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Disintegration Schemes of Radioactive Substances. VI. Mn^{56} and Co^{56}

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The radiations accompanying the decay of Mn^{56} and of Co^{56} were studied by means of the magnetic lens spectrometer and coincidence methods. Both of these nuclei decay to stable Fe^{56} as the product nucleus. Four excited states of the Fe^{56} nucleus are definitely established with excitation energies 0.845 Mev, 2.11 Mev, 2.66 Mev, and 2.98 Mev, respectively. De-excitation of the three high energy states always leads to the 0.845-Mev level and thence to the ground state. The negatron spectrum of Mn^{56} consists of three groups of maximum energies 2.86 Mev, 1.05 Mev, and 0.73 Mev, respectively, and relative abundance 60 : 25 : 15 leading to the first, third, and fourth of the excited states mentioned above. The positron spectrum of Co^{56} consists mainly of a single group of maximum energy 1.50 Mev, leaving the Fe^{56} nucleus in the 2.11-Mev state. Orbital electron capture also takes place involving several other excited states. Altogether the energies of eight gamma-rays emitted by the Fe^{56} nucleus are determined: 0.845 Mev, 1.26 Mev, 1.74 Mev, 1.81 Mev, 2.01 Mev, 2.13 Mev, 2.55 Mev, 3.25 Mev. Within the experimental uncertainty five of these energies appear to be the multiples 2, 3, 4, 5, and 6 of 0.425 Mev. All of the beta-ray spectra involved seem to have the "allowed" shape of the Fermi theory. The significance of this and of the relative probability of orbital electron capture is discussed in terms of the tensor interaction. It appears that all of the transitions should involve nuclear angular momentum changes $\Delta J=\pm 1$ or $\Delta J=0$, with or without parity change. From the disintegration schemes one obtains the mass differences between neutral atoms, namely, $Mn^{56}-Fe^{56}=3.98$ mMU and $Co^{56}-Fe^{56}=4.96$ mMU, and the threshold for the reaction $Fe^{56}(p, n)Co^{56}$: 5.47 Mev.

INTRODUCTION

THE preceding papers of this series[1] have described investigations leading to the assignment of energy levels in product nuclei of radioactive disintegrations. The question naturally arises whether any particular radioactive decay involves all, or even most, of the energetically available levels of the product nucleus. The results of the previous investigations indicate that only a few of the possible transitions take place with sufficient frequency to be detected by our present methods. Thus, for example in the decay of I^{130} (paper V) only two of five possible beta-ray transitions and four of ten possible gamma-ray transitions between the known levels are actually observed. In the case of Br^{82} (paper II) only one of four possible beta-ray transitions and three of six gamma-ray transitions are found. So far it has always been possible to account for the absence of the other transitions on the basis of known selection rules for gamma-ray transitions and the Gamow-Teller selection rules for beta-ray emission. Consistent assignments of total angular momenta and parity have been possible, in this way, although these assignments are by no means unique. Generally the average level spacings are found to be of the same order of magnitude as

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[1] Phys. Rev. **60**, 470L (1941); **60**, 544 (1941); **61**, 686 (1942); **62**, 3 (1942); **64**, 268 (1943), hereafter referred to as papers I to V.

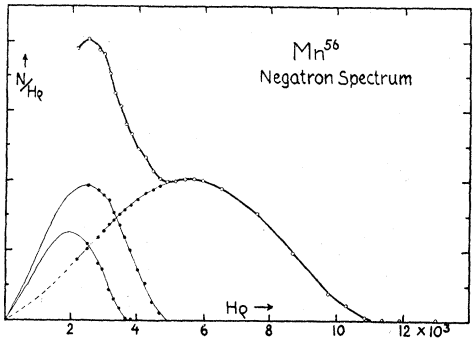

FIG. 1. The beta-ray spectrum of Mn^{56}. The open circles and heavy line represent the experimental data. The full circles indicate the three partial spectra, as derived from the Fermi plot.

those found in transmutation[2] and inelastic scattering[3] experiments. A comparison of the results of heavy particle studies with radioactive disintegration schemes should permit an estimate of the fraction of all states likely to be detected by any one of the methods. Unfortunately very few nuclei have been studied with sufficient accuracy by more than one of these methods giving information about low lying excited states.

It will probably be necessary to improve the resolution of the heavy particle studies, possibly by substituting magnetic analysis for the present absorption methods before they can be used for actual identification of energy levels. It is doubtful whether, e.g., the accuracy of any of the present transmutation and scattering experiments would be sufficient to resolve the two known excited states of Co^{59} (paper IV) or to decide the order of the two states in Ni^{60}.[4]

One may hope, however, to obtain valuable information by studying the radioactive decay of different parent nuclei to the same product nucleus. This may occur either by the decay of independent (genetically unrelated) isomers or by the decay of radioactive isobars differing by two in atomic number. The first case occurs rather rarely such as in Co^{60} which is, however, difficult to study[4,5] because of the short life of one of the isomeric activities. The convergent decay of two isobars occurs fairly frequently, but only a few of these isobaric pairs of activities are suitable for our purpose. In some cases (e.g., Cr^{52}) the half-life of one or both of the activities is inconveniently short. Others (e.g., Cu^{63}) lack interest because one or both of the disintegrations involves only the ground state of the product nucleus.

