Angular Correlation of the Gamma Rays from Mn^{56}†

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The angular correlations of the gamma rays of Fe^{56} emitted in the decay of Mn^{56} have been studied using sodium iodide scintillation counters. All three excited states of Fe^{56} involved in the decay of Mn^{56} were found to have spin 2, even parity. The spin of the ground state of Mn^{56} is probably 2, the parity even.

The admixture of electric quadrupole radiation to the magnetic dipole 2–2 transitions is 2 percent for the 1.8-Mev gamma ray and 8 percent for the 2.1-Mev transition, i.e., small compared to the admixtures in other 2–2–0 cascades.

INTRODUCTION

OUR knowledge of the properties of the excited states of even-even nuclei has recently been summarized.[1] The first excited states emerge from this survey as a very uniform group, 95 percent of all spins being 2+, the rest 0+. All first excited states discussed in the summary[1] have even parity. As one proceeds to higher excited states, the amount of information available decreases rapidly and so does the uniformity. The second excited states fall into three equal groups: 2+, 4+ and "others." Here, too, the preference for even parity is still large; at least $\frac{4}{5}$ of all second excited states have even parity. Odd-parity states seem to appear as the excitation exceeds ~2 Mev, e.g., at 2.75 Mev in Sr^{88} (reference 2) and at 2.3 and 2.6 Mev in Te^{124} (reference 3).

In a search for more of these odd-parity states, we decided to investigate the 2.65- and 2.95-Mev excited levels in Fe^{56} which are involved in the decay of Mn^{56} (Fig. 1). The decay scheme of Fig. 1 is essentially the one proposed by Elliott and Deutsch.[4] The two cross-over transitions were reported by Bishop *et al.*,[5] who observed the photoprotons produced by the Fe^{56} gamma rays in a deuterium filled ion chamber.

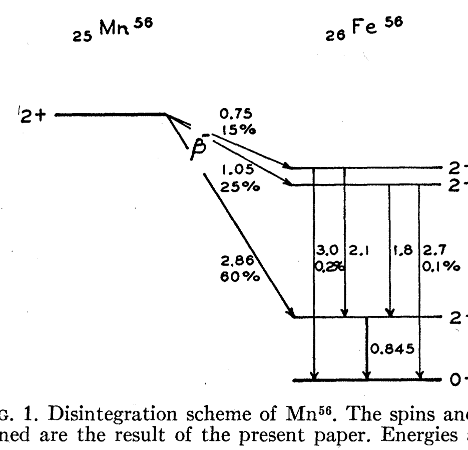

FIG. 1. Disintegration scheme of Mn^{56}. The spins and parities assigned are the result of the present paper. Energies are given in Mev.

A measurement of the internal pair formation coefficients[6] indicates that the 1.8-Mev gamma ray is probably $E1$, the 2.1-Mev transition $E2$. However, the logft values of 5.3 and 5.6 for the β-ray transitions to the two levels in question seem to indicate the same parity for both levels.

Lifetime measurements[7] restrict the spin of the 0.845-Mev level to 1 or 2, spin 2+ being the more likely assignment. No information concerning the internal conversion of the Fe^{56} gamma rays is available. At these low Z values, conversion measurements are very difficult and, in the case of Fe^{56}, impossible with the means we had at our disposal. On the other hand, the simple decay scheme encouraged an investigation of the angular correlations of the gamma rays of Fe^{56}, the only handicap being the relatively short half life of Mn^{56}.

MEASUREMENTS

Sodium iodide scintillation counters with conventional electronics equipment were used for all the measurements. The resolving time of the coincidence circuit was $\sim 1.5\times 10^{-7}$ second; the solid angle subtended by the crystals at the source was ~0.1 steradian.

Sources of metallic manganese and manganese chloride sources were prepared from manganese metal which had been irradiated for a few hours in the Brookhaven National Laboratory pile.

