REVIEWS OF MODERN PHYSICS VOLUME 19, NUMBER 2 APRIL, 1947

The Interaction of γ-Rays With Matter and the Spectroscopy of γ-Radiation

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I. INTRODUCTION

DESPITE the wide diversity of phenomena caused by the action of γ-rays on atoms of matter, up to the present not one of these phenomena has been studied in a manner that would permit of sufficiently accurate measurements of the absolute or relative intensities of the lines in the γ-ray spectrum.

The probabilities of all the enumerated phenomena depend quite markedly on the energy of the quanta. Therefore, in order to determine the relative intensity of two γ-lines from the ratio of the number of times some elementary phenomenon has been observed, it is necessary to know how the probability of this process depends on the energy of the quanta. At the present time these relations have been computed theoretically from relativistic quantum mechanics for individual elementary acts.

The probability of the scattering of quanta on free electrons as a function of the energy of the quanta can be computed from the well-known Klein-Nishina formula. Bethe and Heitler have carried out similar calculations for the process of formation of an electron-positron pair. Jaeger and Hulme subsequently introduced corrections in these computations. The probability of photoelectric absorption for different energies of the quanta has been calculated by Hulme, Buckingham, and others.

The most widespread method in γ-spectroscopy is that of observing the secondary particles which arise from the internal conversion of γ-rays, that is, from a process whereby the energy of the excited nuclei is transmitted directly to the secondary particles without passing through the stage of γ-radiation. Taylor and Mott developed a theory of the internal conversion of γ-rays on the electronic orbits of the atom and deduced the dependence of the conversion coefficient on the energy and multipolarity of the γ-radiation for different shells of the atom. Similarly, Jaeger and Hulme developed a theory of internal conversion with the formation of electron-positron pairs and determined the dependence of the conversion coefficient on the energy and multipolarity of the radiation for a nucleus of charge 82, and one of charge approaching zero.

It is possible to check the correctness of the conclusions following from the theories of the enumerated phenomena, and, in particular, to verify the relation between the effective cross sections and the energy of the quanta by observing the secondary particles produced, only if the ratio of the intensities of the applied lines has been measured. This, however, necessitates experimental verification of the theoretical law, giving the variation of the probability of one of the enumerated phenomena with the energy of the quanta. A solution of this problem can be obtained in the following manner.

On the basis of exact measurements of the absorption coefficient of γ-rays of different energy in light elements, when absorption is completely determined by the Compton effect, it is now well-known that the Klein-Nishina formula shows excellent agreement with experiment. For γ-rays of 2620-kev energy the measurements of Tarrant, Meitner, and Hupfield, and, in particular, of Gentner[1] lead to an absorption coefficient which lies within 3 percent of that calculated from the Klein-Nishina formula. Furthermore, the papers of Read and Lauritsen[2] furnish highly accurate measurements of the absorption coefficients of monochromatic artificial γ-rays of energies from 200 to 600 kev and show fine agreement with the absolute values of the absorption coefficients calculated from the Klein-Nishina formula.

It can thus be considered established that in an energy interval ranging from several hundred to 3000 kev, the dependence of the probability of the Compton effect on the energy of the quanta is known and agrees very closely with the data of the relativistic quantum theory of the Compton effect. It should also be observed here that from the theoretical point of view of all the phenomena enumerated, the Compton effect—i.e., the scattering of a quantum by a free electron—is the most elementary. In all the other cases, factors, such as the bond between the electrons and the atom (photo-effect) or the perturbing action of the nuclear electric field (pair formation), constitute an essential part of the theory, complicating calculations. In view of this, the relativistic theory of the Compton effect has more claims than the theory of any of the other phenomena to be considered theoretically above reproach and, correspondingly, most exact. It follows from these considerations that the most accurate and trustworthy method of measuring the intensity of γ-lines and subsequently verifying the theories of the photo-effect and pair formation is that of measuring the number of recoil electrons ejected by each individual γ-line, a method applied by D. V. Skobeltzyn as far back as 1927.

The approximate data on the intensities of the γ-lines in the γ-ray spectrum of RaC, given by Ellis and Aston were based, not very clearly, to be true, on these measurements by Skobeltzyn.[3] Ellis and Aston[4] determined the intensities of γ-lines from RaC by measuring the intensity of photoelectron emission from a thick plate of a heavy substance and making use of Gray's empirical curve[5] for the dependence of the coefficient of photoelectric absorption on the energy of the quanta.