Preliminary investigations indicated that the isobaric pair $Mn^{56}-Co^{56}$ is very well suited for a study of the levels of Fe^{56} since both disintegrations involve several gamma-rays and proceed sufficiently slowly for careful investigation. A brief report on some results of such a study was made in a Letter to the Editor[6] and the present paper extends these results and describes the experiments leading to them.

A. Mn^{56}

The 2.59-hr. activity of manganese is definitely assigned to the species Mn^{56} since it is produced by slow neutron bombardment of stable Mn^{55}. The radiations accompanying its decay have been studied by a number of authors. We shall refer here only to some of the more recent results. Townsend[7] found that the beta-ray spectrum, observed in a 180° focusing spectrometer, appears to consist of two groups with maximum energies 2.88 Mev and 1.01 Mev, respectively. This is in good agreement with the results of Langer, Mitchell, and McDaniel[8] and of Dunworth[9] who

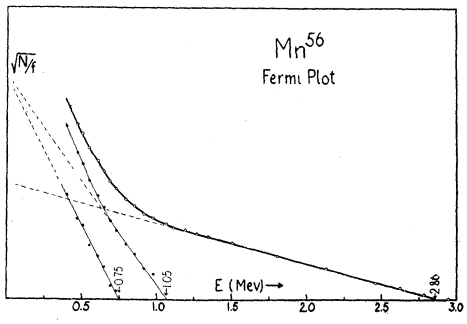

FIG. 2. Fermi plot of the spectrum shown in Fig. 1. The end points of the low energy spectra deduced from this plot are in excellent agreement with the level scheme found from gamma-ray energy and coincidence measurements.

[2] E. F. Shrader and E. Pollard, Phys. Rev. **59**, 277 (1941).
[3] R. H. Dicke and J. Marshall, Jr., Phys. Rev. **63**, 86 (1943).
[4] M. Deutsch and L. G. Elliott, Phys. Rev. **62**, 558A (1942).
[5] H. E. Nelson, M. L. Pool, and J. D. Kurbatov, Phys. Rev. **62**, 1 (1942).
[6] L. G. Elliott and M. Deutsch, Phys. Rev. **63**, 321L (1943).
[7] A. A. Townsend, Roy. Soc. Proc. **A177**, 362 (1941).
[8] L. M. Langer, A. C. G. Mitchell, and P. W. McDaniel, Phys. Rev. **56**, 422 (1939).
[9] J. V. Dunworth, Nature **143**, 1065 (1939).

found that all beta-rays of energy greater than about 1 Mev are accompanied, on the average, by the same gamma-rays whose energy the latter author estimated to be about 0.60 Mev, while the beta-rays of lower energy are accompanied by harder gamma-rays. Langer *et al.*[8] estimated the energy of these harder gamma-rays as 1.7 Mev. Gamma-gamma coincidences showed that some gamma-rays are emitted in cascade, and Dunworth[9] proposed a disintegration scheme in

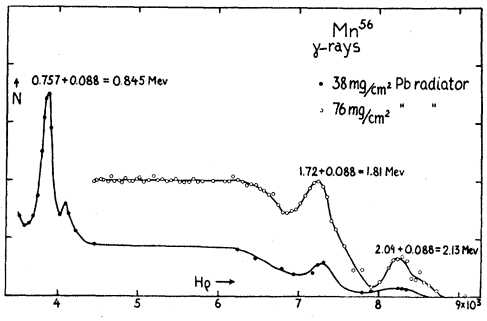

FIG. 3. Secondary electron spectra due to the gamma-rays of Mn^{56}. The two curves do not correspond to sources of equal strength.

which 60 percent of the beta-rays are accompanied by a single 0.6-Mev gamma-ray, while the remainder is accompanied by a 1.7-Mev and a 0.6-Mev gamma-ray in cascade. However, Curran, Dee, and Strothers[10] found two gamma-rays of 0.91-Mev and 2.01-Mev energy, respectively, by studying the Compton electrons ejected by the gamma-rays of Mn^{56} in a 180° focusing spectrometer. Deutsch and Roberts[11] studying photoelectrons as well as Compton recoils found values of 0.835 and 2.13 Mev, respectively. Although these measurements were not incompatible with Dunworth's disintegration scheme, the disagreement between the best beta-ray[7] and gamma-ray[11] energy determinations was serious enough to make the proposed scheme rather unsatisfactory. Recent improvements in spectrometer technique have allowed us to discover a third gamma-ray of energy 1.81 Mev which resolves these difficulties and leads to a satisfactory modification of the disintegration scheme.[6]

[10] S. C. Curran, P. I. Dee, and J. E. Strothers, Proc. Roy. Soc. **A174**, 546 (1940).
[11] M. Deutsch and A. Roberts, Phys. Rev. **60**, 362L (1941).

PREPARATION OF SOURCES

Sources of Mn^{56} were usually prepared by exposing a saturated solution of $KMnO_4$ to slow neutrons from the M.I.T. cyclotron for several hours. The solution was then filtered through a fritted glass filter, and most of the activity was found in the MnO_2 precipitate. Filtering the $KMnO_4$ solution through paper increases the amount of precipitate without increasing the activity recovered, probably because of the reducing action of the paper.

Thin sources for beta-ray studies were prepared by depositing a drop of active $MnCl_2$ solution and then a drop of $(NH_4)_2S$ solution on a thin flake of mica and evaporating to dryness. The source was then heated for several minutes to drive off excess reagent. This procedure is preferable to simple evaporation of a chloride solution since the finely divided sulfide precipitate forms a much more uniform and coherent deposit than a salt which crystallizes from the solution. The mica was mounted in the spectrometer without backing to minimize back scattering of the beta-rays.

