where e and M are the charge and mass of the scatterer, k_0 and k are the initial and final quantum energies, and θ is the scattering angle. The first term is the Klein-Nishina formula, and the remaining terms arise from the "Pauli part" of the magnetic moment. The total cross section is

$$\sigma=\pi(e^2/Mc^2)^2\left[\left\{-\frac{(2+2\gamma-\gamma^2)}{\gamma^3}\ln(1+2\gamma)+\frac{4}{\gamma^2}+\frac{2(1+\gamma)}{(1+2\gamma)^2}\right\}+\lambda\left\{\frac{2}{\gamma}\ln(1+2\gamma)-\frac{4(1+3\gamma)}{(1+2\gamma)^2}\right\}\right.$$
$$+\lambda^2\left\{\frac{1}{2\gamma}\ln(1+2\gamma)-\frac{(1+3\gamma-8\gamma^2)}{(1+2\gamma)^2}\right\}+\lambda^3\left\{-\frac{1}{\gamma}\ln(1+2\gamma)+\frac{2(1+3\gamma+4\gamma^2)}{(1+2\gamma)^2}\right\}$$
$$\left.+\lambda^4\left\{-\frac{1}{4\gamma}\ln(1+2\gamma)+\frac{(1+3\gamma+4\gamma^2+2\gamma^3)}{2(1+2\gamma)^2}\right\}\right],\quad(\gamma=k_0/Mc^2).$$

In the extreme relativistic limit, the term in λ^4 is dominant:

$$\sigma\approx\pi(e^2/Mc^2)^2(\gamma/4).$$

It is this term which leads, by the method of Weizsäcker and Williams, to formula (2) above.

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Radiations of Uranium Y*

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The radioactivity of UY (Th_{231}) has been re-investigated. Samples were prepared by growth from U_{235} largely freed of U_{238}, and absorption, decay, and coincidence experiments were run. The presence of the 210-kev beta-ray was re-confirmed, and a 35-kev gamma-ray 82 percent converted in the L shell was discovered. The half-life of UY was determined as 25.5 hours.

INTRODUCTION

URANIUM Y is the second member of the naturally occurring actinum series of radioactive isotopes. It rapidly approaches equilibrium with the parent U_{235}, having a half-life of about one day, and is isotopic with thorium, ionium, and UX_1. Since UX_1 is formed at a considerably greater rate from the U_{238} in natural uranium, it is not possible to prepare UY in radioactively pure form from this source. Thus, despite its discovery by Antonoff[1] in 1911, relatively little work has been reported on its radioactive properties.

The International Radium Standards Commission[2] reported in 1931 a half-life of 24.6 hours and a beta-ray absorption coefficient of about 300 cm^{-1} in aluminum. This absorption coefficient, reported by Kirsch,[3] corresponds to an energy of 200 kev on the basis of recent range-energy-absorption curves of Libby.[4] Gratias and Collie[5] redetermined the half-life in 1932, arriving at a value of 24.0 hours after discounting a 25.4-hour determination obtained by an electroscope method. These authors give references to several earlier investigations of the half-life. In 1937 Erchova[6] reported extensive absorption measurements on UY. She found two components of the radiation with absorption coefficients of 19.6 and 216 cm^2 per gm. These were both considered as beta-radiation and correspond[4] to beta-ray energies of 160 kev and 0.6 Mev. (The more penetrating component, if considered as electromagnetic radiation, would have an energy of about 11 kev.)

In 1945 at the Metallurgical Laboratories in

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[1] G. N. Antonoff, Phil. Mag. **22**, 419 (1911), and **26**, 1058 (1913).

[2] Int. Rad. Stds. Comm., Rev. Mod. Phys. **3**, 427 (1931).

[3] G. Kirsch, Wien Ber. IIa **129**, 309 (1920).

[4] W. F. Libby, Anal. Chem. **19**, 2 (1947).

[5] O. Gratias and C. H. Collie, Proc. Roy. Soc. **A135**, 299 (1932).

[6] Z. V. Erchova, J. de phys. et rad. **8**, 501 (1937).

