Coincidence Experiments in Ni^{65}, Ni^{57}, Ag^{110} and In^{114}

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Absorption in aluminum of the beta-radiation from Ni^{57} gave a maximum beta-energy of 1.97 Mev. Beta-gamma-coincidence absorption indicated another beta-ray group at 0.46 Mev. Gamma-gamma-coincidences were obtained, and coincidence absorption of the Compton-recoil electrons gave gamma-rays of 1.64 and 0.3 Mev. The maximum energy of the positrons from Ni^{57} was found to be 0.72 Mev by absorption in aluminum. Beta-gamma-coincidences indicated the presence of only a single beta-ray group. Gamma-gamma-coincidences were obtained, and the energy of the most energetic gamma-ray was found to be 1.97 Mev. The beta-spectrum of Ag^{110} was shown to consist of beta-ray groups of 0.09, 0.55 Mev and a very high-energy component of low intensity. Beta-gamma-coincidences showed that the most energetic group leads to the ground state. A large gamma-gamma-coincidence rate was obtained, and the most energetic gamma-ray was found to have an energy of 1.48±0.1 Mev. In^{114} was found to emit a 0.196 Mev gamma-ray and a 2.05 Mev beta-ray as has been shown previously. In addition, gamma-rays of about 0.5, 0.7, and 1.3 Mev were found. Gamma-gamma-coincidences showed that two of these are in cascade and beta-gamma-coincidence absorption showed that they are not in coincidence with the 2.05 Mev beta-ray.

I. INTRODUCTION

COINCIDENCE and absorption measurements have been made on the radioactive isotopes Ni^{65}, Ni^{57}, Ag^{110}, and In^{114}. The G-M counters and coincidence amplifier used have been previously described.[1] The arrangement of the counters with respect to the source was that generally used for coincidence and absorption measurements.[2]

Earlier work on the two nickel isotopes, other than the mass assignments, has been performed by Livingood and Seaborg.[3] These investigators reported a half-life of 2.6±0.03 hours for Ni^{65} and a range for the most energetic beta-ray of 0.90±0.1 gm/cm² of aluminum. The gamma-ray half-value thickness was 10.8 gm/cm² of lead. Ni^{57} was found to be a positron-emitter with a half-life of 36±2 hours. The most energetic beta-radiation had a range of 0.25±0.05 gm/cm² of aluminum.

The radiations of Ag^{110} have been extensively studied on the beta-ray spectrometer.[4–7] The most recent of these investigations, that of Siegbahn,[7] indicated a complex beta-spectrum with groups at 0.087, 0.530, and 2.79 Mev. Ten gamma-rays were reported, with strong groups at 0.656, 0.885, and 1.389 Mev. A gamma-ray of 0.116 Mev was reported to be fairly highly converted and the most energetic gamma-radiation was given as 1.516 Mev. Cloud-chamber measurements have shown the presence of beta-ray groups of 0.09 and 0.59 Mev.[8]

In^{114} has been shown by Cork and co-workers to have an isomeric state which decays by a highly converted gamma-ray.[9] The gamma-ray energy was determined from the conversion lines in a magnetic spectrometer as 0.192 Mev and the half-life as 48 days. This level then was shown to decay by emission of a beta-ray of 1.98 Mev. The half-life of this transition was 72 sec. Absorption of the gamma-radiation in lead gave an energy of 0.81 Mev.[6]

All range-energy relations used in the following experiments were taken from the curves of Glendenin.[10]

II. NICKEL 65

Sources of radioactive Ni^{65} were prepared by bombarding pure (99.96 percent) nickel targets with slow neutrons from the Indiana University cyclotron. No chemical separation was necessary with these sources. The half-life of all samples was found to be 2.6±0.1 hours.

Absorption measurements of the beta-radiation were

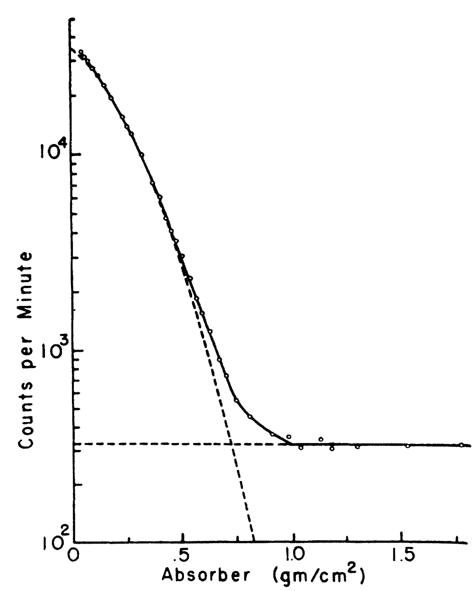

FIG. 1. Beta-ray absorption in Ni^{65}. The dotted curve has the gamma-ray background subtracted.