For the study of gamma-ray energies, active MnO_2 was sealed into a brass capsule of sufficient wall thickness to stop all primary beta-rays. Suitable lead and bismuth radiators were fixed to this capsule with wax for the measurement of photoelectron distributions.

THE BETA-RAY SPECTRUM OF Mn^{56}

Figure 1 shows the momentum distribution of the beta-rays of Mn^{56}, obtained in the magnetic lens spectrometer. We believe that source and backing were thin enough to meet the rigorous criteria for reliable beta-ray measurements. Figure 2 shows the same data as a Fermi plot. Our results agree very closely with those obtained by Townsend.[7] It is quite obvious from Fig. 2 that there are at least two groups of beta-rays with maximum energies 2.86 Mev and about 1 Mev, respectively. The particular analysis of the Fermi plot into three straight lines as shown in Fig. 2 is based on evidence about the disintegration scheme obtained from the gamma-ray energies and coincidence measurements. It is by no means to be taken for granted that the Fermi plot can be analyzed into straight lines repre-

senting various groups since some simple "forbidden" spectra are known not to be represented by straight Fermi plots,[12] and it is unlikely that all of the groups emitted by Mn^{56} are emitted in "allowed" transitions. The significance of the fact that, nevertheless, when the beta-ray spectrum of Mn^{56} is analyzed into groups with the maximum energies predicted by independent information about the disintegration scheme, each group is represented by a straight Fermi

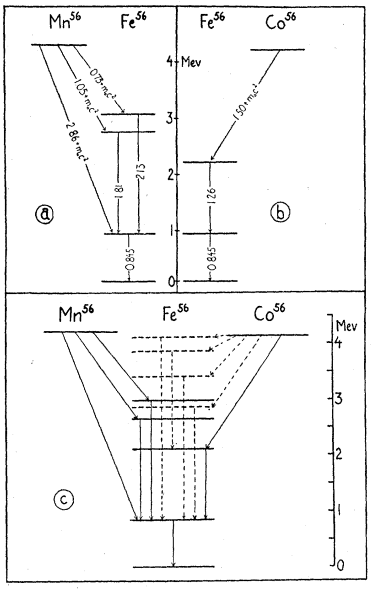

FIG. 4. a. Disintegration scheme of Mn^{56}. b. Level scheme for the most abundant mode of disintegration of Co^{56}. c. Proposed level scheme for the transitions to Fe^{56}. Solid lines and arrows indicate levels and transitions which appear well established. Dotted lines and arrows indicate an arrangement of the observed gamma-rays of Co^{56}, consistent with the probable selection rules.

plot, will be discussed further in Section C below. This result is similar to those obtained in the case of Fe^{59} (paper IV) and of I^{130} (paper V). The three groups are shown in Fig. 1. Their maximum energies are 0.75 ± 0.1 Mev, 1.05 ± 0.03 Mev, and 2.86 ± 0.05 Mev, respectively, and their relative abundance 15 : 25 : 60.

THE GAMMA-RAY SPECTRUM

Figure 3 shows the spectra of secondary electrons produced in lead radiators of two different thicknesses (and in the brass capsule containing the source) by the gamma-rays of Mn^{56}. The observed counting rates were *not* divided by $H\rho$ as is customary, since the heights of the photoelectron lines, representing intensities of nearly monokinetic groups of electrons, should not be so divided.[13] There appear three pronounced photoelectron lines due to K electrons of lead ejected by gamma-rays of 0.845 ± 0.015-Mev, 1.81 ± 0.04-Mev, and 2.13 ± 0.04-Mev energy, respectively. The incompletely resolved L-electron group due to the lowest energy gamma-ray gives rise to the peak on the high energy side of the corresponding K electrons. The continuous background consists of Compton recoil electrons due to the same three gamma-rays. Only the energy range above 0.7 Mev is shown since no gamma-rays were found below that energy.

The resolution obtained in the experiments of Curran, Dee, and Strothers[10] and of Deutsch and Roberts[11] was not sufficient to resolve the two high energy gamma-rays.

The relative abundance of the three gamma-rays can be obtained from the heights of the photoelectron lines if the effect of finite radiator thickness and the variation of the photoelectric cross section with energy are considered. The result is:[14]

$$I_{2.13} : I_{1.81} : I_{0.845} = 20 : 30 : 100.$$

COINCIDENCE MEASUREMENTS OF Mn^{56}

Coincidences between beta- and gamma-rays were observed with varying amounts of absorber between source and beta-ray counter as well as coincidences between gamma-rays. The beta-ray counter used was of the helium-filled bell type described in paper II. The gamma-ray counters, also helium filled, had platinum screen cathodes (paper III). The arrangement of the counters, designed to reduce the number of spurious coincidences due to scattered radiations to a minimum, has been described in paper V. The results are in good qualitative agreement with those of other observers[8, 9] The number of beta-

[12] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **60**, 308 (1941).

[13] L. G. Elliott, M. Deutsch, and A. Roberts, Phys. Rev. **63**, 386L (1943).