Figure 2 represents the pulse-height distribution, due to the Fe^{56} gamma rays, obtained with a sodium iodide crystal 35 mm in diameter and 40 mm long. No indication of gamma rays different from the reported ones was found below 2.1 Mev. All the small peaks in the Compton distributions can be satisfactorily assigned to the pairs produced by the 1.8- and 2.1-Mev gamma rays.

In a first set of correlation experiments both channels accepted all pulses corresponding to more than 580-kev energy. The correlation thus obtained is presented in Fig. 3; it is a mixture of the two individual correla-

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[3] F. R. Metzger, Phys. Rev. **90**, 328 (1953).
[4] L. G. Elliott and M. Deutsch, Phys. Rev. **64**, 321 (1943).
[5] Bishop, Wilson, and Halban, Phys. Rev. **77**, 416 (1950).
[6] H. Slätis and K. Siegbahn, *Manne Siegbahn Commemorative Volume* (Uppsala, Sweden, 1951), p. 153.
[7] T. C. Engelder, Phys. Rev. **90**, 259 (1953).

tions in a ratio dependent on the discriminator settings. Analyzing the pulse-height distribution of Fig. 2 into the contributions of the individual gamma rays one finds that, for the discriminator settings used, the 1.8–0.85 Mev cascade contributed 1.60 ± 0.25 times as many counts as the 2.1–0.85 Mev cascade.

To arrive at the two individual correlations, one has to take a second set of measurements with a very different mixing ratio. The most drastic change is obtained if one moves the discriminator in one channel above the photopeak of the 1.8-Mev gamma ray, accepting the 2.1-Mev photopeak only, i.e., if one measures the pure 2.1–0.85 Mev correlation. By subtracting this correlation with the proper weight from the bulk correlation, one obtains the pure 1.8–0.85 Mev correlation.

The counting rate in the 2.1-Mev photopeak is rather small and limits the accuracy with which the

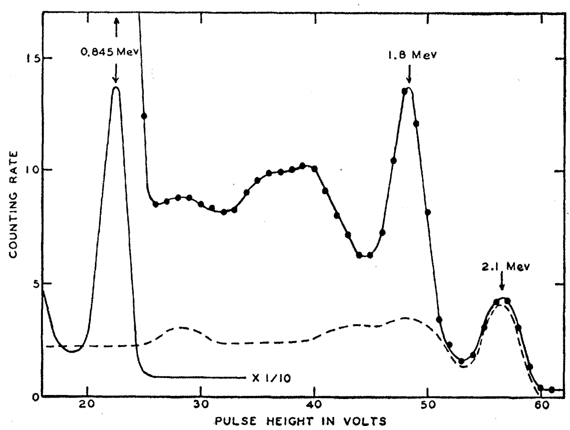

FIG. 2. Pulse-height distribution due to the gamma rays accompanying the decay of Mn^{56}. The dashed line indicates the contribution of the 2.1-Mev gamma ray. The residual counting rate above 2.25 Mev is due to the cross-over gamma rays.

pure 2.1–0.85 Mev correlation can be measured. Figure 4 gives the experimental points with their statistical uncertainties. Fitting these points with a distribution of the form $1+a\cos^2\theta$, one obtains $1+(0.07\pm0.04)\cos^2\theta$ as the best fit. However, if one admits $\cos^4$ terms also, a large variety of combinations will fit within the experimental error, the best fit being obtained with $1+0.14\cos^2\theta-0.08\cos^4\theta$.

Using for the ratio of the two cascade contributions the value 1.60 ± 0.25 and for the pure 2.1–0.85 Mev correlation the form $1+0.07\cos^2\theta$, one calculates for the pure 1.8–0.85 Mev correlation, after correcting for finite resolution, $1+0.51\cos^2\theta+0.13\cos^4\theta$. In view of the uncertainity in the coefficients of the 2.1–0.85 Mev correlation, the relative magnitude of the $\cos^2$ and $\cos^4$ terms is subject to considerable error. However, the uncertainty in the value of $W(180°)$ is less than six percent, i.e., $W(180°)/W(90°)=1.64\pm0.10$.