Ellis and Aston's method of determining the intensities of the lines from the blackening of a photographic plate by electrons torn out of a thick plate can hardly be considered correct in view of a number of considerations. Ellis and Aston checked Gray's empirical curve in the region of high energies by comparing the intensities of the photoelectron lines which they observed with the number of recoil electrons for the individual γ-lines reported by Skobeltzyn. This was done in the following manner. They assumed that the intensity of the photoelectron line F is proportional to the coefficient of photoelectric absorption τ and to the intensity of the γ-line, i.e., that $F=k_1\tau I$, where k_1 is a proportionality factor. On the other hand, the number of recoil electrons R observed by Skobeltzyn is proportional to the absorption coefficient for the Compton effect, σ, and to the same intensity of the γ-line, i.e., $R=k_2\sigma I$, where k_2 is also a proportionality factor. By forming the ratio

$$\frac{F}{R}=\frac{k_1}{k_2}\cdot\frac{\tau}{\sigma}\frac{I}{I},$$

it is possible to compute a quantity proportional to τ/σ for each γ-line, whence, knowing $K=k_1/k_2$ and σ, one can evaluate τ. The coefficient K can be calculated if the ratio F/R has been measured for some γ-line, while τ is known from other experiments, and σ is computed by the Klein-Nishina formula. For soft γ-lines the value of τ can be taken from measurements of the absorption of hard x-rays. The values of τ thus obtained for a number of γ-lines gave satisfactory agreement with Gray's curve. After verifying Gray's curve in this manner, Ellis and Aston utilized it to determine the intensities of the γ-lines from the same experimental data by putting $I=A(F/\tau)$, where $A=1/K_1$—the proportionality factor—is obtained from Gray's curve.

In addition to the objections which can be raised against the measurements of Ellis and Aston, it should be added that Skobeltzyn's measurements, though above reproach as regards the choice of method of determining the intensities of the lines, are inaccurate because of the small number of recoil electrons observed. Skobeltzyn measured only 400 tracks in a Wilson chamber for the whole recoil electron spectrum of γ-rays from RaC, which is far from enough for any accurate determination of the γ-line intensities.

The problem posed in the present investigation was as follows: to work out a method permitting accurate measurements of the intensities of γ-lines from RaC and Th(C+C″) with energies exceeding $2mc^2$ from the recoil electron spectra; and by utilizing these data to verify all the phenomena accompanying the interaction of hard γ-rays with matter.

All the experiments were conducted according to a method first proposed and worked out by A. I. Alikhanov and M. S. Kozodaev. It represents a combination of the Danysz method of focusing electrons with a transverse magnetic field, and the method of registering charged

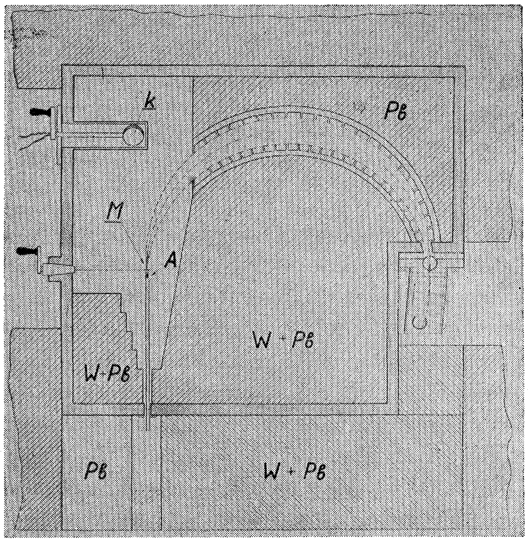

FIG. 1. Diagram of magnetic spectrograph. Cross section in the plane perpendicular to the magnetic field. A—radioactive source; M—target; K—coil for measuring the magnetic field; W+Pb—tungsten screen to shield the counter from the γ-rays of the source.

