$\langle l^2\rangle$ from the semiclassical value:

$$(\gamma^2)_{\min}=[\beta^2(\beta^2+Q^2)]^{\frac{1}{2}}, \tag{A4}$$

$$\langle\Delta l^2\rangle_{\min}=\tfrac{1}{2}[1+Q^2/\beta^2]^{\frac{1}{2}}+\beta^2\rho_0{}^2-\tfrac{1}{2}. \tag{A5}$$

It is found from these expressions that the wave packets are so large as to invalidate the model only if QR is very close to the classical cutoff, $QR=l$. The packets sharpen up very rapidly as (Q^2R^2/l^2) becomes very slightly greater than unity, reach their best breadths for $(Q^2R^2/l^2)\approx 2$, then slowly deteriorate as this parameter goes to much larger values. A typical value for $\langle\Delta l^2\rangle_{\min}$ is that for the sharpest packet,

$$\langle\Delta l^2\rangle_{\min}\approx\tfrac{1}{2}(1+2l^2)^{\frac{1}{2}}. \tag{A6}$$

In the same circumstance the radial thickness of the packet is found to be

$$(1/\gamma\sqrt{2})=(R/\sqrt{2})(1+2l^2)^{-\frac{1}{4}}. \tag{A7}$$

Evidently the model becomes better for the larger values of l. It already seems reasonable if $l=2$.

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Al^{26} Decay Scheme*

JAMES M. FERGUSON†
Radioactivity Center of the Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received June 12, 1958)

The energies and intensities of the beta and gamma radiations from the long-lived ground level of Al^{26} were studied with scintillation spectrometers. The positron spectrum was obtained using a plastic scintillator with 4π geometry and was found to have a forbidden shape and an endpoint of 1.160 ± 0.008 Mev. The positrons are in coincidence with a gamma ray with an energy of 1.84 ± 0.01 Mev, which is presumably from the first excited level of Mg^{26}. There is also a weak gamma ray with an energy of 1.10 ± 0.05 Mev, in coincidence with the 184-Mev gamma ray, and with an intensity of 0.03 relative to the 1.84-Mev gamma ray. This would be from the second excited level of Mg^{26}, to which the Al^{26} decays weakly by electron capture. No other gamma rays are observed. It appears that a peak in the pulse-height spectrum at 700 kev is due to scattering effects rather than a gamma-ray photopeak.

THE beta and gamma radiations from the long-lived ground level of Al^{26} were studied using scintillation spectrometers. The measurements were made on a 0.01-microcurie source of Al^{26} recovered from several old magnesium cyclotron targets which had undergone a few thousand microampere hours of 15-Mev deuteron bombardment. A Kurie plot of the beta spectrum was obtained and two gamma rays were detected.

The beta spectrum was measured using a plastic scintillator designed to give 4π geometry. The scintillator is a rectangular block of plastic with a 2/100-in. slot cut in it. The source to be counted was deposited on a 0.25-mg/cm^2 sheet of rubber hydrochloride. The resolution (full width at half-height, divided by peak pulse height) of the Ba^{137} conversion electron peak (640 kev) was 13%. To check the linearity of the instrument the spectra of several known beta emitters (Na^{22}, P^{32}, Ca^{45}) were obtained and, after applying a resolution correction using the method of Owen and Primakoff,[1] Kurie plots were made. All were found to be linear down to about 150 kev.

Figure 1 shows a Kurie plot of the Al^{26} positron spectrum obtained with this instrument. The plot is linear when either the unique first forbidden or second forbidden correction factors[2] are added (Figs. 2 and 3). The endpoint is 1.160 ± 0.008 Mev. Coincidence experiments show that this spectrum is in coincidence with the annihilation radiation and the 1.84-Mev gamma ray.

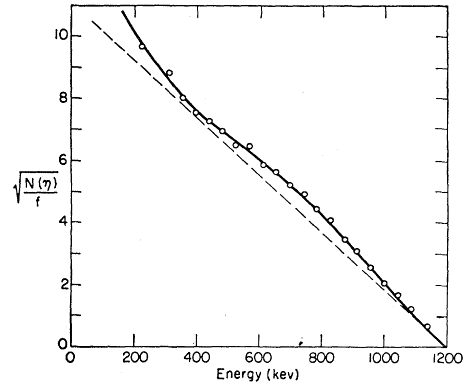

FIG. 1. Kurie plot of the Al^{26} positron spectrum, *not* corrected for forbiddenness.

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* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Now at the U. S. Naval Radiological Defense Laboratory, San Francisco, California.

[1] G. E. Owen and H. Primakoff, Phys. Rev. **74**, 1406 (1948).

[2] E. J. Konopinski and L. M. Langer, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 261.

The gamma-ray spectrum was studied with a 2-in. ×2-in. NaI(Tl) crystal. The pulse-height spectrum (Fig. 4) shows prominent peaks corresponding to 0.51- and 1.84-Mev photons and weaker peaks for 0.7- and 1.1-Mev photons. The energy of the 1.84-Mev gamma ray was determined by comparing it with the 1.85-Mev peak of the Y^{88} gamma-ray pulse-height spectrum. An energy of 1.84 ± 0.01 Mev was obtained for the Al^{26} gamma ray.