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[1] J. L. Meem, Jr. and F. Maienschein, Phys. Rev. **76**, 328 (1949).
[2] A. C. G. Mitchell, Rev. Mod. Phys. **20**, 246 (1948).
[3] J. J. Livingood and G. T. Seaborg, Phys. Rev. **53**, 765 (1938).
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[6] Cork, Shreffler, and Fowler, Phys. Rev. **74**, 1657 (1948).
[7] K. Siegbahn, Phys. Rev. **75**, 1278 (1949).
[8] W. S. Emmerich and J. O. Kurbatov, Phys. Rev. **75**, 1446 (1949).
[9] J. Lawson and J. Cork, Phys. Rev. **57**, 983 (1940).
[10] L. E. Glendenin, Nucleonics **2**, 12 (1948).

made with a cylindrical glass counter with relatively thick walls (about 45 mg/cm^2). The geometry used corresponded closely to that of Bleuler and Zünti.[11] Figure 1 shows the counting rate *vs.* g/cm^2 of aluminum absorber. The dotted curve shows the beta-

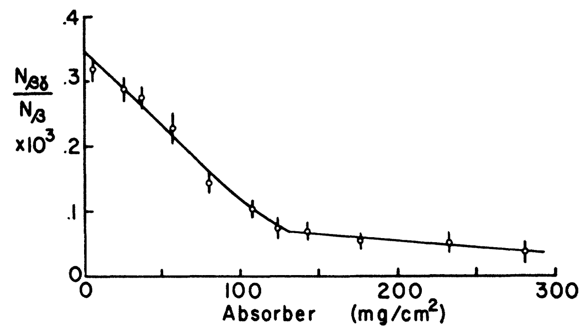

FIG. 2. Beta-gamma coincidence absorption in Ni^{65}.

absorption with the gamma-ray background subtracted. An analysis of this curve by the method of Bleuler and Zünti gives an energy for the most energetic beta-ray of 1.97±0.13 Mev. Although no obvious break occurs in the absorption curve, this analysis requires the presence of another beta-ray of about 0.3 or 0.4 Mev. This lower energy group was seen more clearly by using a thin window counter (5.6 mg/cm^2). However, the energy of this group may be best determined from absorption of beta-gamma-coincidences.

The geometry used for beta-gamma-coincidences consisted of a cylindrical lead cathode counter for counting gamma-rays and a thin window beta-counter. Figure 2 shows the beta-gamma-coincidence rate per recorded beta-ray plotted against the amount of aluminum absorber. This curve clearly shows the presence of a low energy beta-ray with an end point corresponding to 0.44±0.04 Mev. It also follows from Fig. 2 that a more energetic beta-ray is in coincidence with gamma-radiation. This is true since the ratio $N_{\beta\gamma}/N_\beta$ does not drop to zero at the lower beta-end point but continues to fall slowly with increasing absorber thickness. No measurements were made at the end point of this beta-ray group since the number of beta-rays was very small and the errors would be correspondingly large. However, Siegbahn[12] has found a beta-ray group of 1.01 Mev, in addition to the other two groups. This 1.01 Mev group, therefore, is presumably in coincidence with gamma-radiation, while the most energetic beta-ray leads to the ground state.

The gamma-ray spectrum was investigated by coincidence absorption of Compton recoil electrons using the counter arrangement previously described.[1] The Compton radiator used was the wall of the first counter, and the combined window thickness, through which the secondaries had to pass, was 11.2 mg/cm^2. Figure 3, showing the coincidence rate plotted against absorber, indicates a range in aluminum of 0.626±0.03 gm/cm^2. This is equivalent to an electron energy of 1.42±0.07 Mev. The corresponding gamma-ray energy, according to the Compton formula, is 1.64±0.08 Mev. Closer investigation of the low energy region, shown in the insert of Fig. 3, indicates a break in the curve at a gamma-ray energy of about 0.3 Mev. Gamma-gamma-coincidences were obtained, thus confirming the presence of more than one gamma-ray. The coincidence rate was rather small (0.233±0.044)$\times 10^{-3}$, as would be expected if one gamma-ray is of low energy.