[14] Since the photoelectric cross section in this energy range is not well known experimentally, the theoretical values of Hulme *et al.*, Proc. Roy. Soc. **149A**, 131 (1935), were used.

gamma coincidences per recorded beta-ray is independent of beta-ray energy above about 1 Mev and has the value $1.00\pm0.05\times10^{-3}$ in the standard arrangement (paper V). When absorber is removed so that electrons of lower energy than 1 Mev are admitted into the beta-ray counter, the number of coincidences per recorded beta-ray increases rapidly and reaches a value of $1.92\pm0.08\times10^{-3}$ when all absorber except the counter window (5 mg/cm^2) is removed. The number of gamma-gamma coincidences per recorded gamma-ray is $0.92\pm0.07\times10^{-3}$ in the standard counter arrangement.

THE DISINTEGRATION SCHEME OF Mn^{56}

Since Mn^{56} can decay only by negatron emission, the level scheme shown in Fig. 4a seems to be the only one consistent with the experimental results. The fact that the high energy spectrum is accompanied by a single 0.845-Mev gamma-ray is established by the excellent agreement of the observed coincidence rate of 1.00×10^{-3} and the efficiency curve for the counter used (paper V). If either of the two high energy gamma-rays found in the secondary electron spectrum were emitted in transitions leading directly to the ground state, the maximum energy of the second beta-ray spectrum would have to be considerably higher than the value of about 1 Mev deduced both from the shape of the beta-ray spectrum and from the coincidence measurements. On the other hand there is not enough energy available for two high energy gamma-rays to be emitted successively. The proposed disintegration scheme predicts a value of 1.88×10^{-3} for the number of beta-gamma coincidences per beta-ray recorded without absorber, on the basis of the efficiency curve (Fig. 4, paper V) compared with the observed value of $1.92\pm0.08\times10^{-3}$. Similarly the predicted value of 0.99×10^{-3} gamma-gamma coincidences per recorded gamma-ray is in excellent agreement with the observed value of $0.92\pm0.07\times10^{-3}$. Thus the disintegration scheme of Mn^{56} may be considered well established.

B. Co^{56}

In contrast to Mn^{56} very little work has been done previously on the disintegration of Co^{56}. Livingood and Seaborg[15] have shown that the high energy positrons emitted with a half-life of 70–80 days by cobalt obtained from deuteron bombardment of either iron or nickel must be due to Co^{56}, since pure Co^{58} which was produced by alpha-particle bombardment of manganese emits much softer radiations. This was confirmed by producing Co^{58} by fast neutron bombardment of nickel.[16]

Cook and McDaniel,[17] using absorption and coincidence methods, reported that the positron spectrum is simple with a maximum energy of 1.2 Mev, that the average gamma-ray energy is 1.74 Mev, the energy of the highest energy gamma-rays 2.9 Mev, that the positrons are accompanied by gamma-rays, and that orbital electron capture seems to occur.

In a Letter to the Editor[6] we have described a partial disintegration scheme for Co^{56}. We shall now discuss the experiments leading to the adoption of that scheme and describe some other features of the disintegration of Co^{56}.

PREPARATION OF SOURCES OF Co^{56}

A study of the stable nuclear species in this region of the periodic table shows that it is impossible to produce Co^{56} free from other cobalt activities by any method used at present. It can be prepared by deuteron bombardment of

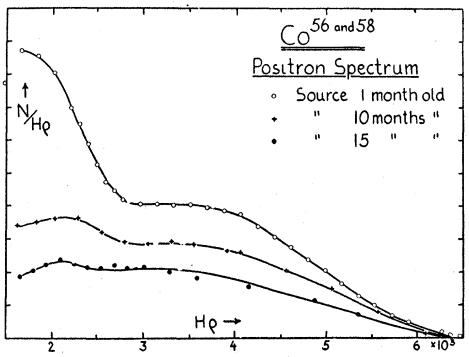

FIG. 5. Positron spectrum of radioactive cobalt separated from iron bombarded with deuterons. The curves represent spectra of three different sources.

[15] J. J. Livingood and G. T. Seaborg, Phys. Rev. **60**, 913L (1941).
[16] L. G. Elliott and M. Deutsch, Phys. Rev. **63**, 219A (1943). (See also paper VII, to appear soon.)
[17] C. S. Cook and P. W. McDaniel, Phys. Rev. **62**, 412 (1942).

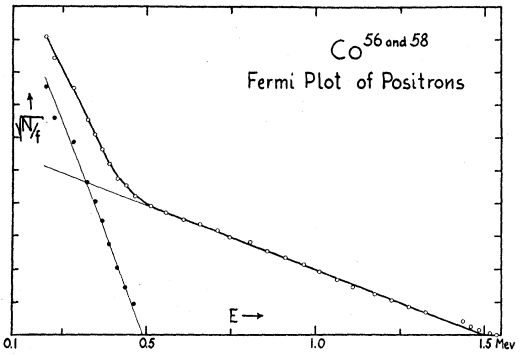

FIG. 6. Fermi plot of the positron spectrum of cobalt from (Fe+d). The plot represents the data shown in the top curve of Fig. 5. The low energy spectrum is due to Co^{58}.

iron in which case it is accompanied by Co^{55}, Co^{57}, and Co^{58}. Or it may be prepared by deuteron bombardment of nickel in which case Co^{58} and Co^{60} are also produced. We have studied sources prepared by both of these methods. Most of the experiments were carried out with samples obtained from iron. The iron targets were treated as described in paper IV. The filtrate of the pyridine precipitation was freed repeatedly of elements of the hydrogen sulfide group (by using inactive copper carrier) and cobalt was precipitated as potassium cobaltinitrite, and finally as oxide. Carrier material was added for all likely impurities, and all separations were repeated with additional carrier until all of the activity remained in the cobalt fraction.