Chicago[7] a few samples of UY were examined under the direction of Ghiorso and Jaffey. These samples were derived from nearly pure U_{235} but, unfortunately, were contaminated with Pa_{233}. Several components of the radiation based on absorption measurements were reported. The 0.2-Mev beta-ray was observed together with a weaker component reported as a 50–60-kev beta-ray. The 1.45-mg/cm² half-thickness for absorption of the latter is, however, quite close to the value for the 3-kev M-shell x-rays. The Chicago group proposed two decay schemes. One involved a branched beta-decay with 67 percent of the UY atoms emitting a 60-kev beta-ray and a 140-kev gamma-ray in cascade. This was rejected because no such gamma-ray could be detected in sufficient intensity. The other decay scheme called for two consecutive highly converted low energy gamma-rays following the 0.2-Mev beta-ray. The observed intensity ratio of 2 of the weak components

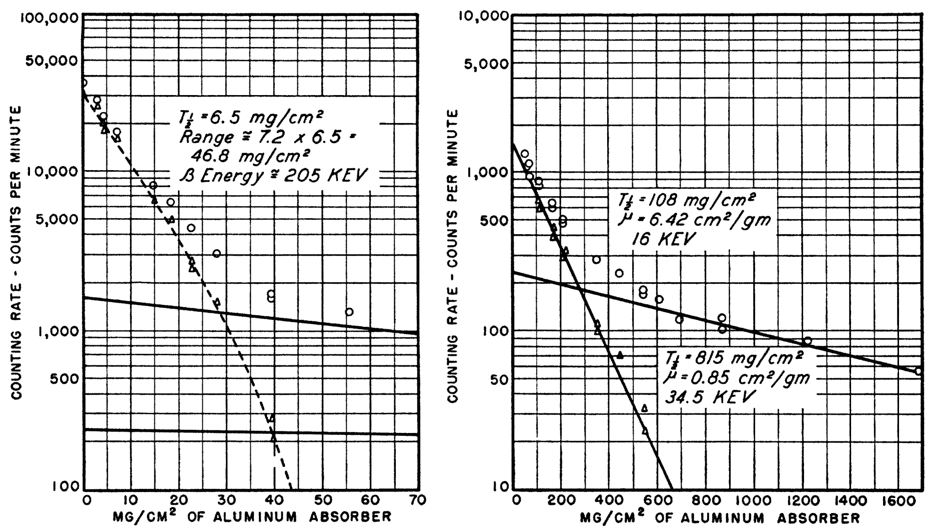

FIG. 1. Uranium Y absorption data, sample 1.

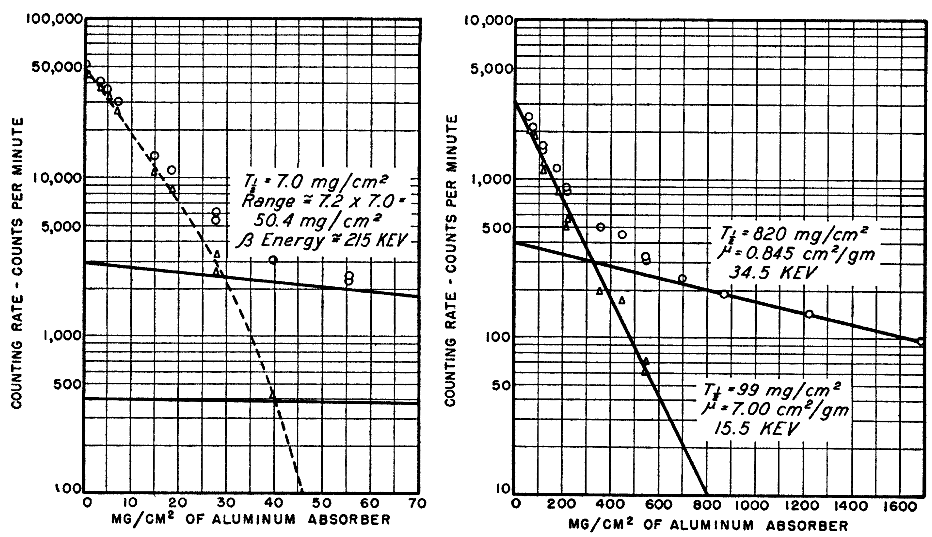

FIG. 2. Uranium Y absorption data, sample 2.

[7] Chicago University Metallurgical Laboratory Progress Report for May, 1945, CN 3001.

TABLE I. Uranium Y half-life data.

Half-life of UY (hours)	Weight
25.664	148.1
25.391	283.7
25.822	94.2
25.118	49.4
25.128	2.5

and the 0.2-Mev beta-ray required the proposal of two weak gammas in cascade. This mechanism was considered improbable.

SAMPLE PREPARATION

As starting material it was possible to use U_{235} largely freed of U_{238} and exceptionally free of all other radioactive elements. The residual U_{238} evolves UX_1, another thorium isotope with a 24-day half-period. For this reason a growth period of from one to three days was used in order to effect an even larger increase in the $UY/(UX_1+UX_2)$ disintegration rate ratio over the equilibrium ratio. Values above 200 for this ratio were obtained with some samples. This compares with the normal equilibrium value of 0.023 and the maximum value 0.56 attainable with natural uranium.

