} state is given by the sum of intensities of the 1.15-Mev gamma ray $[(3.7\pm0.3)\%]$ and the 2.97-Mev gamma ray $[(0.30\pm0.03)\%]$, emitted respectively in stop-over and cross-over de-excitations of the 2.97-Mev state; this is $(4.0\pm0.3)\%$. By difference, the branching fraction for electron capture to the 1.82-Mev Mg^{26} state is $(11.4\pm1.9)\%$.

The resulting complete disintegration scheme of Al^{26} is shown in Fig. 1. The fact that electron capture to the second excited Mg^{26} state, for which 1.04 Mev is available, is somewhat but not much less frequent than to the first excited state, for which 2.19 Mev is available, indicates that both transitions are of the same order of forbiddenness (second), so that the 2.97-Mev state must have spin-parity 2+ or 3+. However, if this state were 3+, the cross-over transition would be $M3$ and the stop-over transition would be $M1$, so that the former would be much slower and probably unobservable. This limits the 2.97 state to 2+, according to which the cross-over transition is $E2$ and the stop-over transition again $M1$, consistent with the cross-over transition's being only moderately slower than the stop-over transition.

It is necessary to consider the following additional transitions which are energetically possible:

(a) *Direct transitions from* Al^{26} *to the ground state of* Mg^{26}.—These would be fourth forbidden, whereas all of the observed transitions are only second forbidden. Hence both positron emission and electron capture to the Mg^{26} ground state would be completely negligible in comparison.

(b) *Positron emission to the 2.97-*Mev *state.*—Table II gives the f factors (used in computing comparative half-lives) for allowed transitions of the same energy as those to the various accessible excited states of Mg^{26}. They should be roughly proportional to the proper factors for second-forbidden transitions. Theoretical branching fractions are calculated by dividing each f factor by the sum of the f factors for all modes of disintegration. It is seen that positron emission to the 2.97-Mev state is completely negligible because of the very small amount of energy available.

(c) *Electron capture to the 3.97-*Mev *state.*—Table II shows that this is also completely negligible because of the small available energy.

4. Sources of Error

There are possibilities of error in this analysis resulting from peak depletions or enhancements which were not considered. Coincident events should lead to the following changes in peak intensities: (a) depletion of the 0.51-Mev peak by addition to the 1.82-Mev peak and its Compton-scattered radiation; (b) enhancement of the 0.51-Mev peak by the addition of the 0.17-Mev backscatter peak to the 0.30-Mev Compton-edge peak; (c) depletion of the 1.15-Mev peak by addition to the 1.82-Mev peak and its Compton-scattered radiation; (d) depletion of the 1.82-Mev peak by addition to the 0.51-Mev annihilation peak and its Compton-scattered radiation; (e) enhancement of the 1.82-Mev peak by the addition of the 1.31-Mev "escape" peak to the 0.51-Mev annihilation peak; (f)

TABLE II. Theoretical branching fractions for Al^{26}.

Mg^{26} state to which transition occurs	1.82 Mev	2.97 Mev	3.97 Mev
Energy available for electron capture (Mev)	2.193 ± 0.022	1.044 ± 0.021	0.047 ± 0.021
Energy available for positron emission (Mev)	1.171 ± 0.022	0.022 ± 0.021	0
f_K	0.095[a]	0.020[a]	$\sim5\times10^{-5}$ [b]
f_{LI}/f_K	0.07[c]	0.07[c]	0.07[c]
f_ϵ	0.105	0.022	$\sim5\times10^{-5}$
$f_{\beta+}$	5.4[d]	$\sim10^{-6}$ [d]	0
Electron-capture branching fraction	0.019	0.004	$\sim1\times10^{-5}$
Positron-emission branching fraction	0.977	$\sim2\times10^{-7}$	0

[a] From Houtermans, Geiss, and Müller, in *Landolt-Börnstein Zahlenwerte und Functionen* (Springer-Verlag, Berlin-Göttingen-Heidelberg, 1952), sixth edition, Vol. 1, Part 5, p. 456.
[b] From King, Dismuke, and Way, Oak Ridge National Laboratory Report ORNL-1450, 1952 (unpublished).
[c] From M. E. Rose and J. L. Jackson, Phys. Rev. **76**, 1540 (1949). The total non-K-capture is taken as $\sim1.5\times$ the L_I-capture.
[d] From E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950).

enhancement of the 1.82-Mev peak by the addition of the 1.6-Mev Compton edge to the 0.17-Mev backscatter peak; (g) enhancement of the 2.97-Mev peak by the addition of the 1.82-Mev peak to the 1.15-Mev peak. The latter effect is the only one for which a correction was determined and applied in the above analysis.