The peak for 700-kev photons was found to be due to a scattering effect rather than the photopeak of a gamma ray. With the source lying directly on top of the crystal, the crystal is in position to absorb Compton backscattered radiation from the walls and furniture in the laboratory. For every annihilation quantum absorbed in the crystal, another annihilation quantum and a 1.84-Mev gamma ray are emitted into the laboratory. A certain fraction of these undergo "head on" Compton collisions, and some of the backscattered quanta (having an energy of about 200 kev) are absorbed in the crystal, producing the 700-kev hump in the pulse-height spectrum. In other words, the 511-kev photopeak and the well-known backscatter peak will "add" to produce a 700-kev peak. Experimental evidence for this is that the magnitude of the 700-kev peak changes when the position of the crystal with respect to nearby objects is changed. Also, a $\frac{1}{8}$-in. lead jacket around the crystal completely removes the 700-kev peak by absorbing the backscatter quanta. If the peak were due to a gamma ray, the lead would reduce it by only about 15%. This effect in the Al^{26} pulse-height spectrum was independently observed by Johnson and Moffat.[3]

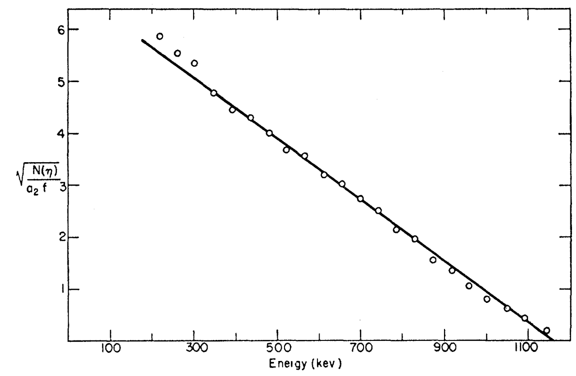

FIG. 2. Kurie plot of the Al^{26} positron spectrum with unique second forbidden correction factor.

The peak at 1.1 Mev appears to be a true gamma-ray photopeak with an energy of 1.10 ± 0.05 Mev. A gamma-gamma coincidence experiment indicates it is in coincidence with the 1.84-Mev gamma ray, and has an intensity of 0.03 relative to the 1.84-Mev gamma ray. It represents the transition from the second excited level at 2.97 Mev[4] to the first excited level. A 1.1-Mev gamma ray was observed by May and Foster, who studied the Mg^{26} levels using the $Na^{23}(\alpha,p)Mg$ reaction.[5]

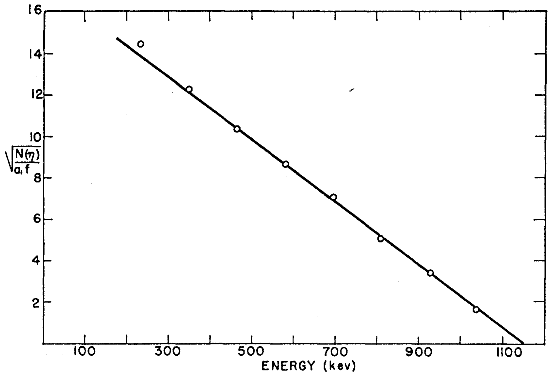

FIG. 3. Kurie plot of the Al^{26} positron spectrum with unique first forbidden correction factor.

The 2.97-Mev gamma ray observed by Handley and Lyon[6] in the Al^{26} decay spectrum was not observed in this study. However, our 2-in.×2-in. crystal is quite inefficient for total absorption of gamma rays of this energy. Taking Handley's and Lyon's value of 0.005 for the relative occurrence of the 2.97-Mev gamma ray, the calculated height of the 2.94-Mev photopeak would be too small to be distinguished from background in our experiment. Hence we would not expect to observe it.

The relative intensities reported by May and Foster,[5] Handley and Lyon,[6] and this paper may be intercompared. Taking our value of 0.03 for the 1.1-Mev gamma ray and Handley's value of 0.004 for the 2.97-Mev gamma rays, one obtains a ratio of 7.5. May and Foster obtained a value of 6 for this ratio. In view of the difficulty in measuring the intensities of the weak gamma rays, these numbers agree within the limits of experimental error.

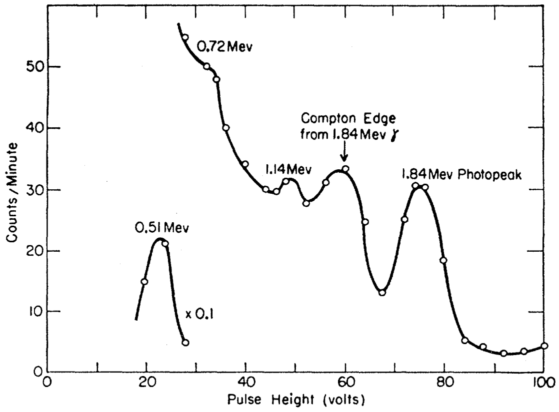

FIG. 4. Al^{26} gamma ray pulse-height spectrum in NaI(Tl) crystal.