Sources for beta-ray studies were prepared either by deposition as sulfide as in the case of manganese or by electroplating on thin brass or copper foil. Gamma-ray sources were prepared by sealing the oxide into a suitable brass capsule.

Samples prepared by deuteron bombardment of nickel were treated similarly.

THE BETA-RAY SPECTRUM OF Co^{56}

Figure 5 shows the positron spectra emitted by sources of cobalt prepared by deuteron bombardment of iron. These curves do not represent the decay of a single source but spectra of sources prepared at different times before the experiments. It is seen that the spectrum is complex and that the soft component decays somewhat more rapidly than the high energy radiation. Since the specific activity of the oldest source was rather low, the corresponding positron spectrum is probably distorted by scattering in the source material. An estimate of this decay showed that very few, if any, of the soft positrons of Co^{57} reported by Livingood and Seaborg[15] were present. On the other hand, the conversion lines due to the gamma-rays of Co^{57} with energies 0.119 and 0.131 Mev[18,19] were very pronounced, particularly in the older sources, and the intensity of these soft gamma-rays exceeded that of the gamma-rays of Co^{56} and Co^{58} many-fold. A discussion of Co^{57} will appear in another paper. Figure 6 shows the positron spectrum of the strongest source as a Fermi plot. The plot is a straight line above 0.48 ± 0.01 Mev and indicates a maximum energy of the positrons of 1.50 ± 0.05 Mev. After subtracting the high energy group, the low energy portion also appears to be represented by a straight Fermi plot. The maximum energy of 0.48 Mev suggests strongly that it is due to the positrons[16] of Co^{58}. This is supported by the more rapid decay of this group. Because of the presence of these positrons of Co^{58}, the low energy portion of the Co^{56} spectrum cannot be studied thoroughly, but it seems reasonably

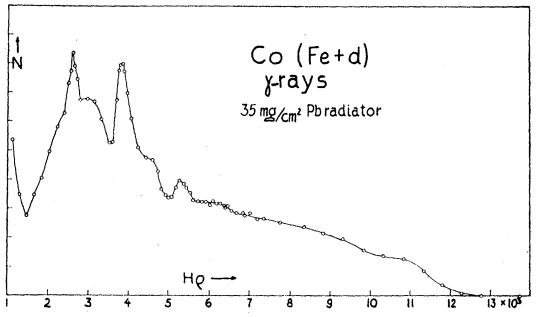

FIG. 7. Secondary electron spectrum due to gamma-rays of cobalt from (Fe+d), obtained with moderate resolution. The rapid rise near $H\rho=1000$ is due to gamma-rays of Co^{57}.

certain that any low energy group of Co^{56}, if it exists at all, must be much less abundant than the main group of maximum energy 1.50 Mev. No decay curves were taken of any of the sources, but the variation of the relative intensity of the two spectra (and of the gamma-rays as discussed in the next section) in sources prepared at

[18] E. H. Plesset, Phys. Rev. **62**, 181 (1942).
[19] M. Deutsch, A. Roberts, and L. G. Elliott, Phys. Rev. **61**, 389A (1942).

different times from the same bombardment is consistent with the values of 85 days and 65 days for the periods of Co^{56} and Co^{58}, respectively.

THE GAMMA-RAY SPECTRUM OF Co^{56}

In a paper read before the Physical Society, Deutsch, Roberts, and Elliott[19] have reported gamma-ray energies of 0.119, 0.131, 0.510 (annihilation radiation), 0.835, 1.25, 3.40 Mev and a doubtful gamma-ray of 1.75 Mev from a mixture of long-lived cobalt activities produced by deuteron bombardment of iron. Figure 7 shows an example of the data on which that report was based. It was pointed out at that time that the photoelectron line due to the 0.835-Mev gamma-ray appeared wider than would be expected from instrumental effects and also that there was reason to believe that other gamma-rays exist of energies between 1.25 and 3.4 Mev. No trace of the 0.20- and 0.22-Mev gamma-rays reported by Plesset[18] was found, and it seems that the photoelectron lines ascribed by him to these gamma-rays were due to L and M electrons of lead ejected by the two known gamma-rays of lower energy definitely assigned to Co^{57} which were the only ones found with energy less than that of the annihilation radiation.

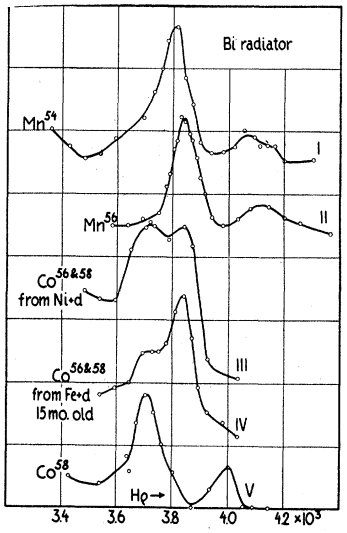

FIG. 8. Study of secondary electrons in the neighborhood of 0.75 Mev with high resolution. Comparison of curves II, III, and IV shows the identity of the energy of the 0.845-Mev gamma-rays of Mn^{56} and Co^{56}. Curves III, IV, and V show the varying relative abundance of Co^{58} in sources of mixed cobalt isotopes. Note separation of K and L photoelectron peaks in curves I, II, and V.