The total depletion of the 1.82-Mev peak amounts to about 5%, as estimated from the area under the 2.33-Mev peak. The compensating enhancement of the 1.82-Mev peak appears to be of the order of several percent. Hence the net error in intensity of this peak is probably only a very few percent. Because of the greater intensity of the 0.51-Mev peak, the errors involved are estimated (from the area under the 2.33-Mev peak) to be less than 1%. Corrections for depletion of the 1.15-Mev peak would probably be less than the standard deviation resulting from counting statistics. The most important of these errors affect the ratio of 0.51-Mev to 1.82-Mev intensities. There will be partial compensation from the use of Na^{22} in the same geometry for the calibration curve.

Ideally, such errors might be made negligibly small by using a large source-to-detector distance, a carrier-free source, and a scatter-free geometry. The weakness of available Al^{26} sources prevents large distances. These effects undoubtedly were present in the work of Handley and Lyon[19] and of Johnson and Moffat.[21] For the Al^{26} spectrum taken by Handley and Lyon the source was placed directly upon a 3-in.×3-in. scintillator. For larger crystals the depletion of the 1.82-Mev peak is greater, while the compensating enhancement factors are less (because of the decrease in Compton-scattered and "escape" peaks). It appears from the intensity of the 2.34-Mev peak in their published spectrum that the net depletion in the 1.82-Mev peak was of the order of 15–20%. Their deduction of equality in the emission rates of positrons and 1.82-Mev gamma rays can probably be attributed to failure to consider this effect.

It is felt that the errors arising from measurement of the areas under the various peaks, including the uncertainties in background interpolations, are probably less than 1%. The uncertainties resulting from counting statistics are given as standard deviations and are included with the data in Table I. From the foregoing, it is evident that the actual uncertainties are somewhat but not substantially greater than those listed.

5. Comparative Half-Lives

The half-life of Al^{26} has recently been determined[33] from specific activity measurements to be $(7.38\pm0.29)\times10^5$ years $=2.33\times10^{13}$ seconds. Using this, the branching fractions deduced in Sec. D3, and the f factors given in Table II, comparative half-lives can be calculated for the various observed modes of disintegration. These are given in Table III. They are all consistent with the second-forbidden nature of the transitions. The mutual agreement is satisfactory considering that allowed f factors were used.

TABLE III. Comparative half-lives of Al^{26} transitions.

Transition	Branching fraction	t = partial half-life (sec)	f	log ft
β^+ to 1.82-Mev state	0.846	2.75×10^{13}	5.4	14.17
ϵ to 1.82-Mev state	0.114	2.0×10^{14}	0.105	13.33
ϵ to 2.97-Mev state	0.040	5.8×10^{14}	0.022	13.11

E. PROPORTIONAL COUNTER SPECTROMETRY OF ELECTRON-CAPTURE RADIATIONS

1. Counter and Energy Calibration

Pulse spectra in the low-energy region were taken with a thin Al^{26} source mounted in 2π geometry in a large internal-sample proportional counter. The stainless-steel cathode was 4 inches in diameter with a 0.003-inch tungsten wire anode. A mixture of A(90%) and CH_4(10%) was used as the counting gas. The pulse analyzer was gated in anticoincidence by a sheath of guard Geiger counters surrounding the proportional counter, which was shielded by mercury, iron, and lead.

At each voltage and gain setting used for Al^{26}, an energy calibration curve was constructed from x-ray peaks appearing either in the Al^{26} spectrum or in the spectrum of an Fe^{55} source covered by a 4.1-mg/cm^2 aluminum foil. The latter source gave the 5.9-kev Mn K x-ray, the 2.8-kev Mn-A escape peak, and the 1.5-kev fluorescent Al K x-ray. The Al^{26} source gave the Fe and Ni fluorescent K radiation at 6.4 and 7.5 kev, respectively, and, when covered by a plastic absorber, peaks attributed to Mg and Al K x-rays at 1.25 and 1.49 kev, respectively. The Fe and Ni radiation is presumably produced by photoelectric absorption of gamma rays near the surface of the stainless steel without the photoelectrons' entering the gas. The Al radiation could be produced from macroscopic Al^{27} purity in the source by K-shell excitation of Al^{27} atoms by positrons under the condition that neither the positrons nor the ejected electrons enter the gas.