The results of these experiments are consistent with the disintegration scheme proposed by Siegbahn. The

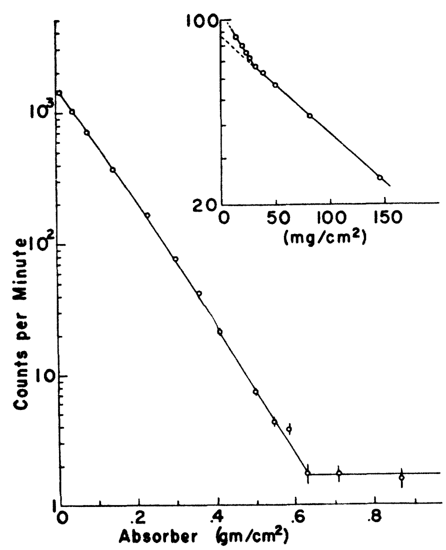

FIG. 3. Coincidence absorption of Compton-recoil electrons in Ni^{65}. The insert is an enlargement of the low-energy region.

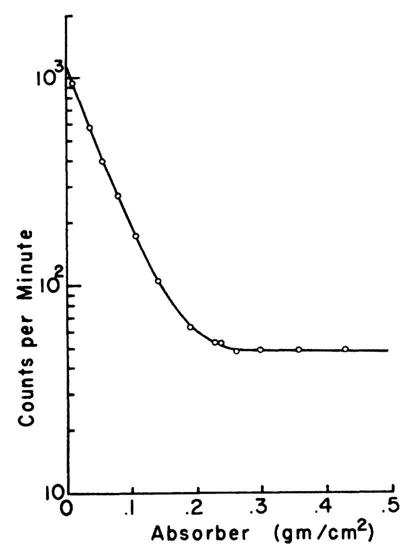

FIG. 4. Absorption of the beta-rays from Ni^{57}.

[11] E. Bleuler and W. Zünti, Helv. Phys. Acta **XIX**, 375 (1946).

[12] K. Siegbahn, private communication.

1.97 Mev beta-ray apparently leads to the ground state. The 0.44 Mev group is followed by both the 1.64 Mev gamma-ray group and two gamma-rays in cascade. One of these is the 0.3 Mev gamma-ray and the other was determined by Siegbahn as 1.12 Mev. This group would not appear on the Compton-recoil curve (Fig. 3) because its energy is so close to that of the most energetic group. The 1.01 Mev beta-group also leads to the 1.12 Mev gamma-ray.

III. NICKEL 57

The source of Ni^{57} used in these experiments was obtained by the (α, n) reaction on iron. Bombardment was by 23 Mev alpha-particles from the Indiana University cyclotron. The nickel activity was separated chemically as the dimethylglyoxime after removal of iron, cobalt, manganese, and copper. A determination of the half-life, which was followed for twelve days, gave a value of 35.7 ± 1 hours.

Absorption of the beta-radiation in aluminum with a 5.6 mg/cm^2 counter is shown in Fig. 4. The energy of the most energetic beta-ray is 0.725 ± 0.03 Mev. No break, corresponding to a lower energy group, is apparent from the absorption curve.

The energy of the gamma-radiation was investigated by absorbing the Compton-recoil electrons in the same geometry as was used for Ni^{65}. The maximum recoil-electron energy was found to be 1.75 ± 0.05 Mev (Fig. 5), which corresponds to a gamma-energy of 1.97 ± 0.06 Mev. There is a break in the absorption curve at an electron energy of 0.315 ± 0.04 Mev. Since this corresponds to a 0.48 ± 0.06 Mev gamma-energy, it is probably due to annihilation radiation.

Definite confirmation of the presence of annihilation radiation was obtained by measuring gamma-gamma-coincidences with counters at right angles and at 180° with respect to the source. Strong angular correlation is to be expected with annihilation radiation since the quanta are emitted in opposite directions. Measurements with a known positron emitter, Cu^{64}, gave coincidences with the counters at 180° but essentially none at 90°. With Ni^{57}, coincidences were observed in both positions, the values of $N_{\gamma\gamma}/N_{\gamma}$ being $(1.37\pm0.05)\times10^{-3}$ at 180° and $(0.59\pm0.03)\times10^{-3}$ at 90°. The much greater ratio at 180° shows that annihilation radiation is present.

