Continuous Gamma-Radiation Accompanying Internal Conversion in Ba^{137m}

HARRY B. BROWN AND ROBERT STUMP
Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas
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A weak continuous gamma-radiation accompanying internal conversion has been observed from the decay of the isomeric state of Ba^{137}. The probability of this emission is $(1.17\pm0.27)\times10^{-3}$ photons in the energy range 50 to 100 kev per conversion electron, and $(3.4\pm0.8)\times10^{-3}$ photons in the energy range 50 to 200 kev per conversion electron. The angular distribution of the continuous radiation in the energy range 50 to 200 kev has been measured at angles from 90° to 160° with the electron direction. There appears to be no deviation from isotropy.

I. INTRODUCTION

WHEN a nucleus decays by the emission of a high energy electron, it is to be expected that there will also be a weak continuum of γ-rays. This continuum is explained classically as the radiation arising from the large acceleration of the electron as it receives energy from the nucleus. Wang Chang and Falkoff[1] have shown that the radiation accompanying β-decay calculated by a second-order perturbation calculation does not differ markedly from the semiclassical result. Experimental measurements of both the radiation probability and the angular distribution of the γ-radiation accompanying β-decay are in good agreement with the theory.[2,3]

The continuous γ-radiation accompanying internal conversion is, on the basis of the semiclassical theory, identical with that accompanying β-decay. It is of some importance to determine how closely the effect agrees with the theory, if for no other reason than that it is necessary to take the continuous radiation into account when measuring internal conversion coefficients. This experiment was performed to determine the amount of continuous radiation, as well as its angular distribution, in the case of the conversion electrons from the isomeric state of Ba^{137}.

II. EXPERIMENTAL DETAILS

Cs^{137}, obtained from Oak Ridge National Laboratory, was used as a source of conversion electrons. The most probable contamination of this source is Cs^{134}.[4] The decay schemes of these isotopes are shown in Fig. 1.[5]

The transition from the isomeric state of Ba^{137} is about 10 percent internally converted. Thus the source produces a very considerable background of γ-rays, x-rays, and continuous γ-rays accompanying the β-decay. In the presence of this background, the continuous radiation accompanying the internal conversion was identified by means of a coincidence experiment. The conversion electrons are in coincidence only with x-rays and with the continuous radiation.

Scintillation counters with RCA 5819 photomultiplier tubes were used to detect both γ-rays and electrons. The crystal for the electron counter was of anthracene, $\frac{1}{16}$-in. thick, $\frac{1}{2}$-in. in diameter. The γ-ray counter used a $\frac{1}{8}$-in. thick, 1-in. diameter thallium activated sodium iodide crystal. The sodium iodide crystal was shielded from electrons by a $\frac{3}{16}$-in. Lucite cover.

The pulses from the counters were amplified and sorted by means of single-channel pulse-height selectors. Those pulses which were accepted by the pulse-height selectors went to a coincidence circuit. The number of counts from each pulse-height selector and from the coincidence circuit were recorded.

III. RESULTS

In a preliminary experiment to establish the existence of continuous radiation accompanying internal conversion, the two counters were placed about $\frac{1}{4}$ in. apart with the source on a Nylon film between them. The β-counter was set to count only electrons of energy greater than 530 kev and the γ-counter to count only quanta of energy above 50 kev. The range of energy of the continuous radiation which could be observed was then roughly from 50 to 100 kev. The lower limit was set by the γ-counter, the upper by the fact that the β-counter would not observe electrons which had lost more than 100 kev to the continuous radiation.

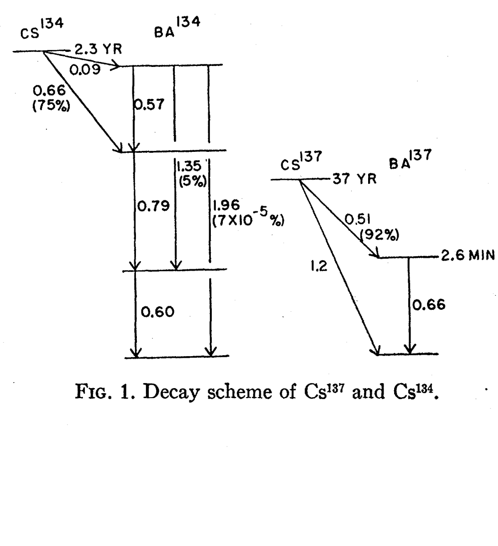

FIG. 1. Decay scheme of Cs^{137} and Cs^{134}.