All secondary electrons of energy greater than 0.85 Mev decay at the same rate, as shown by the fact that the shape of the distribution curve was found to be independent of the age of the source. The relative abundance of the annihilation radiation and of the peak due to the 0.84-Mev radiation decreases with increasing age of the source while the intensity of the low energy radiation due to Co^{57} decays much more slowly than the rest of the radiations.

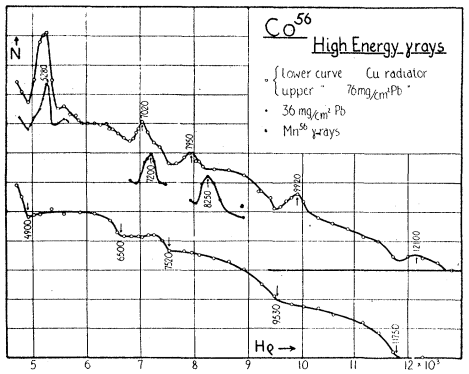

FIG. 9. Secondary electron spectra due to the high energy gamma-rays of Co^{56}, observed with good resolution. Numbers indicate the location of the peaks and high energy end points, respectively. Solid circles show the location of the peaks due to high energy gamma-rays of Mn^{56}, obtained with the same resolution.

Since a 0.805-Mev gamma-ray has been definitely assigned[16] to Co^{58} and since a 0.845-Mev gamma-ray was found in Mn^{56} which decays to the same product nucleus (Fe^{56}) as Co^{56}, the photoelectron group at 0.75 Mev, previously ascribed to a gamma-ray of 0.835 Mev, was investigated in more detail. The spectrometer was adjusted for better resolution and an arrangement was provided by which sources could be changed without disturbing the radiator. This eliminated any possibility of slight changes in the calibration of the spectrometer due to shifts in the effective source of photoelectrons. Figure 8 shows the result of this study. A thin bismuth radiator was used rather than lead to take advantage of the larger photoelectric cross section and to increase the separation between the K and L photoelectron groups. Curves I, II, and V of Fig. 8 show this separation and illustrate the resolution used. It will be seen that both of the sources containing mixtures of Co^{56} and Co^{58} show two peaks. One

TABLE I. Gamma-rays accompanying the decay of Co^{56}. Relative intensities referred to that of the 0.845-Mev gamma-ray. If all disintegrations involve this gamma-ray, relative intensities also represent number of quanta per disintegration. Note that intensity of annihilation radiation is only 0.5. If all transitions were by positron emission, this intensity should be 2.

E (Mev)	0.510 annihil. rad.	0.845	1.26	1.74	2.01	2.55	3.25
Intensity	0.5	1.0	0.5	0.2	0.1	0.2	0.2

of these corresponds accurately to the peak found with the source containing Co^{58} only. The other peak has an energy about 5 percent greater. The source prepared by deuteron bombardment of nickel shows a greater relative intensity of the Co^{58} gamma-ray, and a positron spectrum of the same sample showed a greater relative abundance of the Co^{58} spectrum. The higher energy peak obviously belongs to Co^{56}, and it is seen by a comparison of curves II and IV in Fig. 8 that its energy agrees very closely (within 0.5 percent or better) with that of 0.845-Mev gamma-ray of Mn^{56}.

Figure 9 shows a spectrum of secondary electrons due to the higher energy gamma-rays of Co^{56}. Because of the large number of gamma-rays in this region and their low relative intensities, it was necessary to take special precautions to reduce background effects (e.g., through coincidence counting) and to adjust the spectrometer for very good resolution. In this manner it was possible to resolve five distinct gamma-rays where our previous measurements[19] revealed only three. The upper curve shows the five groups of K photoelectrons, while the lower curve shows the Compton recoil groups due to the same five gamma-rays. The photoelectron group due to the highest energy gamma-ray appears somewhat wider than the others, suggesting the possibility of two unresolved peaks. Table I lists the energies of all of the gamma-rays of Co^{56} together with their estimated relative intensities.

Two of the gamma-ray energies, 1.74 Mev and 2.01 Mev, are within a few percent of the values 1.81 Mev and 2.13 Mev found in Mn^{56}. However, they are certainly different transitions. The peaks due to the Mn^{56} gamma-rays, obtained under the same geometrical conditions as those of Co^{56}, are also shown in Fig. 9. There can be no doubt but that the difference between the energies is real. It should be clearly understood that, while we estimate the probable errors in the absolute energy values to be about two percent, this allows for possible errors in the calibration of the instrument and the effect of finite radiator thickness, while relative energy determinations within a narrow energy range should be reliable to about 0.5 percent.

COINCIDENCE MEASUREMENTS OF Co^{56}

Coincidences between positrons and gamma-rays are studied preferably in the spectrometer since even with considerable precautions the annihilation quanta tend to introduce spurious effects when absorption methods are used. Coincidences between gamma-rays and positrons focused in the spectrometer were studied for several positron energies between 0.48 Mev and 1.50 Mev. About three millimeters of lead had to be inserted between the source and the gamma-ray counter in order to absorb the very intense gamma-radiation of Co^{57}. In this arrangement the number of coincidences per recorded positron was found to be independent of positron energy and to have the value $4.0\pm0.2\times10^{-3}$. By measuring coincidences between beta- and gamma-rays of Mn^{56}, Co^{58}, and Co^{60}, whose disintegration schemes are known, it was found that the coincidence rate expected if each positron of Co^{56} is accompanied by a 0.845- and a 1.26-Mev gamma-ray in cascade is $4.1\pm0.2\times10^{-3}$. This is in good agreement with the observed value. However, nearly the same coincidence rate would be expected if each positron were accompanied by a single gamma-ray of about 2-Mev energy. Therefore the average energy of the gamma-rays accompanying the positrons was determined by observing the variation of coincidence rate as lead absorber is placed between source and gamma-ray counter. Figure 10 shows the result of this experiment, corrected for chance coincidences. On the same figure is shown the absorption (in the same geometry) of the gamma-rays from Co^{60}, whose disintegration is known to be accompanied by two gamma-rays of 1.1- and 1.3-Mev energy, respectively.[4] The other dotted lines show the absorption expected with 2.1-Mev and with 0.85-Mev gamma-radiation. The absorption co-

