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Decay of Ionium (Th^{230})

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Gamma-ray coincidence studies of the decay of ionium yield the total conversion coefficient of the 68-kev gamma ray as $\alpha=46\pm5$, and a value of $f=0.52\pm0.05$ for the fluorescent yield from the L shell of Ra^{226}. The mean lifetime of the 68-kev state of Ra^{226} was found to be $T_{1/e}\leq10^{-9}$ second.

INTRODUCTION

MEASUREMENTS of the energies and intensities of the gamma rays following the decay of ionium have been made by Curie[1] using selective absorbers, and by Rasetti and Booth,[2] Bouissieres *et al.*,[3] and Stephens *et al.*,[4] using scintillation spectrometers. Rasetti and Booth[2] performed coincidence experiments which showed that the 142-kev gamma ray is emitted in a transition from the 210-kev state to the 68-kev first excited state of Ra^{226}. Angular correlation measurements by Temmer and Wyckoff,[5] Valladas *et al.*,[6] and Falk-Vairant and Petit[7] showed that the spins and parities of the 68-kev, 210-kev, and 255-kev states are 2^+, 4^+, and 1^-, respectively.

In experiments described below, the gamma-ray intensities were measured using higher resolution than was previously available. The conversion coefficient of the 68-kev gamma ray was measured, the fluorescent yield from the L shell of Ra^{226} was measured, and an upper limit for the lifetime of the 68-kev state was established.

PROCEDURE AND RESULTS

The gamma-ray spectrum of ionium was measured using a scintillation spectrometer with a NaI(Tl) crystal one inch thick. The ionium source was supplied by the Argonne National Laboratory and contained 90 percent ionium and 10 percent Th^{232}. Radium was removed from the source by means of a barium precipitation. The gamma-ray spectrum is shown in Fig. 1. The gamma-ray energies and intensities are shown in Table I. The gamma-ray intensities have been corrected for absorption, solid angle, K-radiation escape, crystal efficiency, and the ratio of the number of pulses in the photoelectric peak to the total number of pulses.[8] The intensities of the 195-kev and 255-kev gamma rays relative to the 68-kev gamma ray are somewhat greater than those found by Stephens *et al.*[4]

Coincidences were observed among gamma rays and x-rays detected by two NaI(Tl) crystals. The coincidence spectrum obtained by fixing one channel on the 14-kev photopeak and sweeping the other channel over the gamma-ray spectrum is shown in Fig. 1. The coincidence peak at 142 kev is normalized to the same area as the single-channel peak. Figure 1 shows that the number of coincidences per 142-kev gamma ray is much greater than the number per 255-kev gamma ray. More detailed coincidence measurements showed that the number of coincidences per 195-kev gamma ray was the same, to within a factor of two, as the number of coincidences per 142-kev gamma ray.

The fluorescent yield of the L shell is defined as the number of L x-rays emitted per excitation of the L shell. The fluorescent yield, f, was obtained from the measurement of coincidences between the 142-kev gamma ray and the 14-kev L x-ray. The coincidence rate is given by

$$N_c=N_{142}f\Omega_{14}\alpha_L/(1+\alpha),$$

where N_{142} is the number of 142-kev gamma rays detected per second, Ω_{14} is the probability of detecting an L x-ray, and α_L and α are conversion coefficients for the 68-kev gamma ray. Falk-Vairant[9] gives $\alpha_L/(1+\alpha)=0.73\pm0.04$. The result of the measurement was $f=0.52\pm0.05$.

The total conversion coefficient for the 68-kev gamma ray was obtained by measuring the coincidences between the 142-kev gamma ray and the 68-kev gamma ray. The coincidence rate is given by

$$N_c=N_{142}\Omega_{68}/(1+\alpha),$$

where Ω_{68} is the probability of detecting a 68-kev gamma ray. Coincidence measurements were made using different thicknesses of tantalum absorber for the 68-kev gamma ray. These measurements showed that about 5% of the coincidences were caused by crystal-to-crystal scattering of the high-energy gamma rays. The result of the coincidence measurement was $\alpha=45\pm5$.

The lifetime of the 68-kev excited state was measured by observing the coincidences between pulses from the 68-kev gamma rays or the 14-kev L x-rays and delayed pulses from the alpha particles. The coincidence circuit used was the type[10] which combines energy selection

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TABLE I. Energies and intensities of the gamma rays and x-rays of ionium.