2. Auger-Electron and X-Ray Spectra

The Al^{26} was from a high-specific-activity preparation isolated by a carrier-free procedure[34] from a high-purity magnesium target bombarded with protons at the Oak Ridge National Laboratory. According to measurements described elsewhere,[33] the resulting dilute nitric acid solution had a specific positron activity of $(1747\pm26)\beta^+$ min^{-1} ml^{-1} and contained 68 μg ($Al^{26}+Al^{27}$)

[33] Rightmire, Kohman, and Hintenberger, Z. Naturforsch. **13a**, 847 (1958).

[34] Rightmire, Kohman, and Allen, J. Appl. Radiation Isotopes **2**, 274 (1957).

ml^{-1}, A 1.000-ml aliquot was evaporated onto a Lucite disk over an area of 1.75 cm^2. The aluminum was evaporated as $Al(NO_3)_3$, then converted to Al_2O_3 under a heat lamp. The resulting sample thickness was therefore ~ 75 μg cm^{-2}. The sample appeared under a low-power microscope to be distributed quite uniformly over the surface of the disk.

Spectra of Al^{26} were taken with 0, 2, and 20 collodion foils of average thickness ~ 8.4 μg cm^{-2}. These were removed from the water surface on which they were prepared by evaporation on a metal ring, by means of which they were placed on top of the source. After the desired number of foils had been deposited, the source was placed in the counter and dried by evacuation overnight.

The broad peak in the spectrum without absorber shown in Fig. 7 is due to the Auger electrons from nascent Mg^{26} atoms and from Al^{27} atoms in the source. The latter Auger electrons result from K-shell excitations of the type described above to explain the characteristic x-rays. The fact that a peaked distribution is obtained indicates that the source is quite thin and uniform, although some energy degradation is evident.

The spectrum taken with an ~ 16.8-μg cm^{-2} film covering the source shows that the electrons have all been lowered in energy somewhat, but they still mask any x-ray peaks. The high-energy tail may be due to nonuniformity of the absorber.

The spectrum taken with an ~ 168-μg cm^{-2} covering shows that the electrons have been completely absorbed. The spectrum shown in Fig. 8 is the result of several long runs with the same absorber. Both the Mg x-ray (1.25 kev) and Al x-ray (1.49 kev) appear unambiguously in the spectrum.

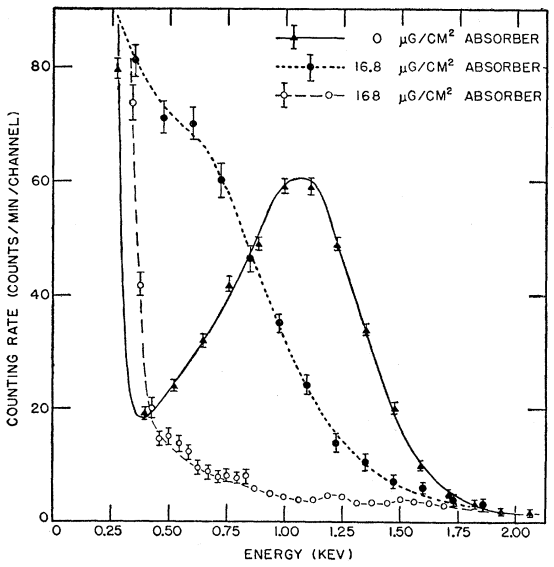

FIG. 7. Auger-electron spectrum from Al^{26} source in proportional counter.

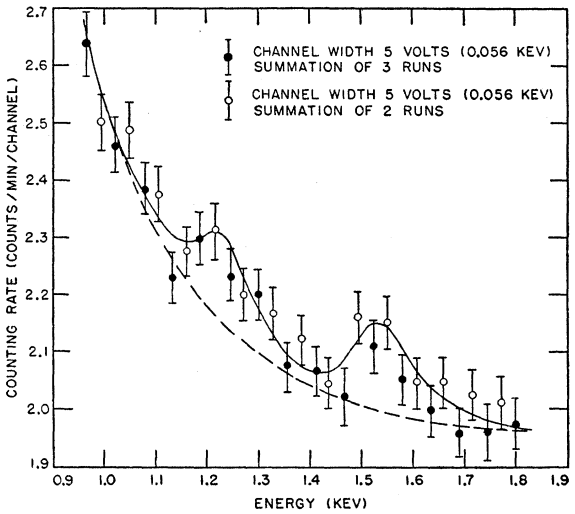

FIG. 8. X-ray spectrum from Al^{26} source in proportional counter.