efficients found in this geometry are slightly larger than the accepted values because of the obliquity of the gamma-rays traversing the absorber. It appears that the observed absorption for the case of Co^{56} agrees very well with that expected for a 0.845-Mev and a 1.26-Mev gamma-ray in cascade, but would be quite inconsistent with the assumption of a 2-Mev gamma-ray.

X-ray-gamma and gamma-gamma coincidences were also observed, but because of the unavoidable presence of other cobalt activities, particularly Co^{58}, the results have little quantitative significance.

THE DISINTEGRATION SCHEME OF Co^{56}

In the preceding section it was shown that the positron spectrum of Co^{56} is accompanied by a 1.26- and a 0.845-Mev gamma-ray as shown in Fig. 4b. The order of emission of the two gamma-rays is not directly established by experiment but the arrangement chosen in Fig. 4b seems very probable since a state of 0.845-Mev excitation energy in the Fe^{56} nucleus was previously found in the disintegration of Mn^{56} (Fig. 4a).

The positron spectrum is certainly simple above 0.48 Mev and if any branching occurs at lower energies, the low energy spectrum is almost certainly not very abundant because of the competing orbital electron capture and the relatively low intensity of the high energy gamma-rays. It appears that the high energy gamma-rays accompany orbital electron capture almost exclusively.

Any attempt to arrange these high energy gamma-rays into a level scheme is necessarily largely conjectural at the present time. A few features of the scheme can, however, be established with a certain degree of probability: It seems very unlikely that either the 1.74-Mev or the 2.01-Mev gamma-ray is emitted in a transition directly to the ground state from a level to which orbital electron capture takes place, since positron transitions to such a level would almost certainly be observed. The same argument holds—with less force—for the 2.55-Mev gamma-ray and for transitions of a 1.74-Mev gamma-ray to the 0.845-Mev level. The fact that the 0.845-Mev gamma-ray is about twice as abundant as the 1.26-Mev gamma-ray must have one of three possible explanations: 1. Orbital electron capture directly to the 0.845-Mev state. 2. Other transitions of the same energy but between two excited states. 3. Other gamma-ray transitions, besides the 1.26-Mev gamma-ray, leading to the 0.845-Mev level.

The first possibility seems extremely unlikely. In view of the great energy available for this transition (3.3 Mev), positron emission would certainly compete to a considerable extent with electron capture; and positron emission leading directly to this level is not observed. The second cannot be entirely excluded but seems somewhat improbable. The most reasonable assumption is the third. In Fig. 4c all of the states of Fe^{56} are definitely established and the transitions between them are indicated by solid lines, while the dotted lines indicate an assignment of the remaining gamma-rays to terms which are consistent with the above considerations. This particular arrangement is rather arbitrary and must necessarily remain so until further improvements in technique permit, for example, the study of coincidences between selected gamma-rays.

The fact that the annihilation radiation is only half as abundant as the 0.845-Mev gamma-ray indicates that the total probability of orbital electron capture to all states is at least three

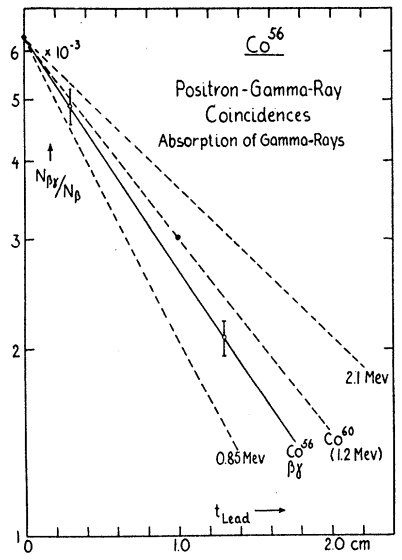

FIG. 10. Absorption of the gamma-rays coinciding with the positrons of Co^{56}.

times as great as that of positron emission (except on assumption 2 above). The relative probabilities of the two modes of transition to the 2.11-Mev level alone cannot be determined, however, since part of the disintegration scheme is not yet fully understood. For the particular scheme indicated by dotted lines in Fig. 4c the probability of orbital electron capture leading to the 2.11-Mev level is about one-fifth of that of positron emission.

C. DISCUSSION

The existence of four excited states in Fe^{56} with excitation energies of 0.845 ± 0.015 Mev, 2.11 ± 0.04 Mev, 2.66 ± 0.05 Mev, 2.98 ± 0.06 Mev has been definitely demonstrated. Of these levels only the lowest one is excited both by the decay of Mn^{56} and of Co^{56}. It can be seen, then, that neither disintegration involves *all* of the excited states which are energetically possible, and it is reasonable to assume that there are other states which are not excited in either disintegration. On the other hand the two sets of levels are not entirely unrelated since they have the lowest excited state in common.

