and gamma-ray peaks as well as in the yield of inelastic neutrons. It will be noted also in the data to be given on U^{238}, and has no significant bearing on the results.

For U^{238} the data was obtained using a sample whose size was the same as that of the smaller gold sample above. The raw data are shown in Fig. 5, and in Fig. 14 are given the results of an analysis whose object is to resolve the spectrum into the components of neutrons which are due to inelastic scattering and those which are due to fission.

Thus far there are no data on the fission neutrons from U^{238}, but there are data available on the spectrum of fission neutrons for the case of U^{235} which has been caused to fission by thermal neutrons. This has been studied extensively and is well known.[23] Over the range[24] 0.18 to 9.0 Mev this spectrum is described by the function $E^{\frac{1}{2}}e^{-0.775E}$. This is the function which is shown plotted as a straight line in the semilogarithmic plot of Fig. 14. The line has been normalized to fit the observed neutron spectrum above the energy of the primary neutrons, where the contribution must be due entirely to fission. If one assumes that below 2.5 Mev the fission spectrum follows the empirical formula given above, then a resolution of the spectrum into fission and inelastic components is possible. Subtracting the fission neutrons and taking account of another factor of $E^{\frac{1}{2}}$, one may test the possibility of describing the data in terms of an effective temperature. The result of this analysis is that, except for the strong structure previously noted corresponding to levels in the vicinity of 1.18 Mev, an effective temperature of 0.3 Mev fits the data reasonably well. The uncertainty in this temperature is 10%.

The inelastic data on gold and uranium have also been fitted to a function of the form[4] $E\exp\{2[a(E_0-E)]^{\frac{1}{2}}\}$, where E_0 is the primary energy, but the fit is not improved.

It is not clear at this time to what extent the nuclear temperature concept describes nuclear excitations in the energy range considered here. A more extensive investigation of this matter is contemplated.

[23] B. Watt, Phys. Rev. **87**, 1037 (1952).
[24] Rosen, Frye, Nereson, and Cranberg (to be published); also Los Alamos Report LA-1916 (unpublished).

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Decay of Co^{58}†

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Co^{58} decays not only to the first but also to the second excited state of Fe^{58}. Both of these states in Fe^{58} possess spin 2, even parity, and the transition between them is a mixture of $E2$ and $M1$, with a mixing ratio $\delta(E2/M1)=+2.2\pm0.3$. The intensities of the 1.62-Mev and 0.81-Mev gamma rays originating from the second excited state (relative to the main 0.81-Mev transition) are 0.005 ± 0.001 and 0.016 ± 0.005, respectively.

INTRODUCTION

COBALT-58 belongs to the relatively small class of nuclei which can be investigated by nuclear alignment techniques.[1] Such work, in order to be of value, requires a detailed knowledge of the nuclear decay scheme. In the case of Co^{58}, the interpretation of the alignment experiments[2,3] is based on the decay scheme proposed by Deutsch and co-workers.[4,5] According to Deutsch, Co^{58} decays by K capture and positron emission entirely into the first excited state of Fe^{58}, and from there into the ground state by emitting a single gamma ray of 0.81-Mev energy. The alignment experiments confirm this scheme and, in addition, yield a consistent spin and parity assignment.

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* Research Fellow under the U. S. Exchange Program; on leave from the University of Milan, and from the Istituto Nazionale di Fisica Nucleare, Milan, Italy.
[1] See, e.g., Blin-Stoyle, Grace, and Halban, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955), p. 600 ff.

[2] Daniels, Grace, Halban, Kurti, and Robinson, Phil. Mag. **43**, 1297 (1952).
[3] Bishop, Daniels, Goldschmidt, Halban, Kurti, and Robinson, Phys. Rev. **88**, 1432 (1952).
[4] M. Deutsch and L. G. Elliott, Phys. Rev. **65**, 211 (1944).
[5] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).