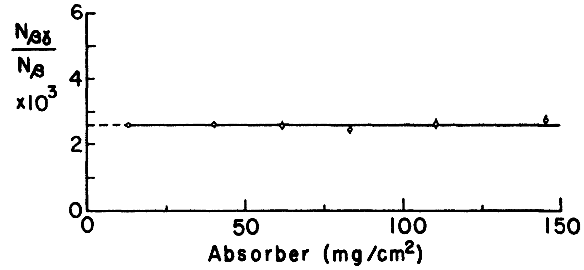

FIG. 6. Beta-gamma coincidences in Ni^{57}.

The presence of coincidences at 90° indicates that at least two nuclear gamma-rays are in cascade. It is true that with only one nuclear gamma-ray, annihilation-gamma-coincidences would be observed. However, from a knowledge of the solid angle and counter efficiencies, it may be shown that this rate would be less than 15 percent of that observed at 180°. Since gamma-gamma-coincidences are present, two gamma-ray groups should appear on the Compton curve. However, if the energy of the second gamma-ray were less than 0.5 Mev, it

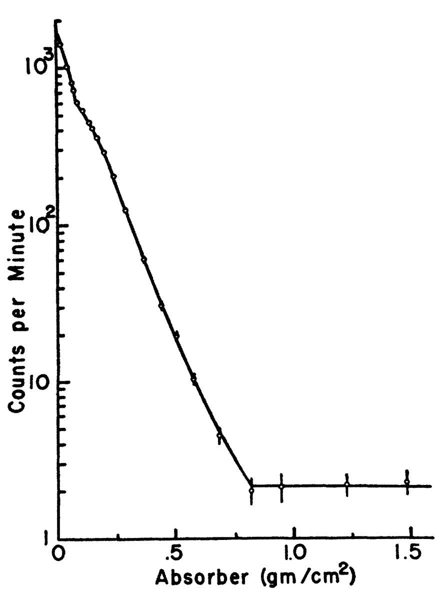

FIG. 5. Coincidence absorption of Compton-recoil electrons from Ni^{57}.

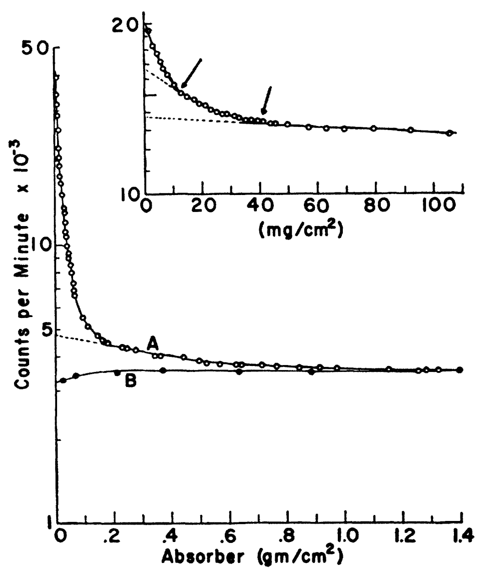

FIG. 7. Beta-ray absorption in Ag^{110}. Curve B shows the gamma-ray background. The insert is an enlargement of the low energy region.

would presumably be masked by the annihilation radiation.

A large beta-gamma-coincidence rate per recorded beta-ray was observed. Figure 6 shows that this ratio is independent of absorber thickness down to about 10 mg/cm^2. Such a straight line beta-gamma-curve indicates again that only one beta-ray is present. An attempt was made to measure coincidences between beta-rays and any possible internal conversion electrons. None were obtained with absorbers down to 20 mg/cm^2, which corresponds to 0.130 Mev.

The experiments on Ni^{57} indicate that the mode of disintegration consists of a 0.725 Mev positron followed by gamma-radiation. At least two gamma-rays are present in cascade. The energy of the most energetic gamma-ray is 1.97 Mev.

IV. SILVER 110

Slow neutron bombardment of silver nitrate by the Oak Ridge Pile was used to produce Ag^{110}. The silver was chemically separated as the chloride by the usual procedure after taking out mercury and lead.

Absorption of the beta-radiation of Ag^{110} in aluminum is shown in Fig. 7. Curve A is a composite curve taken with two different counters, one of which had a very thin window (0.8 mg/cm^2). The end-point at 0.19 gm/cm^2 corresponds to a beta-ray group of 0.57 ± 0.04 Mev. There is a higher energy group apparent with an energy of more than 2 Mev. The points of curve B were taken with a magnet arranged to deflect the beta-rays away from the counter and thus represent the gamma-ray background. It is interesting to note that this gamma-counting rate increases with small absorber thicknesses. This is probably due to the fact that the absorber acts as a radiator for producing secondary electrons and thus increases the counter efficiency for counting gamma-rays.