Energy in kev	Number per disintegration
14 (L x-ray)	0.11 ± 0.015
68 ± 1	$(6.4\pm0.8)\times10^{-3}$
88 (K x-ray)	$(4.2\pm1.3)\times10^{-4}$
142 ± 2	$(8.0\pm1.3)\times10^{-4}$
195 ± 5	$(5\pm2)\times10^{-5}$
255 ± 3	$(3\pm1)\times10^{-5}$

with a resolving time of 10^{-9} second or less. The alpha particle was detected in a plastic scintillator, the 68-kev gamma ray in a NaI(Tl) crystal, and the 14-kev L x-ray in a plastic scintillator. The L x-ray is emitted about 10^{-15} second after the internal conversion of the 68-kev gamma ray. The effect of photoelectron statistics on the slope of the delayed coincidence curve has been discussed by Post and Schiff.[11] In order to estimate the increase in the apparent lifetime due to photoelectron statistics, prompt coincidence curves were taken using the annihilation radiation of Na^{22}. The pulse heights were made equal to those from the ionium by means of light absorbers. The delayed coincidence rates were taken for the ionium and the Na^{22} without changing any settings of the pulse-height analyzers, with the result that the mean lifetime of the 68-kev state is $T_{1/e}\leq10^{-9}$ second.

DISCUSSION OF RESULTS

The coincidence spectrum in Fig. 1 shows that the 255-kev gamma ray is not in coincidence with the 142-kev or 68-kev gamma rays, so it is assumed to be a transition to the ground state. The 195-kev gamma ray is in coincidence with the 68-kev gamma ray, and is evidently the 187-kev gamma ray[4] emitted in a transition from the 255-kev to the 68-kev state. The decay scheme of Ra^{226} is shown in Fig. 1. The 68-kev and 210-kev states are described by the Bohr-Mottelson model[12] of the nucleus, but the higher energy states can only be explained by a refinement of the simple Bohr-Mottelson model. The spin and parity of the 255-kev state have been established as 1^- by Falk-Vairant *et al.*,[7] in agreement with the predictions

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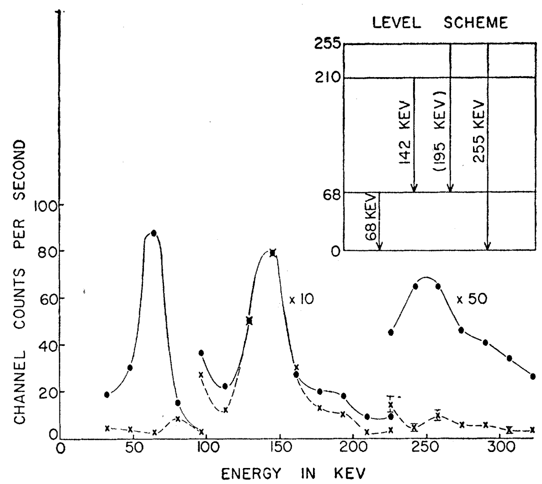

FIG. 1. Gamma-ray spectrum of ionium taken with scintillation spectrometer. Broken line shows coincidences between the 14-kev L x-ray and the gamma rays. The inset shows the level scheme of Ra^{226}.

based on the spins of similar states in U^{230}, Th^{228}, and Th^{226} as measured by Stephens, Asaro, and Perlman.[13]

An independent measurement of the L conversion coefficient of the 68-kev gamma ray is obtained from the ratio of the intensity of the L x-ray to the intensity of the 68-kev gamma ray. The conversion coefficient is given by $\alpha_L=(N_L/N_{68})(1/f)$. The result is $\alpha_L=35.6\pm4.6$ and $\alpha=48\pm7$. The average value of α is 46 ± 5, in agreement with the theoretical value[14] for electric quadrupole radiation.

The fluorescent yield, $f=0.52\pm0.05$, is in agreement with the theoretical value, $f=0.5\pm0.1$, calculated by Kinsey.[15]

The Bohr-Mottelson theory relates the energy, spin, and radiative lifetime of an excited state to its intrinsic nuclear quadrupole moment. The lifetime of the 68-kev state of Ra^{226} is multiplied by $1+\alpha$ to give a radiative lifetime of $T\leq4.7\times10^{-8}$ second, corresponding to an intrinsic quadrupole moment of $Q_0\geq7.7\times10^{-24}$ cm^2.

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