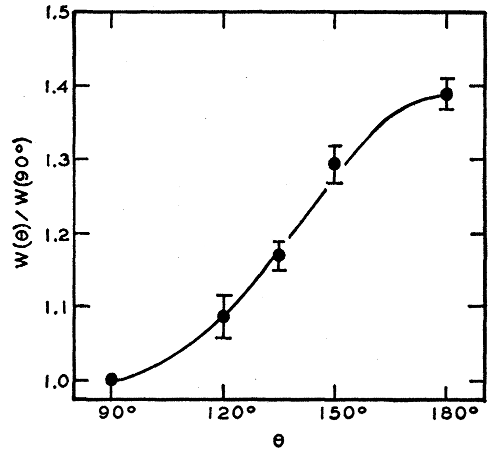

FIG. 3. Angular correlation of the Fe^{56} gamma rays (bulk correlation). All pulses corresponding to energies greater than 580 kev were accepted in both channels. The solid line represents the least square fit to the experimental points:

$$W(\theta)=1+0.32\cos^2\theta+0.066\cos^4\theta.$$

DISCUSSION

Summarizing the results of the preceding section, we write down the two angular correlations:

1.8–0.85 Mev cascade: $1+0.51\cos^2\theta+0.13\cos^4\theta$,
$W(180°)/W(90°)=1.64\pm0.10$;

2.1–0.85 Mev cascade: $1+0.07\cos^2\theta$.

For the following it is assumed that the spin of the first (0.85 Mev) excited state of Fe^{56} is 2+. The spin assignment 2–2–0 is then the only one agreeing with the experimental evidence for the 1.8–0.85 Mev cascade.

The combination 3–2–0 cannot exceed a value of 1.43 for the ratio $W(180°)/W(90°)$ and, moreover, cannot have a positive $\cos^4$ term for any mixture.

For 0–2–0 and 4–2–0 no mixtures are expected and the pure correlations are very different from the ex-

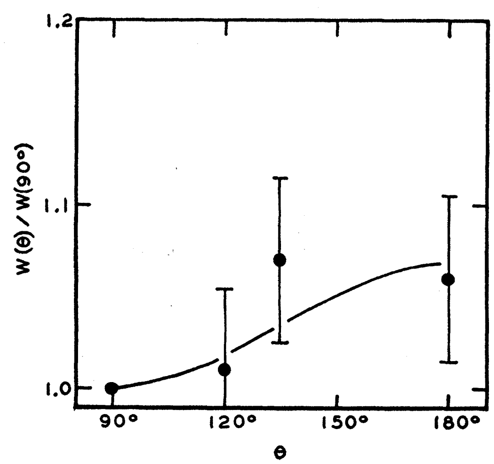

FIG. 4. Angular correlations of the 2.1–0.85 Mev cascade. The solid line represents the distribution $1+0.07\cos^2\theta$ used in correcting the bulk correlation.

perimental one. For 1–2–0 one can find a mixture which gives the correct value at 180°, however, the distribution would have the form $1+2\cos^2\theta-1.38\cos^4\theta$ which certainly does not match the experimental correlation. In addition, one would have difficulties understanding the very low cross-over intensity.

The spin combination 2–2–0 gives the correct value for $W(180°)/W(90°)$ if the admixture of quadrupole radiation to the dipole radiation is 2.2 percent and if the phase is 180°. The uncertainity of the $W(180°)/W(90°)$ ratio allows mixtures ranging from 0.5 percent quadrupole to 4 percent quadrupole. For 2.2 percent quadrupole admixture the correlation has the form[8] $1+0.60\cos^2\theta+0.04\cos^4\theta$ which agrees satisfactorily with the experimental correlation.

The 2 percent quadrupole admixture makes it rather certain that the 1.8-Mev transition involves no change in parity; i.e., that it is magnetic dipole with a small electric quadrupole admixture. The angular correlation measurements in the cases of Sr^{88} [9] and Te^{124} [3] indicate that admixture of $M2$ to $E1$, though present, is smaller than one part in a thousand.