Since the chemical procedure used was designed to remove magnesium thoroughly from the radio-aluminum, the Mg x-ray provides additional proof of the importance of electron capture in the disintegration of Al^{26}.

3. *K*-Shell Fluorescence Yields of Magnesium and Aluminum

Table IV contains an analysis of the spectra of Figs. 7 and 8, under the assumption that the Mg x-ray can result only from electron capture in Al^{26}. The absolute x-ray emission rates for Mg and Al were computed from the counting rates in the peaks in Fig. 8 above the dashed line, which represents the continuum caused mainly by positrons. The absolute total Auger-electron emission rate was obtained by dividing the area under the peak of Fig. 7 which was removed by absorbers (261 ± 6 counts min^{-1}) by the geometry factor (0.50 ± 0.05), and this was partitioned between the two elements as indicated in the table and footnotes.

The K-shell fluorescence yield of Mg and Al can be computed as the ratio of the absolute K x-ray emission rate to the absolute K-shell vacancy production rate for the respective element. The resulting values are

$$\text{Mg: } 0.008 \pm 0.003,$$
$$\text{Al: } 0.008 \pm 0.003.$$

The indicated uncertainties are standard deviations and result from the standard deviations of the total net x-ray counts (taken as the square root of the sum of the total counts in the peak and the total interpolated counts in the background) and the uncertainty in the film thickness (determined by weighing several films).

TABLE IV. Analysis of x-ray and Auger-electron spectra of Al^{26} source.

Element	Mg	Al
Area under x-ray peak (counts min^{-1})	0.45 ±0.09	0.51 ±0.08
Thickness of film covering source ($\mu g\ cm^{-2}$)	168±28	168±28
Absorber mass absorption coefficient ($cm^2\ mg^{-1}$)	1.918[a]	1.188[a]
Absorber thickness in x-ray mean free paths, T	0.32	0.20
Sample thickness ($\mu g\ cm^{-2}$)	35[b]	35[b]
Sample mass absorption coefficient ($cm^2\ mg^{-1}$)	1.384[a]	0.925[a]
Sample thickness in x-ray mean free paths, t	0.048	0.032
Emission factor, $f(t,T)$	0.43[c]	0.55[c]
Geometry factor	0.50	0.50
K-x-ray emission rate (min^{-1})	2.2 ±0.8	1.9 ±0.6
K-electron vacancy rate (min^{-1})	286±42[d]	240±67[f]
K-shell Auger-electron emission rate (min^{-1})	284±42	238±67[e]
K-shell fluorescence yield	0.008±0.003	0.008±0.003

[a] Computed from data in *Handbook of Chemistry and Physics* (Chemical Rubber Publishing Company, Cleveland, Ohio, 1953), thirty-fifth edition, p. 2398.
[b] Computed from the known amount of Al_2O_3 in and the estimated area of the sample.
[c] Computed with an equation given by G. I. Mulholland, Atomic Energy Commission Document NYO-3228, 1953 (unpublished).
[d] Obtained by multiplying the positron emission rate (1747 ±26 min^{-1}) by the ratio of electron capture to positron emission (0.182 ±0.026) and by the fraction of the captures which occur in the K-shell (0.90 ±0.03, see Table II, footnote c).
[e] The difference between the total Auger-electron emission rate (522 ±52 min^{-1}) and the calculated Mg Auger-electron emission rate.
[f] The sum of the K-Auger-electron and K-x-ray emission rates.

The value obtained for the K-shell fluorescence yield of Mg is in fair agreement with an experimental value 0.013 of Haas.[35] No experimental value for aluminum has been reported previously. The equation of Arends,[36]

$$W_K = 0.957Z^4/(0.9847\times10^6+Z^4),$$

is said[37] to give the best fit to the data of all equations proposed. This yields 0.020 for Mg and 0.027 for Al. Both calculated values are significantly greater than our experimental values.

[35] M. Haas, Ann. Physik **16**, 473 (1933).
[36] E. Arends, Ann. Physik **22**, 281 (1935).
[37] Broyles, Thomas, and Haynes, Phys. Rev. **89**, 715 (1953).

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