Recently, Cork *et al.*[6] proposed a new decay scheme, in which Co^{58} decays into a second excited state of Fe^{58}, and by emission of two successive gamma rays, of energies 0.5 Mev and 0.8 Mev, into the ground state. Since such a scheme would require a revision of the interpretation of the alignment experiments and the spin assignment, we decided to check this new proposal.

According to the decay scheme of Cork and co-workers, the gamma line observed at 0.5 Mev would consist of a nuclear gamma ray and annihilation radiation. The intensity of this combined line should be considerably larger than that of the 0.8-Mev gamma ray. The experimental results[6] show, however, that the 0.8-Mev gamma line is more intense. This fact casts doubt on the proposed scheme. It actually turns out that there is no evidence for the existence of a 0.5-Mev nuclear gamma ray and that the scheme of Deutsch and co-workers is substantially correct.

During our work we found, however, that one has to complement the original decay scheme of Co^{58} by a low-intensity K-capture branch which leads into the second excited state of Fe^{58}. We were prompted to look for this branch by a recent communication of McFarland *et al.*[7] Investigating the energy levels of Fe^{58} by means of the $Fe^{57}(d,p)Fe^{58}$ reaction, they found that the lowest two excited states possess energies of about 0.79 Mev and 1.62 Mev. It seems very probable that the 0.79-Mev state is identical with the 0.81-Mev state reached by K capture and positron emission from Co^{58}. Energetically then, Co^{58} can also decay into the 1.62-Mev state. We found, in agreement with simultaneous work of Robinson and Fink,[8] that this decay does occur. By further investigating Co^{58}, as described in the present paper, we established the decay scheme which is given in Fig. 1.

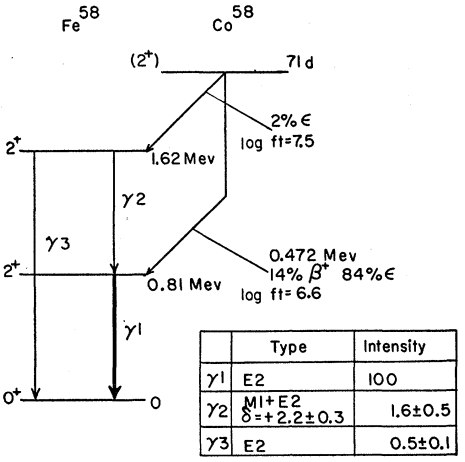

FIG. 1. The decay scheme of Co^{58}, which results from the present work.

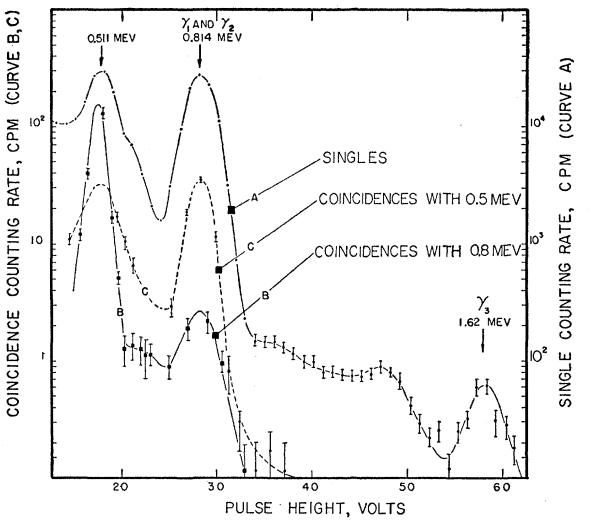

FIG. 2. Gamma ray spectrum of Co^{58}. The coincidence curves (B,C) were taken with the axes of the two counters subtending an angle $\theta=90°$ at the source.

EXPERIMENTS AND RESULTS[9–11]

Apparatus and Source Preparation

We performed most of our measurements with a combined "fast" coincidence ($2\tau=2\times10^{-8}$ sec)—"slow" spectrometer apparatus, using NaI(Tl) scintillation counters.