The $E2$ admixture in the 1.8-Mev transition of Fe^{56} is about 5 times larger than expected on the basis of Weisskopf's lifetime formulas;[10] compared with other 2–2–0 transitions,[11] however, it is unusually small.

The intensity of the 2.65-Mev cross-over transition is of the order of magnitude expected for the competition of an $E2$ of 2.65 with a $M1$ of 1.8 Mev.

Based on all this evidence, spin 2+ is assigned to the 2.65-Mev excited state of Fe^{56}.

In view of the large uncertainity involved in the measurements of the internal pair coefficients, we do not consider the $M1$ assignment to be in disagreement with the pair coefficient experiment.[6] It would be worthwhile to measure the internal pair coefficient with improved accuracy.

The angular correlation measured for the 2.1–0.85 Mev cascade excludes the spin assignments 0 and 4 for the 2.95-Mev excited state. These spins were, however, already ruled out by the observation of the cross-over transitions.[5] Both 2–2–0 and 3–2–0 easily fit the observed points, while 1–2–0 could only be accommodated with difficulty.

It is felt that 2–2–0 is the correct assignment for the 2.1–0.85 Mev cascade. However, the arguments leading to this conclusion are less stringent than those used for the 1.8–0.85 Mev cascade.

The logft values of the two beta transitions leading to the 2.65- and 2.95-Mev excited states of Fe^{56} are 5.6 and 5.3 respectively. Both transitions seem, therefore, to be allowed; hence the two levels have the same parity. Under these circumstances the cross-over transitions will only be of comparable intensity, as observed, if the spins of the two levels are the same. Therefore, we have to assign spin 2, even parity to the 2.95-Mev level.

With this assignment, the 2.1-Mev transition becomes a mixture of 92 ± 3 percent $M1$ and 8 ± 3 percent $E2$ with zero phase. Thus, the disintegration of Mn^{56} leads to three excited states of Fe^{56} which all have spin 2, even parity. The most probable spin assignment for the ground state of Mn^{56} is 2+. The logft value of 6.6 for the transition to the 0.85-Mev excited state is somewhat large for an allowed transition, but does not constitute a serious objection to the spin assignment. It should be mentioned that a β-γ angular correlation experiment[12] on Mn^{56} revealed isotropy, indicating that the β transition to the 0.85 level does not have a forbidden shape and might well be allowed.

The reason for choosing 2+ instead of 3+ for the spin of the Mn^{56} ground state lies in the Co^{56} decay. Already Elliott and Deutsch[4] concluded that Co^{56} has a large spin.[13] The Co^{56} decay does not lead directly to any of the 2+ levels or to the ground state of Fe^{56}, but reaches some of these levels through cascades from levels with presumably high spins. Among others, the Co^{56} decay leads directly to a level 2.1 Mev above the Fe^{56} ground state. From this level, a 1.26-Mev gamma ray leads to the 0.85-Mev, 2+ level in Fe^{56}. It seems quite reasonable to assign spin 4+ to this 2.1-Mev level in Fe^{56}. The fact that this 2.1-Mev, 4+ level in Fe^{56} is not reached in the Mn^{56} beta decay favors strongly spin 2+ over 3+ for the ground state of Mn^{56}.

We are thus led to conclude that Mn^{56} decays from a 2+ ground state to three excited states in Fe^{56} which all have spin 2+. The γ-ray transitions between the 2+ levels are magnetic dipoles with small admixtures of electric quadrupoles. The apparent preponderance of 2+ states in Fe^{56} is due to the low spin of Mn^{56} which favors transitions to low spin states in Fe^{56}.

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[12] Walter, Huber, and Zünti, Helv. Phys. Acta **23**, 697 (1950).
[13] Presumably 5+ from a combination of a $f_{7/2}$ proton with a $p_{3/2}$ neutron.