The low energy region of the beta-absorption curve shows a very steep rise as has been reported by Deutsch.[5] The insert in Fig. 7 which is an expanded curve of the low energy region, shows a break corresponding to a beta-ray group of 0.09 ± 0.02 Mev, as has been reported. In addition, there appears to be another group at 0.19 ± 0.05 Mev. These low energy groups appear to be at least as intense as the 0.57 Mev beta-ray while the very high energy group accounts for less than 5 percent of the total beta-ray transitions.

Figure 8 shows the beta-gamma-coincidence rate per recorded beta-ray that was observed using a 5.6 mg/cm^2 beta-counter and a lead gamma-counter. The end-point obtained corresponds to 0.53 ± 0.04 Mev. Therefore this beta-ray is in coincidence with gamma-radiation while the most energetic beta-ray leads to the ground state. The low energy region was again investigated with the 0.8 mg/cm^2 beta-counter and a lead gamma-counter. A larger ratio for $N_{\beta\gamma}/N_\beta$ was obtained below 10 mg/cm^2 showing that the 0.09 Mev beta-ray group is in coincidence with gamma-radiation. The gamma-gamma background was so large for the geometry used, however, that no end-point could be determined.

The energy of the most energetic gamma-ray was determined by absorption of Compton-recoil electrons in aluminum (Fig. 9). This maximum energy was found

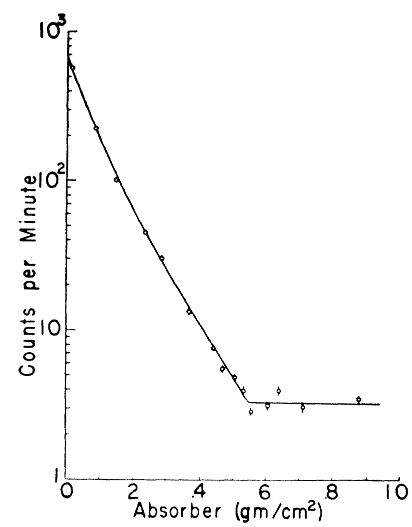

FIG. 9. Coincidence absorption of Compton-recoil electrons from Ag^{110}.

to be 1.48 ± 0.1 Mev, in agreement with the results obtained by Siegbahn.[7] A very large, $(2.13\pm0.03)\times10^{-3}$, gamma-gamma-coincidence rate was obtained as would be expected from the large number of gamma-rays present. Coincidences were obtained between internal conversion electrons and beta-rays. The ratio of these coincidences to the number of recorded particles was $(0.058\pm0.027)\times10^{-3}$ at 50 mg/cm^2. The large errors, which were caused by the large beta-gamma and gamma-gamma backgrounds, made it impractical to obtain an absorption curve.

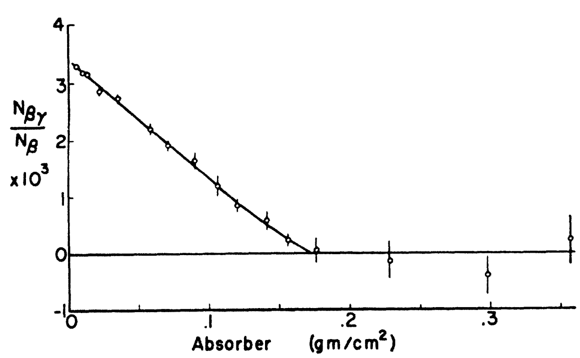

FIG. 8. Beta-gamma coincidence absorption in Ag^{110}.

V. INDIUM 114

One source of In^{114} was prepared by deuteron bombardment of cadmium on the cyclotron. Another was made by exposing indium metal to slow neutrons from the Oak Ridge pile. Both sources were separated chemically.