Inspection of the eight gamma-ray energies assigned to the Fe^{56} nucleus shows that there are several cases in which two of them may be added to obtain the energy of a third observed gamma-ray, or where one gamma-ray has just twice the energy of another. It has been shown in other disintegrations, e.g.,[13] Na^{24} and Br^{82} (paper II) that such energy relationships do not necessarily mean that the same states are involved in the transitions. In Fe^{56}, too, we find, for example, that the excitation energy of the state to which positron emission takes place agrees, within the probable error, with the energy of the 2.13-Mev gamma-ray emitted following negatron emission by Mn^{56}.

Guggenheimer,[20] extending a suggestion of Rutherford and Ellis,[21] has pointed out that this behavior may not be fortuitous, since the energies of the gamma-rays emitted by some radioactive substances seem to occur in simple ratios. In Table II we list all of the gamma-rays emitted by the Fe^{56} nucleus. Inspection of the column headed "$E/0.425$" shows that five of the eight gamma-ray energies are integer multiples of 0.425 Mev, within the experimental uncertainty. It is particularly noteworthy that all integers from two to six are represented. The column headed "Terms" shows the energies of the initial and final states of the transitions wherever these are known.

The fact that the Fermi plots of the various beta-ray spectra are all straight lines within the experimental accuracy is rather surprising, since the positron spectrum of Co^{56} and probably also the high energy negatron spectrum of Mn^{56} must be emitted in "forbidden transitions," if this expression retains any significance with respect to a "Sargent diagram."

This means that all of the transition must involve differences of 0 or 1 in nuclear angular momentum between initial and final state (in the tensor theory), with or without parity change, the dominant matrix element being $\int\alpha$ or $\int 1$, respectively, in the notation of Konopinski and Uhlenbeck.[12] The shape of the lowest (and possibly also the intermediate) spectrum of Mn^{56} is somewhat uncertain, though. It is interesting to note that the ratio of the probability of orbital electron capture to that of positron emission predicted by theory[22] for an allowed transition in the case of Co^{56} is $\lambda_k/\lambda_{e+}=0.25$ in close agreement with the value derived from the scheme shown in Fig. 4c. If the transition is first forbidden, this value could still be consistent with the theory for the tensor interaction in certain transitions if the dominant matrix element is $\int\alpha$.[12] If the transition is of a different type, agreement with theory could be obtained only by revising the uncertain parts of the level scheme.

TABLE II. Gamma-rays emitted by the nucleus Fe^{56}.

E	Disintegration	Terms	$E/0.425$
0.845	Mn^{56}, Co^{56}	0.845–0	1.99 (2.0)
1.26	Co^{56}	2.11 –0.845	2.97 (3.0)
1.74	Co^{56}	?	4.09 (4.0)
1.81	Mn^{56}	2.66 –0.845	4.26 —
2.01	Co^{56}	?	4.73 —
2.13	Mn^{56}	2.98 –0.845	5.01 (5.0)
2.55	Co^{56}	?	6.00 (6.0)
3.25	Co^{56}	?	7.65 —

[20] K. H. Guggenheimer, Proc. Roy. Soc. **A181**, 169 (1942).

[21] Lord Rutherford and C. D. Ellis, Proc. Roy. Soc. **A132**, 667 (1931).

[22] R. E. Marshak, Phys. Rev. **61**, 431 (1942).

TABLE III. Possible angular momentum quantum numbers and parity of states of Mn, Fe, and Co.

Nucleus	Excitation energy Mev	Angular momentum $h/2\pi$	Parity
Fe^{56}	0	0	*e*
	0.845	1	*o*
	2.11	6	*e*
	2.66	3	*o*
	2.98	3	*o*
Mn^{56}	(4.21)	2	*o*
Co^{56}	(4.12)	6	*o*

It is possible to explain the absence of cross-over transitions in the disintegration scheme (Fig. 4c) on the basis of the known selection rules for beta- and gamma-ray transitions, as was done in other papers of this series. Table III shows a set of such angular momentum and parity assignments (the parity of a state is indicated by *e* if it is even, by *o* if it is odd). Of course, all the parities could be reversed without changing the character of the transition. The reasoning leading to these assignments is similar to that in paper V. The values proposed are not particularly convincing, and they are given only to show that no further selection rules are required to explain the present data.

From the total disintegration energies of the schemes in Figs. 4a and 4b we can calculate the mass differences between the neutral atoms involved. We find $Mn^{56}-Fe^{56}=3.98\pm0.05\times10^{-3}$ aMU $Co^{56}-Fe^{56}=4.96\pm0.06\times10^{-3}$ aMU.

Similarly one can calculate the threshold for the reaction $Fe^{56}(p, n)Co^{56}$ from the disintegration energies, taking into account the recoil energy of the product nucleus and the mass difference between neutron and proton ($n-p=1.26\pm0.02\times10^{-3}$ aMU). The threshold energy is thus found to be 5.47 ± 0.12 Mev. This high value makes Fe^{56} an interesting nucleus for the study of inelastic proton scattering, since it allows the use of high proton energies for the formation of excited states up to 5 Mev without competition from neutron emission. The much lower threshold[16] for the reaction $Fe^{58}(p, n)Co^{58}$ should eliminate interference by protons scattered inelastically by Fe^{58}.

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