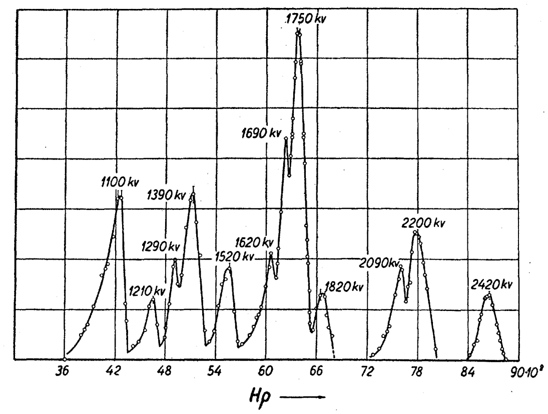

FIG. 2. Recoil electron spectrum of γ-rays from RaC. The abscissae give the energy $H\rho$ of the recoil electrons; the ordinates—the number of electrons. The area of each peak is proportional to the number of recoil electrons generated by the γ-quanta of the given γ-line. The value of the energy of the γ-line in kev is denoted by the number near each peak. The vertical dashes indicate the statistical accuracy of the experimental points.

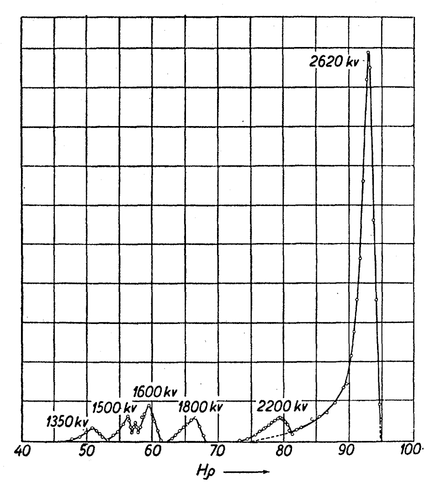

FIG. 3. Recoil electron spectrum of γ-rays from Th(C+C''). (See explanation to Fig. 2.)

particles by two Geiger-Müller counters working in coincidence (Fig. 1).

Such a method of measurement, as well as careful shielding from the direct action of γ-rays on the counters and from electrons ejected from the wall of the apparatus, permitted us to use radioactive preparations of high activity (up to 500*mc*) and, as a result, to have sufficiently strict geometrical conditions and exceedingly narrow sources of secondary electrons which did not distort the true angular distribution of the recoil electrons and their energy.

2. RECOIL ELECTRON SPECTRA OF γ-RAYS

Figures 2 and 3 represent the recoil electron spectra of γ-rays from RaC and Th(C+C'') investigated by G. D. Latyshev[6, 19] and co-workers. The spectra are given in the $H\rho$ scale recalculated for equal intervals of $H\rho$. The areas of the individual peaks in the spectra are proportional to the intensities of the γ-lines. In order to obtain the final intensities of the γ-lines, two corrections must be made: (1) one for the spectral distribution of the recoil electrons and the dependence on the energy of the quanta, and (2), a second for the multiple scattering of the Compton electrons inside the plate, in which they are generated when a beam of γ-rays traverses it.

We carried out special computations for the conditions of our experiment. The ordinates R of the curve in Fig. 4 represent the number of Compton electrons entering the coincidence counter when one quantum strikes the plate, as a function of the energy of the quantum. The curve also takes into consideration multiple scattering of the Compton electrons.[6, 21]

Division of the areas of the peaks by the

TABLE I. RaC.

1. Energy of the γ-line in kev. The braces denote the groups of lines, whose areas can be completely separated in the recoil electron spectrum.
2. Relative intensities of the groups of lines from the data of the recoil electron spectrum. The intensity of the group of lines (2200+2090) kev is taken as unity.
3. Relative intensities of the groups of lines from the data of the spectrum of internal conversion positrons. The intensity of the group of lines (2200+2090) kev is taken as unity.
4. The percentage difference between the values of the line intensities obtained from the recoil electron spectrum, and the values obtained from the positron spectrum.
5. Relative intensities of the γ-lines from RaC obtained on the basis of an analysis of the recoil electron and the positron spectra. The intensity of the 2200-kev γ-line is taken as unity.
6. Multipolarity of the γ-lines from RaC obtained on the basis of an analysis of the recoil electron and the positron spectra.
7. $p\alpha$—according to the data of Constantinov and Latyshev.
8. $p\alpha$—according to the data of Ellis.
9. Multipolarity of the γ-lines obtained on the basis of an analysis of the spectra of the recoil electrons and the internal conversion electrons.