The UY samples were isolated from the parent U_{235} at the end of each growth period with 5 mg of LaF_3 as a carrier precipitate. The precipitations were carried out in 50-ml centrifuge tubes lined with hard wax. The precipitate was carefully washed and deposited in a thin uniform film on a one-inch disk of Whatman No. 2 filter paper. The sample was then mounted for counting. For coincidence experiments a few hundredths of a milligram of LaF_3 precipitate with adsorbed UY were deposited directly on a thin (1 mg/cm^2) aluminum foil.

MEASUREMENTS

In connection with another program, samples of UY were found to exhibit a more penetrating radiation than the 0.2-Mev beta-ray. Upon investigation of the absorption coefficient the *L* x-ray seemed to be indicated along with a suggestion of a gamma-ray estimated at 25 kev. Through the cooperation of Clinton Laboratories more complete absorption curves (Figs. 1 and 2) were obtained with thin mica window-type Geiger counters. Analyses of the components of these curves show a 35-kev gamma-ray, 16-kev *L*-shell x-rays, and a 210-kev beta-ray. The energy of the beta-ray was calculated from the formulae given by Libby.[4] While these semi-logarithmic plots show appropriate convexity, it was not possible to estimate the maximum range accurately or to run Feather analyses. The counter efficiencies for such low energy gamma and x-rays are not well known. The probable values of the counting efficiencies for the rays found will be discussed later in connection with the proposed decay scheme.

An attempt to check the half-life on one

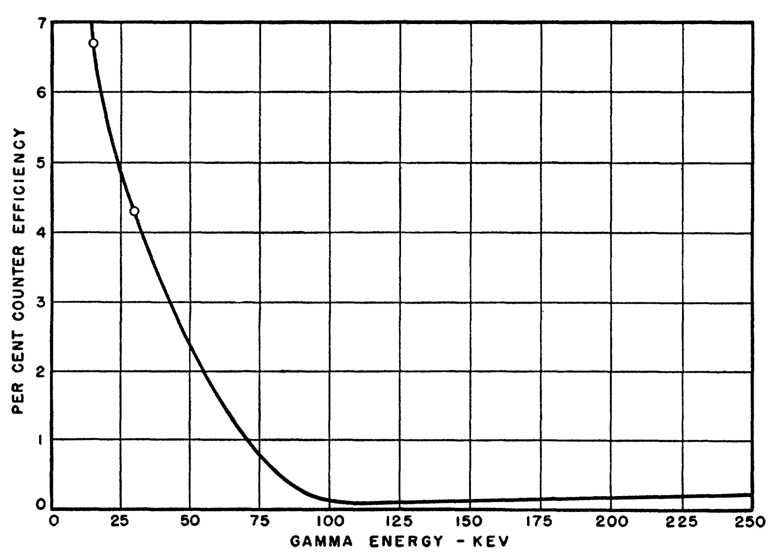

FIG. 3. Approximate counter efficiencies for gamma-rays.

sample gave a value of 25.4 hours. As this was higher than the values reported in the literature, a series of five samples was prepared and their activities followed with two thin wall Geiger counters. Samples of natural uranium were counted daily as operating standards. The data were resolved into three components: a constant activity caused by cosmic rays, counter contamination and U_{235} traces in the sample, a UX_1 and UX_2 activity assumed to decrease with a 24.6-day half-life, and the UY activity. Each of these components was evaluated from the appropriate data by the method of least squares. The activity measurements after 14 days decay were used to evaluate the constant and the UX_1+UX_2 activities. From these the background rates during the first ten days were predicted together with their uncertainties. The net rates during the first ten days of decay were then used to calculate the UY half-life and initial activity. Each rate was weighted in the calculation as the reciprocal of the quantity counting variance plus coincidence correction variance plus background variance. The half-lives obtained from each sample (each an average of the values on the two counters) are given in Table I together with their relative weights as calculated from the fit of the data about the least squares exponential decay curves.

The weighted average half-life is 25.51 hours. The samples were shown to differ among themselves more than expected from the fit of the data to the least squares curves, and hence the confidence belt is calculated from the scatter of half-lives determined from each sample. The limit of error at the 95 percent confidence level arrived at in this manner is 0.93 hour. The corresponding probable error is 0.23 hour.

Through the cooperation of Mr. Francis McGowan of Clinton Laboratories it was possible to run coincidence measurements on one of the samples. The beta-gamma-coincidences were not sufficiently delayed, however, to permit their being counted with the delay circuits available (~ 1 μ-sec.). The apparent immediate coincidence rate includes a back-scattering effect of not well-known magnitude. Thus the data warrant only the conclusion that the half-life of Pa^*_{231} toward emission of the 35-kev gamma is less than one microsecond.