The Co^{58} activity was prepared by irradiating Mn (a layer, about 0.1 mm thick, electroplated onto a copper foil) with alpha particles in the University of Illinois cyclotron. In addition to Co^{58}, some Co^{57} was also produced. Since Co^{57} emits low-energy gamma rays only, it did not affect our measurements. The Co activity was extracted chemically, and a solution in sulfuric acid was prepared as a source.

Gamma-Ray Spectrum

The gamma-ray spectrum, obtained by means of a single-channel analyzer (Fig. 2, curve A), and independently by a gray-wedge analyzer, shows peaks at 0.511 Mev (annihilation radiation), 0.814±0.010 Mev,[6] 1.32±0.02 Mev, and 1.62±0.02 Mev. In order to distinguish between true gamma rays and sum lines, we measured the absorption in lead for each peak. Table I immediately shows that the observed 1.62-Mev peak is due to a gamma ray (γ_3), whereas the 1.32-Mev

[6] Cork, Brice, and Schmid, Phys. Rev. **99**, 703 (1955).

[7] McFarland, Shull, Elwyn, and Zeidman, in *Nuclear Level Schemes*, edited by K. Way, U. S. Atomic Energy Commission Report TID–5300, 1955 (unpublished) and F. B. Shull (private communication).

[8] B. L. Robinson and R. W. Fink, Bull. Am. Phys. Soc. Ser. II, **1**, 40 (1956).

[9] Discussions concerning the experimental methods will be short, since excellent reviews on scintillation methods (see reference 10) and coincidence techniques (see reference 11) are available.

[10] P. R. Bell, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955), p. 132 ff.

[11] R. E. Bell, in reference 10, p. 494 ff.

TABLE I. Theoretical and observed absorption coefficients in lead.

Energy (Mev)	μ_{theoret} (cm^{-1})	μ_{exptl} (poor geometry) (cm^{-1})
0.511	1.69	1.5
0.814	0.96	0.8
1.32	0.66	2.2
1.62	0.57	0.6

peak corresponds to a summation of the 0.5- and 0.8-Mev photopeak pulses. These results were confirmed by observing the effect of changes of solid angle on the gamma spectrum.

Additional information was obtained from the coincidence spectrum (Fig. 2, curves B and C). Curve B, taken with one channel receiving the full 0.8-Mev photopeak, shows the presence of the 0.8−0.8 Mev cascade.

Curve C, measured with one channel sitting on the full 0.5-Mev photopeak, agrees with the corresponding curve obtained by Cork *et al.*[6] The peak appearing at 0.5 Mev is not due to true 0.5−0.5 Mev coincidences, but corresponds to detection of annihilation radiation in one counter, and Compton pulses of the 0.8-Mev line in the other. The spectrum of the single counts (Fig. 2, curve A) agrees with this conclusion: using the photopeaks of the annihilation radiation and of the 0.8-Mev gamma ray, one finds a ratio of positrons to electron captures which is in agreement with the accurate value of Good *et al.*[5] Hence there is no need for assuming the existence of a nuclear 0.5-Mev gamma ray.

Intensities of γ_2 and γ_3

The determination of the intensity of γ_3 (1.62 Mev) relative to γ_1 proceeds in a straightforward way from the ratio of the areas under the photopeaks in the gamma-ray spectrum and the calculated ratio of efficiencies[10,12] for the two energies (Table II).

Unfortunately this simple method does not apply to the γ_2 line, because the energies of γ_2 and γ_1 are not resolved. Therefore we used a coincidence method to determine the intensity of γ_2 relative to γ_1: Assuming that all positrons annihilate in the source, the following formula for the relative intensity $I(\gamma_2)/I(\gamma_1)$ holds in a good approximation:

$$I(\gamma_2)/I(\gamma_1)=i/(1+i),$$

with

$$i=b[C^{0.8-0.8}(\theta)/W(\theta)C^{0.8-0.5}]\times[\epsilon_2(0.5\text{ Mev})/\epsilon_2(0.8\text{ Mev})],$$

and where $C^{0.8-0.8}(\theta)$ is the coincidence rate between γ_2 and γ_1, photopeaks only, at an angle θ; $C^{0.8-0.5}$ the coincidence rate between annihilation radiation (counter 2) and 0.8-Mev gamma rays (counter 1), photopeaks only; b the branching ratio $\beta^+/(\beta^++\epsilon)$ [adopted value[5] 0.14 ± 0.01]; $W(\theta)$ the normalized directional correlation function, and $\epsilon_2(E_\gamma)$ the photopeak efficiency of counter 2 for gamma rays of energy E_γ.