1	2	3	4	5	6	7	8	9
2420	0.34	0.36	−6	0.50	Quadrupole			
2200	1.00	1.00		1.00	Quadrupole	1.5 10^{-4}	0.95 10^{-4}	Quadrupole
2090				0.37				
1820	0.32	0.30	+7	0.41	Quadrupole			
1761				2.42	Quadrupole	4.8 10^{-4}	4.2 10^{-4}	Quadrupole
1690	2.51	2.45	+3	0.40				
1620				0.54				
1520	0.56	0.52	+8	0.71	Quadrupole			
1414						34.5 10^{-4}	25.2 10^{-4}	
1370	1.32	1.19	+11	1.19	Quadrupole	3.5 10^{-4}	0.9 10^{-4}	Quadrupole
1290				0.44				
1234	0.41	0.20	+100	0.56	Quadrupole	2.5 10^{-4}	3.5 10^{-4}	Quadrupole
1120	1.76			2.41		12.4 10^{-4}	12.8 10^{-4}	Quadrupole
606						40 10^{-4}	40 10^{-4}	

TABLE II. Th(C+C″).

1. Energy of the γ-lines in kev.
2. Relative intensities of the γ-lines, from the data of the recoil electron spectrum. The intensity of the 2620-kev γ-line is taken as 100.
3. Relative intensities of the γ-lines from the data of the spectrum of internal conversion positrons. The intensity of the 2620-kev γ-line is taken as 100. (In the computation all the lines were assumed to be of quadrupole origin.)
4. Ratio of intensity values of columns 3 and 2.
5. Multipolarity of γ-lines from Th(C+C″) obtained from an analysis of the recoil electron and positron spectra.

1	2	3	4	5
1350	3.6	10.0	2.77	Dipole
1500	3.7	6.5	1.7	Dipole
1600	10.0	11.0	1.1	Quadrupole
1800	6.2	6.5	1.05	Quadrupole
2200	5.05	10.0	2	Dipole
2620	100	100	1.00	Quadrupole

corresponding ordinates, R, of the curve yields numbers proportional to the intensities of the γ-lines. The ratios of these numbers represent the relative intensities of the γ-lines in the spectra. These are given in Tables I and II.

3. POSITRON SPECTRA

The magnetic spectrograph method was used to investigate positron spectra in the internal conversion of γ-rays with the formation of electron-positron pairs. Figure 5 shows the positron spectrum of γ-rays from RaC investigated by A. I. Alichanov and G. D. Latyshev.[7]

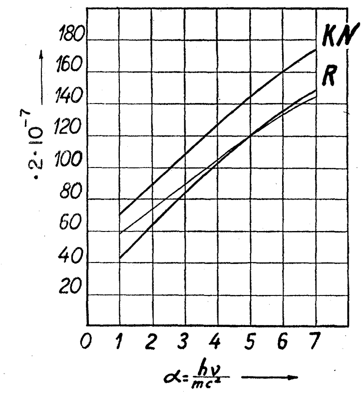

FIG. 4. The abscissae give the energy of the γ-quanta in mc^2; the ordinates, the number of recoil electrons registered by the counters from each γ-quantum striking the target M (see Fig. 1). The curve R takes into consideration both the spectral distribution of the recoil electrons depending on the energy of the γ-quanta and the scattering of the Compton electrons in the target. The curve R is computed for the magnetic spectrograph shown in Fig. 1.

Figure 6 shows the positron spectrum of γ-rays from Th(C+C″) investigated by Alichanov and Dzelepov.[8] The spectra are given in the energy scale, recalculated for equal energy intervals.

4. EXPERIMENTAL VERIFICATION OF THE THEORY OF JAEGER AND HULME

The theory of the internal conversion of γ-rays with the formation of pairs, developed by Hulme and Jaeger,[9] makes it possible to calculate the spectra of the positron and electron components of the pairs. It follows from the theory that the positron spectrum for nuclei of high atomic number should have a sharply expressed characteristic feature. The theoretical curve of the energy distribution of the positrons rises with increase in the energy of the positron to a maximum value $E = h\nu - 2mc^2$ and then drops abruptly to zero. This sharp asymmetry in the energy distribution of the positrons for heavy nuclei can be easily understood on the basis of the fact that the positron is repelled in the coulomb field of the nucleus, whereas the electron, on the contrary, is attracted. Hence each γ-line in the positron spectrum must appear as an abrupt break at $E = h\nu - 2mc^2$. Such breaks were actually observed in the positron spectra of RaC and Th(C+C″); their position on the energy axis corresponds to the values $E = h\nu - 2mc^2$ (E is the maximum kinetic energy of the positron, at