Absorption of the beta-radiation is shown in Fig. 10. An analysis of the high energy beta-ray group by the method of Bleuler and Zünti gave an energy of 2.05 ± 0.10 Mev. A sharp rise, due to the conversion electrons from a low energy gamma-ray, appears in the low energy region. Closer investigation of this region with an 0.8 mg/cm^2 counter gave the results shown in the insert. The electron end point corresponds to a gamma-ray energy of 0.196 ± 0.01 Mev. The total conversion coefficient for this gamma-ray, assuming that it leads to the 2.05 Mev beta-ray, is found from the absorption curve to be 90 ± 5 percent. An absorption curve in lead of the gamma-radiation gives an energy of about 0.78 Mev, in agreement with Cork.[6] Also, a less

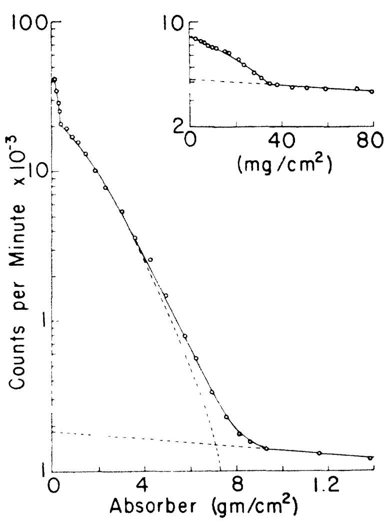

FIG. 10. Beta-ray absorption in In^{114}. The insert shows the low energy region.

energetic gamma-group of about 0.20 Mev is present. This value agrees closely with that found from the conversion electron absorption discussed above. Coincidence absorption of Compton-recoil electrons (Fig. 11) gives a maximum gamma-energy of 1.3 ± 0.1 Mev with an indication of two other groups at about 0.5 and 0.7 Mev. Compton-electrons from the 0.2 Mev gamma-ray are stopped by the combined counter windows. The groups at 0.5 and 0.7 Mev appear to be of equal intensity while the most energetic group accounts for about 10 percent of the gamma-ray transitions.

In order to determine whether the more energetic gamma-radiation might be due to an impurity, two half-life measurements were made. One had just enough absorber to cut out all of the beta-rays and therefore include all the gamma-radiation. The other source was covered with 0.65 cm of lead, enough to reduce the intensity of the 0.2 Mev gamma-ray to less than 1/2000 of its original value. The same period, 49 ± 3 days, was obtained from both curves.

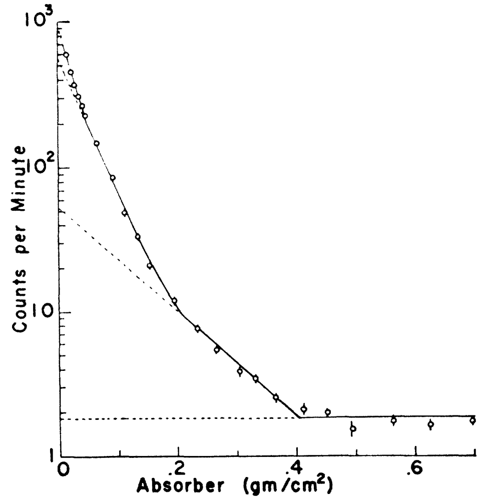

FIG. 11. Coincidence absorption of Compton-recoil electrons from In^{114}.

Very few beta-gamma-coincidences were obtained, the value of $N_{\beta\gamma}/N_\beta$ being $(0.015\pm0.005)\times10^{-3}$. Since this ratio was independent of absorber thickness, there are no less energetic beta-groups present. The smallness of the ratio excludes the possibility that the 2.05 Mev beta-ray is in coincidence with any of the above gamma-rays. In fact, it is possible that such a small coincidence rate could be due to scattered particles. The value of $N_{\gamma\gamma}/N_\gamma$ on the other hand, was much larger $(0.66\pm0.01)\times10^{-3}$. This measurement was made with enough lead in front of one counter to absorb the 0.2 Mev gamma-ray group. If the 0.5 and 0.7 Mev gamma-rays are assumed to be in cascade, the gamma-gamma-coincidence rate may be predicted from a knowledge of the counter efficiencies. This value $(0.8\pm0.1)\times10^{-3}$, is in fair agreement with that obtained experimentally. No coincidences were obtained between internal conversion electrons and beta-particles.

It appears from these experiments that there is another method of disintegration in In^{114} than the well established 0.2 Mev gamma-ray followed by a 2.0 Mev beta-ray. It is possible that this other transition goes by K-capture to two gamma-rays in cascade. The cross-over gamma-ray accounts for about 10 percent of these disintegrations. An approximate idea of the branching ratio of the two transitions above was obtained by counting both the beta-rays and gamma-rays from one source. The beta-ray singles divided by the solid angle gives essentially the disintegration rate. Then with the disintegration rate and the known efficiency and solid angle of the gamma-counter, the branching ratio was calculated as about 5 percent.

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