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Coincidences Between Beta- and Gamma-Rays in Manganese*

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With two reliable high speed counters in a coincidence circuit of resolving time, $\tau = 3.4\times10^{-7}$ min., coincidences have been recorded between beta- and gamma-radiation from Mn^{56} (148 min.) formed by slow neutron capture. By interposing various thicknesses of aluminum between the source and the beta-ray counter, the ratio of beta-gamma coincidences to single beta-counts was observed as a function of the energy of the beta-rays. The number of coincidences per beta-ray was larger when electrons of all energies were striking the beta-ray counter than when only electrons of high energy were recorded. Coincidences were still recorded when only the high energy beta-rays were entering the counter. In addition gamma-gamma coincidences were found. From these experiments it is concluded that Fe^{56} is formed in two excited states from the disintegration of Mn^{56} and that one gamma-ray per disintegration is associated with the high energy group and about two gamma-rays per disintegration with the low energy group.

INTRODUCTION

A CERTAIN amount of work has been done on the beta- and gamma-rays associated with Mn^{56} of period 150 min. The beta-ray spectrum was investigated by Gaerttner, Turin and Crane[1] and Brown and Mitchell.[2] The two sets of observers agreed in fixing an extrapolated K-U end point of between 2.8 and 2.9 Mev. The latter group of observers, using thin emitters of MnO_2 deposited from irradiated $NaMnO_4$, found that the beta-ray spectrum was composite and consisted of two groups with end points at 1.2 and 2.9 Mev. They also pointed out that Gaerttner, Turin and Crane, who used thick emitters of metallic manganese, would probably not have found a composite spectrum because of distortion due to the thick source. Later, Bacon, Grisewood and van der Merwe[3] appear to have confirmed the existence of the two groups reported by Brown and Mitchell.

A measurement of the energy of the gamma-rays emitted by Mn^{56} was made by Mitchell and Langer[4] by recording the coincidences produced by Compton electrons ejected from an aluminum plate placed in front of two counters. Insertion of aluminum foils between the two counters causes a decrease in the number of coincidences and from these measurements the energy of the gamma-ray may be obtained. The value of the energy found by this method was 1.65 Mev. The close agreement between the energy of the gamma-ray and the difference between the energies of the two end points of the composite beta-ray spectrum led the authors to suppose that the two beta-ray transitions give rise to two different states of the product nucleus, Fe^{56}, and that the gamma-ray is emitted as a transition between these two states.

The present experiment was designed to test this hypothesis further and to give some information as to the number of gamma-rays per beta-ray transition.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement is somewhat similar to that used by Norling[5] in his investigation of the beta-gamma coincidences in As^{76}. A concentrated solution of $NaMnO_4$ was irradiated with neutrons from a radium-beryllium neutron source containing 211 mg of radium salt. The MnO_2, containing most of the active material, was filtered and the filter paper mounted between two Geiger-Mueller tube counters arranged to count coincidences.

One of the counters was used as a gamma-ray counter and was separated from the source by 0.60 cm of Al, a thickness large enough to stop

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[1] E. R. Gaerttner, J. J. Turin and H. R. Crane, Phys. Rev. **49**, 793 (1936).

[2] M. V. Brown and A. C. G. Mitchell, Phys. Rev. **50**, 593 (1936).

[3] R. H. Bacon, E. N. Grisewood and C. W. van der Merwe, Phys. Rev. **52**, 668 (1937).

[4] A. C. G. Mitchell and L. M. Langer, Phys. Rev. **52**, 137 (1937).

[5] F. Norling, Zeits. f. Physik **111**, 158 (1938).

all beta-rays. The other counter, which we shall call the beta-ray counter, responded to both beta- and gamma-rays. The apparatus was so arranged that various thicknesses of aluminum could be placed between the source and the beta-ray counter. The aluminum served to define the energy of the beta-rays entering the beta-ray counter, since only electrons having an energy greater than a certain minimum could pass through the aluminum. By varying the thickness of the aluminum the coincidence rate could be measured as a function of the energy of the beta-rays.