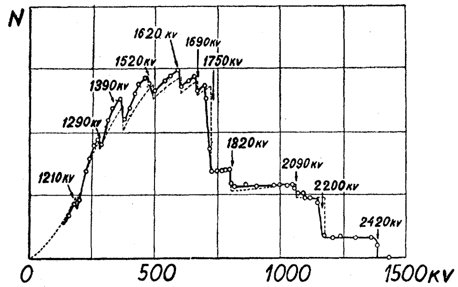

FIG. 5. Spectrum of internal conversion positrons of γ-rays from RaC. The abscissae give the energy of the positrons in kev, the ordinates, the number of positrons. The values given near the drops denote the energy of the corresponding γ-line in kev. The theoretical positron spectrum is shown by the dotted line.

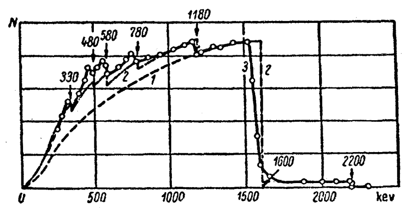

FIG. 6. Spectrum of internal conversion positrons of γ-rays from Th(C+C″). (See explanation to Fig. 5.)

which the break is observed), if the energies of the known γ-lines of RaC and Th(C+C″) are inserted for $h\nu$. By measuring the height of the break in the experimental curve and utilizing the computations of Hulme and Jaeger, it is possible to plot the positron spectrum for each γ-line, and by summing up all the spectra, to obtain the total theoretical spectrum of the positrons formed from all the γ-rays. The dotted lines in Figs. 5 and 6 represent theoretical curves computed in this manner. The coincidence of the theoretical and experimental spectra proves that the theory of Hulme and Jaeger gives a correct energy distribution of the positrons.

Considering this proved and utilizing the data on γ-ray intensities computed from the recoil electron spectrum, one can also verify the theoretical curve giving the dependence of the conversion coefficient on the energy of the γ-rays. For this purpose one computes the intensities of the γ-lines from the experimental curve of the positron spectrum on the assumption that all the lines are of quadrupole origin and that the theory gives the correct relation between the conversion coefficient and the energy of the γ-rays. The intensities of the γ-lines thus computed (see Tables I and II) from the positron spectra are compared with the intensities of the same γ-lines computed from the spectra of recoil electrons. The results of such a comparison for the γ-rays from RaC are presented in Fig. 7, and for the γ-rays from Th(C+C″) in Fig. 8. In case, in the recoil electron spectrum of γ-lines from RaC, not all the peaks corresponding to the individual γ-lines resolve well, the theory can be accurately verified by dividing up all the γ-lines into groups whose areas do resolve well, accurately estimating the intensities of these groups of lines, and then comparing the intensities of these groups of lines computed from the recoil electron spectra with the corresponding intensities computed from the positron spectra. The experimental points lie close to the theoretical curves, thus proving that the theory of Hulme and Jaeger gives a correct relation between the conversion coefficient and the energy of the γ-rays.

In Fig. 8 part of the experimental points lie on the curve of quadrupole transitions and part on the curve of dipole transitions, whence follows that not all the lines in the γ-ray spectrum of Th(C+C″) are of quadrupole origin, as we assumed, but that some are of dipole origin. Thus, a comparison of the line intensities computed from the recoil electron and the positron spectra permits a determination of the multipolarity of the γ-lines; the latter is given in Tables I and II.

Special measurements of the absolute value of the internal conversion coefficient for γ-rays of 2620-kev energy made by A. I. Alichanov[10] and co-workers showed that the observed absolute value of the conversion coefficient—$4\text{–}5\times 10^{-4}$ is in good agreement with the value 4.6×10^{-4} computed from the theory of Hulme and Jaeger.

5. INTERNAL CONVERSION OF γ-RAYS

The method of internal conversion positrons is inapplicable to the spectroscopy of γ-rays of energy $h\nu < 2mc^2$. The most widespread methods in this region of γ-spectroscopy are those based on the observation of the secondary particles arising as a result of the internal conversion of γ-rays on the electrons of the atom. The probability of internal conversion depends both on the energy of the γ-rays and the character of the energy transition in the nucleus. A knowledge of the intensities of the lines obtained from observations of internal conversion electrons, and the corresponding intensities computed from the recoil electron spectrum, also makes it possible to find a unique solution of the problems of γ-ray intensity and multipolarity.