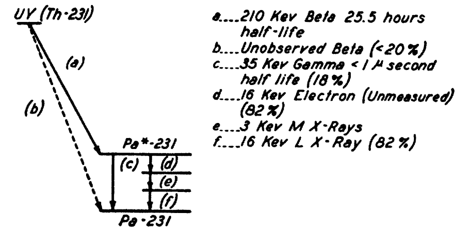

FIG. 4. Decay scheme of uranium Y.

DISCUSSION

The average value of 210 kev of the UY β-particle energy reported here is in substantial agreement with the 0.2-Mev value reported by most previous investigators. The possibility of a pair of beta-rays differing in maximum energy by 35 kev has not been entirely ruled out by the present experiments due to low counting rates and consequent poor precision near the end of the range. The high yield of gamma-rays (q.v.i.), however, indicates that the stronger beta would be present to an extent considerably less than 20 percent of the total. This suggests the supervention of a forbidden transition over the simple beta-decay without gamma-emission.

While the absorption curves of the beta-ray component shown in Figs. 1 and 2 display typical curvature, the two weaker components adhere closely to straight lines in the logarithmic activity plots. From the linear absorption, energies of 16 and 35 kev have been computed for the two

TABLE II. Estimation of counter efficiencies based on equality of beta- and gamma-emission rates. Average extrapolated counting rates observed: Beta: 41,200 counts/min.; x-ray: 2290 counts/min.; gamma: 322 counts/min.

16-kev x-ray		Unconverted 35-kev gamma-ray		
Assumed counter efficiency	Photons through counter per minute	Photons through counter per minute	Derived counter efficiency	Percent of gamma-rays converted in *L* shell
0.060	38167	3033	0.106	93
0.061	37541	3659	0.088	91
0.062	36935	4265	0.076	90
0.063	36349	4851	0.066	88
0.064	35781	5419	0.059	87
0.065	35231	5969	0.054	86
0.066	34697	6503	0.050	84
0.067	34179	7021	0.046	83
0.068*	33676	7524	0.043*	82
0.069	33188	8012	0.040	81
0.070	32714	8486	0.038	80

* Best fitting values (see Fig. 3).

components found. The exact average absorption coefficient to be expected for the several $L-M$ transitions is complicated by two factors. The relative $L\alpha$, $L\beta$, etc., intensities found in x-ray work are caused by excitation with a broad range of energies. In the case of excitation by conversion of a single gamma-ray not too far removed in energy from the L limit, a quite different distribution of relative intensities might result. In addition, the high intensity of a component near the $M-N$ transition energy as observed at Chicago suggests the possibility of an appreciable Auger (auto-ionization) effect which would lead to a further modification of the L x-ray spectrum. A value of 15.5–16.0 kev for the average seems a quite reasonable expectation, in view of the foregoing, for the average L-shell, x-ray energy of protoactinium. Thus the less penetrating electromagnetic component is thought to be the L x-ray resulting from conversion of a 35-kev gamma-ray.

The efficiencies of the counters used in these experiments increase regularly above approximately 0.2 Mev. A rough estimate in that range equates the numerical values of the percent efficiency and the energy in Mev. A minimum efficiency of about 0.1 percent is reached in the neighborhood of 100–150 kev, below which the efficiency rises rather sharply. At 25 kev an efficiency of perhaps 5 percent is to be expected. If both the 16-kev and 35-kev components had a 5 percent counter efficiency, the average extrapolated intensities at the counter would be 45,800 and 6440 c/m, respectively. This compares with an average beta-intensity of 41,200 c/m and indicates that each beta-emission is accompanied by one gamma-ray which often suffers conversion in the L-shell of the atom. Setting the emission rates of gamma-photons and beta-particles equal, it is possible to find values of the counter efficiencies at 16 and 35 kev which best fit the expected efficiency *vs.* energy curve. As can be seen from Table II, the required efficiency at 35 kev for this equality varies more rapidly than the assumed efficiency at 16 kev. The best fitting efficiencies appear to be 6.8 percent at 16 kev and 4.3 percent at 35 kev. These values are plotted with the expected curve in Fig. 3.

The percent conversion is shown not to depend very strongly upon the choice of efficiencies. The value of 82 percent for the best fitting efficiencies is also relatively insensitive to the possible presence of a small beta-ray component unaccompanied by gamma-radiation mentioned above in connection with the beta-ray absorption curves. This high conversion value in the L shell suggests that multipolar radiation of at least quadruple order is involved. Exact calculations are complicated by the relativistic effects in such a heavy nucleus as thorium and by the energetically excluded K conversion.

The decay scheme suggested by these experiments is summarized in Fig. 4.

CONCLUSION

The half-life of UY has been computed as 25.51 hours with a limit of error at the 95 percent confidence level of 0.93 hours. The beta-ray energy was found by absorption measurements to be 210 kev. A gamma-ray of 35 kev was found, about 82 percent converted in the L shell.