Table II contains all the relevant data concerning the calculated efficiencies in our geometry.

From the data in Table II and our measurements we determined the relative intensities $I(\gamma_3)/I(\gamma_1)=0.005\pm0.001$ and $I(\gamma_2)/I(\gamma_1)=0.016\pm0.005$.

In order to establish an upper limit for the difference in energy between γ_1 and γ_2, we measured the 0.8−0.8 Mev coincidence rate sitting with one channel on the entire 0.8-Mev photopeak, and with the other channel alternatively on equal adjacent intervals, at the left and at the right of the center of the 0.8-Mev photopeak. The ratio of the counting rates was 1.00 ± 0.09. Under the assumption of a Gaussian shape for the photopeaks, an upper limit of 10 kev for the energy difference was determined.

Directional Correlation between γ_2 and γ_1

The directional correlation function between γ_2 and γ_1 was measured, sitting with both analyzers on the full 0.8-Mev photopeaks. Using the expansion in Legendre polynomials, $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, and correcting for the finite angular resolution of the detectors, we found $A_2=0.26\pm0.03$ and $A_4=0.28\pm0.05$.

Spin and Parity Assignment

Our results, together with already known data, uniquely determine the spin and parity assignment given in Fig. 1. We discuss in the following how we arrived at this assignment.

The $Fe^{57}(d,p)Fe^{58}$ experiments of McFarland *et al.*[7] indicate that the spin of both excited states in question cannot be larger than 3 and that both states possess even parity. The conversion coefficient[13,14] of γ_1 indicates that this transition involves at most quadrupole radiation. Hence the spin of the first excited state can only be 1 or 2, if we presume spin 0 for the ground state of the even-even nucleus. The fact that the coefficient A_4 is positive then leaves the sequence $2^+\rightarrow2^+\rightarrow0^+$ as the only choice. All other combinations exhibit negative or vanishing A_4.[15] This assignment is in

TABLE II. Calculated photopeak efficiencies of counter 2 for gamma rays of energy E_γ.

Ref.	ϵ_2(0.5 Mev)	ϵ_2(0.8 Mev)	ϵ_2(1.6 Mev)	[ϵ_2(0.5 Mev)/ ϵ_2(0.8 Mev)]	[ϵ_2(0.8 Mev)/ ϵ_2(1.6 Mev)]
(10)	0.176	0.092	0.040	1.9	2.3
(12)	0.2	0.11	0.05	1.8	2.2

[12] Maeder, Mueller, and Wintersteiger, Helv. Phys. Acta **27**, 3 (1954).

[13] K. Strauch, Phys. Rev. **79**, 487 (1950).

[14] Cheng, Dick, and Kurbatov, Phys. Rev. **88**, 887 (1952).

[15] M. Ferentz and N. Rosenzweig, Argonne National Laboratory Report ANL-5324 (unpublished).

agreement with all other data: the ft values for the beta decays ($\log ft=7.5$ for the K capture into the upper 2^+ state, $\log ft=6.6$ for the decay into the lower 2^+ state), the nuclear alignment results,[2,3] and the conversion coefficient of γ_1.[13,14]