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[5] J. E. May and B. P. Foster, Phys. Rev. **90**, 243 (1953).

[6] T. H. Handley and W. S. Lyon, Phys. Rev. **99**, 755, (1955).

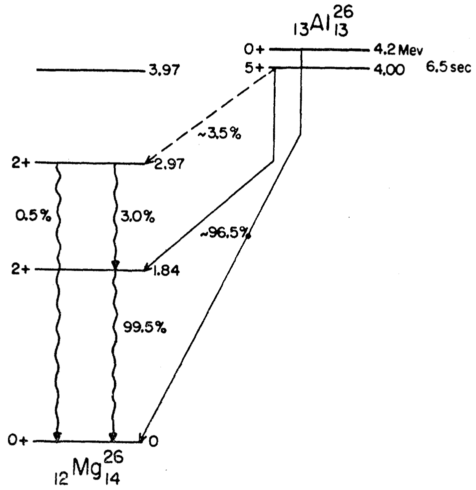

FIG. 5. Proposed Al^{26} decay scheme.

For the most part, the parities and angular momenta of the levels involved in the Al^{26} decay are not uniquely determined. We may, of course, assume the ground level of Mg^{26} is 0^+. The angular distribution work on the $Mg^{25}(d,p)Mg^{26}$ reaction by Holt and Marsham[7] indicates that the first and second excited levels of Mg^{26} each have even parity and angular momenta of 2 or 3. Two is more likely for the first excited level, since Mg^{26} is even-even. Assuming the first excited level is 2^+ and the second excited level is 2^+ or 3^+, the gamma transition from the second to the first excited level is magnetic dipole. The transition from the second excited level to the ground level is electric quadrupole if $I=2^+$ for the second level, magnetic octopole if $I=3^+$. Using Weisskopf's formula[8] for gamma-ray transition probabilities, the ratio of 1.1-Mev gamma rays to 2.97-Mev gamma rays would be 10^7 for an $I=3$ level, 25 for an $I=2$ level. The latter is in much better agreement with the observed ratio, so we assign $I=2$ to the second excited level.

The Al^{26} ground level has been predicted to be 5^+ by King and Peaslee,[9] on the basis of the systematics of odd-odd nuclei. This is in agreement with the observed forbidden positron decay to the first excited level, and the lack of any observable positron decay to the Mg^{26} ground level. The angular momentum and parity assignments are summarized in Fig. 5.

ACKNOWLEDGMENT

Thanks are due to Professor R. D. Evans of the Massachusetts Institute of Technology for suggesting this project and for many helpful discussions.

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PHYSICAL REVIEW VOLUME 112, NUMBER 4 NOVEMBER 15, 1958

Beta-Gamma Correlation and Time-Reversal Invariance*

ICKO IBEN, JR.†
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 22, 1958)

The distribution function for the first-forbidden beta-gamma correlation for randomly oriented nuclei, including beta transverse polarization terms, is presented and discussed in connection with the question of time-reversal invariance. Coulomb field effects are included and it is found that even for relatively small Z the time-reversal testing asymmetry is reduced appreciably compared to that calculated for $Z=0$ by Curtis and Lewis. In the limit of high $(\alpha Z/2R)$, that is, for most first-forbidden decays, a definite relation exists between the ordinary directional correlation asymmetry and the beta polarization-dependent asymmetries. In this approximation it is found that terms which test time-reversal invariance appear in the same manner in all asymmetries but are dominated in general by contributions which do not test time-reversal invariance. For the particular case of Au^{198} it is shown that the experimental results are consistent with time-reversal invariance but are also consistent with an appreciable violation of time-reversal invariance. It is concluded that under favorable conditions it is barely possible that an investigation of the asymmetries for some other beta-gamma cascade could provide a test for time-reversal invariance. However, the *extent* to which this invariance is or is not violated could not be determined by such an investigation.

INTRODUCTION

CURTIS and Lewis[1] have suggested the possibility of testing the time-reversal invariance of the beta interaction Hamiltonian by an examination of the correlation between decay products in a beta-gamma cascade. The proposed test demands a measurement of the correlation between the transverse polarization of the beta particle and the momenta of the electron and the photon.

When the beta transition is allowed, the asymmetries which test time-reversal invariance in the theoretical distribution for the cascade process are negligible relative to the isotropic terms unless the

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* This work was supported in part by the Office of Naval Research, and is based on a portion of a thesis submitted by the author in partial fulfillment of the requirements for the Ph.D. degree at the University of Illinois, June, 1958.

† Now at Williams College, Williamstown, Massachusetts.

[1] R. B. Curtis and R. R. Lewis, Phys. Rev. **107**, 543 (1957).