Utilizing data on the intensity of the γ-lines computed from the spectrum of Compton electrons, we investigated the spectrum of internal conversion electrons of the same γ-rays. Comparison of the intensities of the lines computed from this spectrum with the intensities of the same lines as obtained from the recoil electron spectrum permitted us to verify the theory of the internal conversion of γ-rays on the electrons of the atom.

The investigation of the natural γ-spectrum of RaC was carried out by the method of focusing the electrons in a transverse magnetic field and registering them with two Geiger-Müller counters working in coincidence. A thin-walled glass ampule filled with radium emanation served as the electron source.

Since measurements of the natural γ-spectrum were performed on an electron beam of very small divergence (3°), the electrons gathered in a focus only 0.4 mm wide; this was the width given to the slit in the counter. Hence the electron source had to be accurately fixed in the apparatus. This was achieved by attaching the ampule to a frame which could be moved in the focus of the apparatus by means of a micrometer screw, and thus adjusted in the focus of the spectrograph.

When the position of the ampule is accurately established the conversion electrons appear as narrow and very high peaks on the continuous background of the γ-spectrum. This experimental innovation considerably improved the methodics of investigating natural γ-spectra.

Figures 9 and 10 represent the experimental curve of the natural γ-spectrum of RaC investigated by A. A. Constantinov and G. D. Latyshev.[11]

Figures 11 to 15 depict separate parts of the γ-spectrum of RaC where the conversion peaks from individual γ-lines are most clearly evident.

The entire natural γ-spectrum was investigated on one ampule and the enormous number of 5×10^6 electrons registered. Experimental points were taken down at intervals of 1–2 kev.

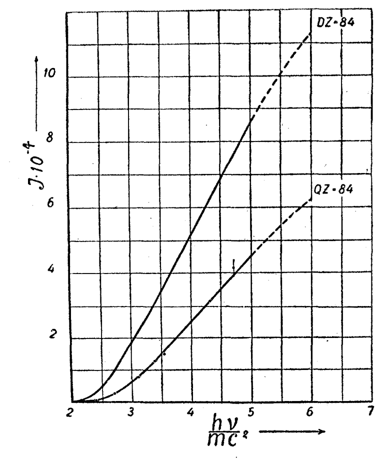

FIG. 7. $DZ=84$ and $QZ=84$—theoretical curves of Jaeger and Hulme for dipole and quadrupole transitions, respectively, computed for an atom of nuclear charge $Z=84$. The abscissae give the energy of the positrons in mc^2; the ordinates, the coefficient of internal conversion with the formation of electron-positron pairs. The circles denote experimental points plotted from the data of Table I, columns 2 and 3. The point corresponding to the group of lines (2200+2090) kev has been placed on the curve of quadrupole transitions, for it is well known that the intensive 2200-kev line is of quadrupole origin.

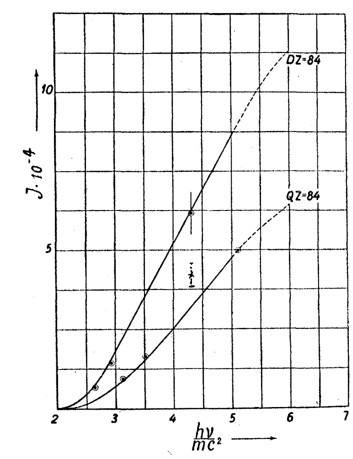

FIG. 8. (See explanation to Fig. 7.) The points are plotted from the data of Table II, columns 2 and 3, the point corresponding to the γ-line 2620 kev being placed on the curve of quadrupole transitions.