Apparatus

The Geiger-Mueller counters used in this experiment are of the self-quenching type.[6] The negative electrode is a thin silver deposit on the inside surface of a glass tube 2.0 cm in diameter. The wall thickness of the glass is only 0.02 cm over the 5-cm length of the sensitive region. The central electrode is 0.010 cm tungsten. In order to insure a surface with a high work function, the counters were rinsed with a very dilute solution of lacquer in amyl acetate. After outgassing at high vacuum with a liquid-air trap, the counters were filled with 8 cm of pure argon and 1 cm vapor pressure of absolute alcohol. These counters have maintained, since their construction, a threshold voltage of about 1000 volts and an operating range of about 200 volts. They appear to be free from the spurious and multiple pulses sometimes encountered with counters and have the added advantage of operating at high counting rates with a simple low resistance-capacity input circuit.

The pulses from the counter are fed into a resistance-capacity coincidence amplifier similar to one previously described.[7] In the present case, the time constants have been further reduced to the minimum values that still give sufficient amplification and also maintain the desirable feature of having all the pulses reaching the mixer tube of the same size.

The output of the amplifier is connected to a hard vacuum tube scale of two, four, eight or sixteen recorder monitored by a cathode-ray oscillograph.

The over-all speed of counter, input circuit, amplifier and recorder is found to be limited by the mechanical counter. Tests in measuring the decay of the 54-minute period of In^{116} show counting losses of less than one percent at counting rates of 25,000 particles per minute.

The resolving time for coincidences was determined by recording the chance coincidences when an independent source of beta-rays was placed over each counter. From the relation

$$N_c = 2N_1N_2\tau,$$

the value of the resolving time, τ, was determined for widely different values of N_1 and N_2, and found to be 3.4×10^{-7} min.[8] independent of the rate of counting.

For coincidence measurements, the counters were mounted in a horizontal plane on a skeleton frame-work with their centers 4.0 cm apart. The source in the form of a thin filter paper about 4×7 cm was mounted midway between the

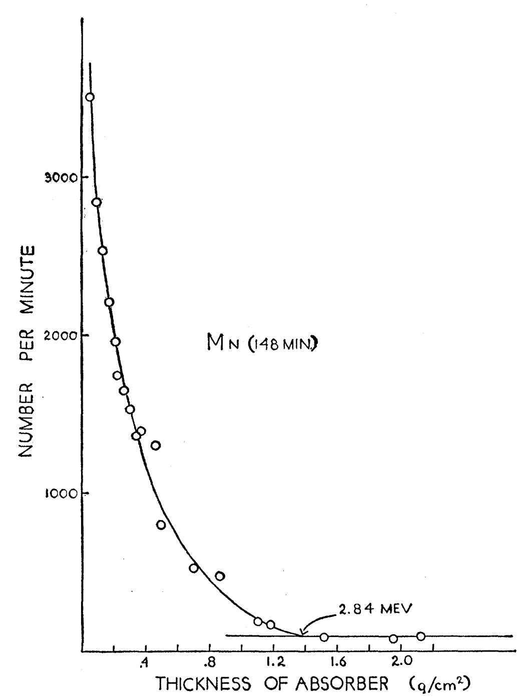

Fig. 1. Absorption of beta-rays from manganese.

[6] A. Trost, Zeits. f. Physik **105**, 399 (1937).

[7] L. M. Langer and M. D. Whitaker, Phys. Rev. **51**, 713 (1937).

[8] The resolving time has since been reduced to 0.56×10^{-7} min. which seems to be about the lower limit for this type of amplifier.

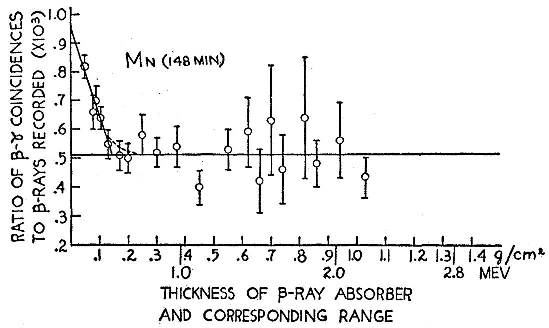

FIG. 2. Beta-gamma coincidences as a function of the beta-ray energy.

counters. For this geometry the coincidence background due to cosmic rays is 0.10 count per minute.