The numerical values of A_2 and A_4 furnish information about the character of the $2^+ \rightarrow 2^+$ transition. As expected, this gamma ray is a mixture of $E2$ and $M1$. Figure 3 displays the coefficients A_2 and A_4 as a function of the mixing ratio $\delta(E2/M1)$.[15] The experimental values for A_2 and A_4 yield $\delta=+2.2\pm0.3$. This value of δ is based on the assumption that the measured correlation is not attenuated by extranuclear effects.[16,17] Two independent arguments speak for this assumption. Firstly, the single-particle lifetime of a 0.8-Mev $E2$ is about 10^{-10} sec, and the neighboring even-even nuclei Fe^{56} and Ni^{60} show lifetimes which are considerably shorter than the single-particle estimate.[18,19] Secondly, the δ value corresponding to A_2 overlaps very well with the one obtained from A_4. Any perturbation would shift these two values apart, as one can see from Fig. 3. The influence of extranuclear fields, if present at all, is thus negligible.

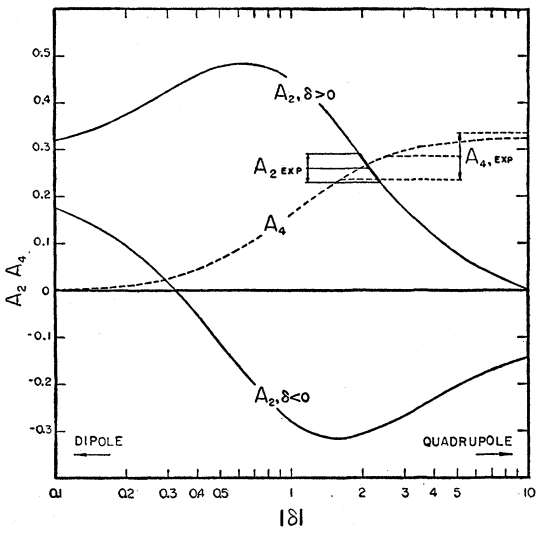

FIG. 3. Coefficients A_2 and A_4 of the directional correlation function for the spin sequence $2 \rightarrow 2 \rightarrow 0$, as a function of the mixing ratio $\delta(E2/M1)$.

DISCUSSION

The primary objective of the present work was to decide whether the interpretation of the nuclear alignment experiments[2,3] rests on firm ground. As one can see from Fig. 1, all but 2% of the decays from Co^{58} lead into the first excited state of Fe^{58}. The results of the alignment experiments thus are only slightly affected. The angular distribution observed at the 0.8-Mev line is actually a sum of two functions. At present, it is unfortunately impossible to determine them separately since the energies of γ_1 and γ_2 are too close. Hence, in order to obtain a very accurate angular distribution for γ_1, one must correct the experimentally observed function for the presence of γ_2 by using the results of directional correlation measurements. The angular distribution of 1.62-Mev gamma ray has been measured by Griffing and Wheatley.[20] Their results are in agreement with the decay scheme given in Fig. 1.

A second interesting observation can be made regarding the decay scheme of Co^{58} as shown in Fig. 1. Scharff-Goldhaber and Weneser,[21] and Wilets and Jean,[22] recently discussed a class of nuclei which show the following main characteristics: the ratio of the energy of the second to that of the first excited state is close to 2, the transition from the second to the first excited state is predominantly $E2$, and the crossover intensity is smaller than that of the transition into the intermediate state. All three characteristics apply to Fe^{58}: the energy ratio is $E_2/E_1=2.0\pm0.02$, the $2^+ \rightarrow 2^+$ transition is predominantly $E2$, and the intensity of γ_3 is three times smaller than that of γ_2.

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[16] H. Frauenfelder, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955), p. 531 ff.
[17] R. M. Steffen, Phil. Mag. Suppl. *Advances in Physics* 4, 293 (1955).
[18] N. P. Heydenburg and G. M. Temmer, U. S. Atomic Energy Commission Report TID-5300, 1955 (unpublished).
[19] F. R. Metzger, Bull. Am. Phys. Soc. Ser. II, 1, 40 (1956).
[20] D. Griffing and J. C. Wheatley (to be published).
[21] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[22] L. Wilets and M. Jean, Phys. Rev. **102**, 788 (1956).