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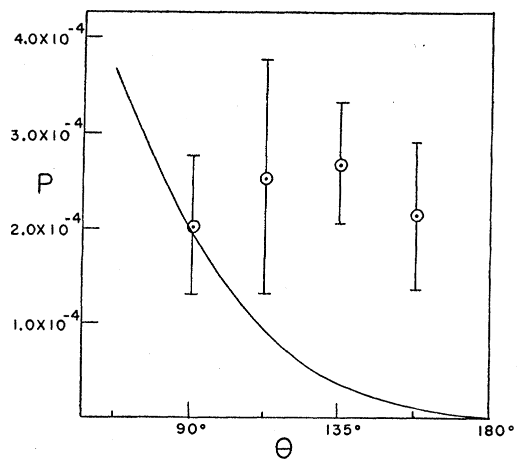

FIG. 2. Angular correlation between direction of conversion electron from Ba^{137m} and of the photon of the continuous radiation. Circled points represent experimental measurements; the solid curve is the value predicted on the basis of semiclassical theory. P: Probability of emission of a photon of the continuous radiation with energy between 50 and 200 kev into a unit solid angle. θ: Angle between the electron and photon directions.

Assuming no angular correlation between the direction of the electron and of the γ-ray, the rate of continuous radiation was found to be $(1.17\pm0.27)\times10^{-3}$ quanta in the energy range 50 to 100 kev per conversion electron. This is in fair agreement with the corresponding theoretical value from the semiclassical formula of Wang Chang and Falkoff of 2.04×10^{-3} quanta per electron.

An additional measurement of the radiation probability was made using 1 in. of lead between the two counters. With this arrangement, it was possible to lower the energy detected in the β-counter without adding spurious coincidences caused by scattering between the crystals. The angle between the two counters and the source was 135°. The β-counter was set to detect particles of energy greater than about 430 kev, and the γ-ray counter to detect those of energy greater than 50 kev. Thus continuous radiation in the range 50 to 200 kev could be detected, together with the coincident electron.

Assuming the radiation to be isotropic, the rate of radiation was found to be $(3.4\pm0.8)\times10^{-3}$ quanta in the energy range 50 to 200 kev per conversion electron. The corresponding theoretical value from the semiclassical formula is 3.24×10^{-3} quanta per electron.

The angular correlation between the direction of the electron and of the continuous radiation in the range 50 to 200 kev was measured for angles from 90° to 160°, using the energy discrimination described above and with 1-inch lead absorber between the counters. The results are shown in Fig. 2. Within the accuracy of the measurement, there is no deviation from isotropy. This is in marked disagreement with the results of the semiclassical theory. The calculated results are shown as a full curve in the figure.

IV. SOURCES OF ERROR

In addition to the coincidences between the conversion electrons and the continuous γ-radiation, there were several other sources of coincidences which could interfere with the experiment.

(1) Electron x-ray coincidences. About 75 percent of the K conversion electrons are in coincidence with x-rays of barium. Since the energy of the K x-ray of barium is about 32 kev, setting the γ-detector to count only those pulses which correspond to γ-ray energies above 50 kev effectively eliminates this source of coincidences.

(2) $\beta-\gamma$ or $\gamma-\gamma$-coincidences from source contamination. If $\beta-\gamma$-coincidences were observed due to source contamination by Cs^{134}, the coincidence rate should vary with setting of the β-counter pulse-height selector, according to the number of β-particles counted at each setting. With the β-detector set to count particles of energy 430 to 570 kev and the γ-ray counter to count only quanta of energy above 50 kev, a coincidence rate above chance of 0.077 ± 0.032 was observed. With the γ-ray detector unchanged, and the β-detector set to count particles in the range 140 to 280 kev, the coincidence rate was 0.00 ± 0.057. This is in contradiction with the fact that the number of β-particles from the 660-kev transition of Cs^{134} is about three times as great in the lower energy range as in the higher. No appreciable number of coincidences is attributable to $\beta-\gamma$-source contamination. Likewise, the possibility of $\gamma-\gamma$-coincidences is ruled out by the fact that the γ-ray efficiency of the β-detector increases at lower energy settings, whereas the coincidence rate decreases.

(3) Scattering between the crystals. If a γ-ray makes a Compton collision in the β-detector, and the γ-ray is counted by the γ-detector, a coincidence would be observed. In the preliminary experiment, this source of coincidences was eliminated by setting the β-detector to count only particles of energy above 500 kev. Since the maximum energy given an electron in a Compton collision by a 661-kev γ-ray is 475 kev, no spurious coincidences should occur. In all later experiments, this source of coincidences was eliminated by placing at least 1 in. of lead between the counters.