MEASUREMENTS

Measurement of the end point by absorption in aluminum

In order to determine, independently of other end-point measurements, the amount of aluminum necessary to absorb all the beta-rays from the source an absorption curve in aluminum was obtained using a single counter. The results are shown in Fig. 1, in which the number of counts per minute is plotted against the thickness of aluminum in g/cm². The point at which the absorption curve intersects the gamma-ray background is 1.38 g/cm². This range, according to the formula of Feather,[9] corresponds to an end point of 2.84 Mev, in good agreement with the cloud chamber measurements.

The half-life for the decay was measured carefully and found to be 148 ± 5 min.

Gamma-gamma coincidences

In order to test for coincidences between time correlated gamma-rays, measurements were made in which 0.60 cm of aluminum was placed between the source and each counter. In order to calculate the number of chance coincidences the single counts in each counter were taken at the beginning and end of each run. The duration of each experiment was two hours. After subtracting the coincidences due to chance[10] and those due to cosmic rays there was a definite residual due to gamma-gamma coincidences of 0.21 ± 0.10 per thousand gamma-rays.

Beta-gamma coincidences

The coincidences between beta- and gamma-rays were next investigated. This was accomplished by keeping 0.60 cm Al between the source and the gamma-ray counter and a thickness of aluminum, sufficient to stop all electrons of less than a given energy, between the source and the beta-ray counter. This thickness was varied in different experiments. The single counts in both the beta-ray counter and the gamma-ray counter were taken before and after each run. The beta-gamma coincidences were obtained from the total number of coincidences after subtracting the coincidences due to chance, cosmic rays, and gamma-gamma coincidences.

The number of beta-rays entering the beta-ray counter was also obtained from the above data and corrected for the relatively small number of counts due to gamma-rays. The number of beta-gamma coincidences per incident beta-ray is shown in Fig. 2 as a function of the energy of the beta-rays.

It will be seen that the errors at large thicknesses of absorber are greater than at the small thicknesses, since in the former case the total number of coincidences obtained is smaller and the gamma-gamma count is a larger fraction of the total. The data in Table I, selected from the results, will illustrate this.

DISCUSSION OF RESULTS

The fact that gamma-gamma coincidences are observed shows that in some cases there is more than one gamma-ray per disintegration. From Fig. 2 it will be seen that since there are beta-gamma coincidences associated with the high energy beta-rays right out to the beta-ray end point, it appears that the high energy part of the beta-ray spectrum leads to a transition to an

[9] N. Feather, Proc. Camb. Phil. Soc. **34**, 599 (1938).

[10] In calculating the chance rate for a source which is decaying with the time one proceeds as follows: Let $N_1(t)$ and $N_2(t)$ be the counting rate in each counter at time t and let ν be the natural background of each counter. The coincidence rate at time t is $2[N_1(t)+\nu][N_2(t)+\nu]\tau$, where τ is the resolving time of the apparatus. The average chance rate for a duration of the experiment of time T is therefore

$$\bar{N}_c = \frac{2\tau}{T}\int_0^T [N_1(t)+\nu][N_2(t)+\nu]dt.$$

Our values of the chance rate were calculated from this equation.

excited state of the product nucleus Fe^{56}. Furthermore, it will be seen from the curve that there are more beta-gamma coincidences per beta-ray when beta-rays of all energies are entering the counter than when the lower energy rays are excluded. This points to the existence of two groups of beta-rays with gamma-rays associated with each group.

One can calculate the average number of gamma-rays associated with each beta-ray transition by making certain plausible assumptions. Let N_{β_1} and N_{β_2} be the numbers of beta-rays emitted in the low and high energy groups, respectively; K_1 and K_2 the average number of gamma-rays per disintegration in each group; and S_β, S_γ the beta- and gamma-ray sensitivities of the counters (including solid angle). The number of beta-gamma coincidences per beta-ray detected is

$$\frac{N_{\beta\gamma}}{(N_{\beta_1}S_{\beta_1}+N_{\beta_2}S_{\beta_2})}=\frac{N_{\beta_1}S_{\beta_1}S_{\gamma_1}K_1+N_{\beta_2}S_{\beta_2}S_{\gamma_2}K_2}{N_{\beta_1}S_{\beta_1}+N_{\beta_2}S_{\beta_2})}. \quad (1)$$

If one assumes that $S_{\beta_1}=S_{\beta_2}=S_\beta$ and that $S_{\gamma_1}=S_{\gamma_2}=S_\gamma$, an average gamma-sensitivity for gamma-rays, then, for zero absorber, (1) becomes

$$\frac{N_{\beta\gamma}}{(N_{\beta_1}+N_{\beta_2})S_\beta}=(n_1K_1+n_2K_2)S_\gamma=0.95\times10^{-3} \quad (2)$$

and for large thicknesses of absorber, at which $N_{\beta_1}S_{\beta_1}=0$, (1) becomes

$$\frac{N_{\beta\gamma}}{N_{\beta_2}S_\beta}=S_\gamma K_2=0.5\times10^{-3}, \quad (3)$$

in which n_1 and n_2 are the fractions of electrons emitted in each group. The numerical values given in Eqs. (2) and (3) are taken from Fig. 2.

The number of gamma-gamma coincidences per gamma-ray, on the other hand, is given by

$$\frac{N_{\gamma\gamma}}{(N_{\gamma_1}+N_{\gamma_2})S_\gamma}=\frac{N_{\gamma_1}S_\gamma{}^2\frac{K_1(K_1-1)}{2}+N_{\gamma_2}S_\gamma{}^2\frac{K_2(K_2-1)}{2}}{(N_{\gamma_1}+N_{\gamma_2})S_\gamma}=0.21\times10^{-3}. \quad (4)$$

Remembering that $N_{\gamma_1}=K_1N_{\beta_1}$ and $N_{\gamma_2}=K_2N_{\beta_2}$, one obtains from Eqs. (2), (3) and (4)

TABLE I. *Data on $\gamma-\gamma$ and $\beta-\gamma$ coincidences.*

G/CM²	TOTAL NO. COINCIDENCES (60 MIN.)	COINCIDENCE RATE MIN.$^{-1}$	CHANCE RATE MIN.$^{-1}$	$\gamma-\gamma$ RATE MIN.$^{-1}$	$\beta-\gamma$ RATE MIN.$^{-1}$
0.05	166	2.67	0.23	0.01	2.43
0.25	160	2.56	0.51	0.03	2.02
0.74	88	1.37	0.58	0.08	0.71

$$(n_1K_1{}^2/K_2{}^2)(K_1-1)+n_2(K_2-1)=1.6 \quad (5)$$

and

$$K_1/K_2=(1.9-n_2)/n_1. \quad (6)$$

In addition

$$n_1+n_2\equiv1. \quad (7)$$

Now, from the fact that the curve in Fig. 2 rises as it approaches the origin it follows that $K_1>K_2$. Furthermore, K_2 cannot be less than 1. It was found by trial that the only solution consistent with these conditions and satisfying (5), (6) and (7) is $K_2=1$. This gives as a result

$$K_1=2.2,\quad n_1=0.75 \quad \text{and} \quad n_2=0.25.$$

The values of n_1 and n_2 obtained from this analysis are consistent with values obtained by integrating under the beta-ray distribution curves given by Brown and Mitchell. The values obtained from their data give $n_1=0.70$ and $n_2=0.30$.

If one places the value $K_2=1$ in Eq. (3), one obtains for the sensitivity of the gamma-ray counter a value $S_\gamma=0.5\times10^{-3}$.

At present the energies and the intensities of the individual gamma-rays have not been measured. It should be pointed out that the method employed by Mitchell and Langer measures only the average energy of the gamma-rays and has no resolving power. It is to be hoped that good measurements on the energies of the individual gamma-rays will be made shortly so that an accurate energy level diagram may be obtained.

We may, however, conclude from the present experiment that there are two groups of beta-rays, both of which go to excited states of Fe^{56}. The high energy beta-ray group is followed by the emission of a single gamma-ray, while the low energy beta-ray group is, on the average, followed by two gamma-rays.

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