(4) β-continuous γ-ray coincidences. The high energy β-transition of Cs^{137} contributes a weak source of continuous γ-radiation in coincidence with the high energy β-particles. Calculations of the coincidence rate were made and all coincidence counts were corrected for this effect. Coincidences due to the low energy β of Cs^{137} and its continuous γ-radiation were not observed, because of energy considerations.

As a further check on the energy of the γ-rays which contributed to the coincidences, aluminum and lead γ-ray coincidence absorption measurements were made. The results were in agreement with the assignment of coincidences to γ-rays of energy between 50 kev and 200 kev.

V. CONCLUSIONS

There appears to be little doubt that internal conversion electrons are accompanied by a weak continuous γ-radiation. The probability of this effect is of the same order of magnitude as given by the semiclassical theory. The angular distribution of the radiation seems to be quite different from that predicted. However, there is some reason to expect that the quantum-mechanical calculation might give results in poorer agreement with the semiclassical calculation in the case of internal conversion than in the case of β-decay, where the agreement is very good. This arises from the consideration of the nature of the calculation. In the case of β-decay the second-order calculation involves a single intermediate state, i.e., the first step of the transition is the emission of an electron from the nucleus, and the second step is then the emission of a photon of the continuous radiation. On the other hand, there are two possible intermediate states involved in the calculation for internal conversion: the first step may be the emission of either an electron or of a photon; the second step then supplies, respectively, a photon or an electron.

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The Photodisintegration Cross Section of Beryllium at 2.185 Mev

BERNARD HAMERMESH AND CLYDE KIMBALL
Argonne National Laboratory, Lemont, Illinois
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The cross section for the photodisintegration of Be^9 at 2.185 Mev has been measured using gamma-rays which follow the beta-decay of Pr^{144}. A value of 3.9×10^{-28} cm² was found, in reasonably good agreement with the valence neutron model. This value is lower than the values at 1.81 Mev and 2.50 Mev, in agreement with the theoretical prediction that a minimum value of the cross section should be found near 2.2 Mev.

THE cross section for the photodisintegration of Be^9 has been measured at several energies.[1,2] The cross section increases from zero at the threshold (1.66 Mev) to a value of 10×10^{-28} cm² at 1.70 Mev (Sb^{124}). At 1.81 Mev (Mn^{56}) it has decreased to 6×10^{-28} cm². At 2.50 Mev (La^{140}) its value is 5×10^{-28} cm², while at 2.76 Mev (Na^{24}) it has increased one again to 7×10^{-28} cm². These results are shown in Fig. 1. It is clear that there is a minimum value of the cross section in the region between 1.81 and 2.50 Mev. The first maximum in the cross section can be ascribed to S neutrons whereas the second increase in the cross section is caused by the emission of higher angular momentum (D) neutrons. Measurements of the angular distribution of the neutrons[3] indicate that the distribution is spherically symmetric near the first peak and is of the form $a+b\sin^2\theta$ near the region of the second increase in cross section.

Guth and Mullin[4] have calculated the cross section and angular distribution as a function of gamma-ray energy using a valence neutron model. The Be^9 nucleus is pictured as consisting of a neutron moving in the field of a Be^8 core. Although Be^8 is unstable against decay into two alpha-particles by about 120 kev, the lifetime is very long compared to the time required to emit a neutron from Be^9. The cross section is calculated for $P\rightarrow S$ and $P\rightarrow D$ transitions. The former is the major contributor to the cross section near threshold whereas the latter interaction is more important at higher energies, i.e., near the second maximum. Guth's curve is shown in Fig. 1.

The cross-section data and angular distributions agree with the theoretical predictions made with the valence neutron model. However, no data have been available to check the theory in the region of the minimum. There is a scarcity of gamma-ray emitters with useful half-lives having energies near 2.2 Mev. When the presence of a line near this energy[5] was reported in the fission product chain $Ce^{144}-Pr^{144}$, a study of the $Be(\gamma,n)$ cross section was undertaken using these isotopes.

METHOD

Approximately one curie of 282-day[6] Ce^{144} was obatined from Oak Ridge as a sulfate in solution; it was treated with 6M NH_4OH and precipitated as $Ce(OH)_4$. The precipitate was ignited to CeO_2, which was canned in a 0.030-inch-wall stainless steel cylinder, one centimeter in diameter and one centimeter in height. The capsule was placed in a cavity in a beryllium sphere. The sphere had an outer diameter of 1.5 inches and was made in two sections and was assembled by screwing

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