The ampule containing the electron source possessed extremely thin walls. The nitrocellulose films on the first windows of the counters did not exceed 2–3μ in thickness; in addition, we took a number of precautionary measures with regard to the work of the counters, the amplifier, measure-

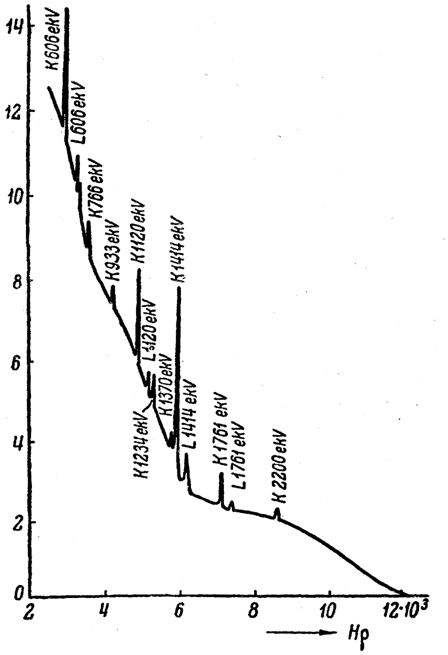

FIG. 9. Natural β-spectrum of RaC. The β-spectrum is given in the $H\rho$ scale without recalculation for equal intervals of $H\rho$. The numbers near the conversion peaks denote the energy of the corresponding γ-line in kev. The letters K, L, denote the electron shell of the atom where conversion of the γ-ray takes place.

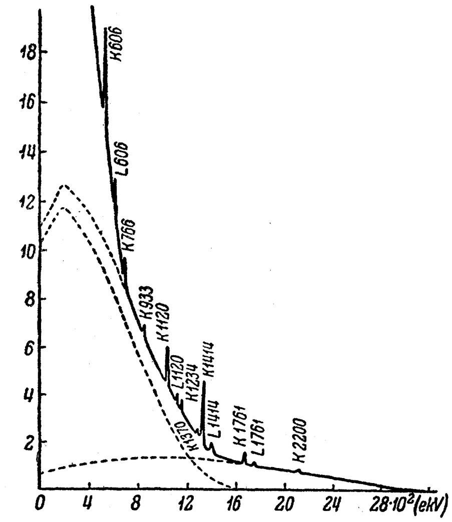

FIG. 10. Natural β-spectrum of RaC. The β-spectrum is given in the energy scale, recalculated for equal energy intervals. The β-spectrum of RaC is a continuous spectrum. Analysis of the given experimental curve by means of the formula of Uhlenbeck and Konopinsky makes it possible to resolve the β-spectrum of RaC obtained into two elementary β-spectra with upper limits at 1650 kev and 3173 ± 20 kev. The soft component of the β-spectrum accounts for 77 percent of the electrons of the disintegration, the hard component—for 23 percent. These spectra are shown in Fig. 10 by dotted lines; while their sum coincides with the experimental curve of the β-spectrum of RaC right up to the energy 720 kev, where the β-spectrum of RaB begins to superimpose upon the β-spectrum of RaC. The area of the β-spectrum of RaC is taken equal to the area bounded by the experimental curve of RaC up to the energy 720 kev, beyond which it is bounded by the dotted theoretical curve.

ments of the magnetic field, etc., so that we feel justified in considering the above curve of the natural β-spectrum of RaC to be most exact, up to date, and extremely close to the true natural γ-spectrum.

The area of an individual conversion peak in Figs. 11 to 15 is evidently proportional to the number of conversion electrons from the given γ-line, that is, to the product of the intensity of the γ-line by its conversion coefficient. Hence, division of the area of each conversion peak by the area of the β-spectrum of RaC yields the quantities $p\alpha$, where p is the ratio of the number of quanta to the total number of disintegrations, and α is the internal conversion coefficient of the given γ-line.

Column 7 of Table I gives the values of $p\alpha$ according to our data, and column 8 of the same table gives $p\alpha$ according to the data of Ellis.[12] The values of $p\alpha$ refer to conversion on the K-level. Division of the values in column 7 by the relative intensities of the γ-lines yields quantities proportional to the internal conversion coefficients. Figure 16 shows the theoretical curves which give the dependence of the internal conversion coefficient on the energy of the γ-rays.

Comparison of our values of $p\alpha$ with the data of Ellis and Aston[4] reveals the greatest divergence for the γ-line 1370 kev. As a result of this divergence, the data of Ellis and Aston place the point corresponding to the line 1370 kev on the

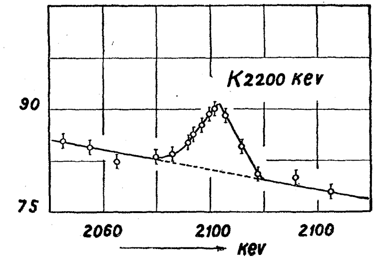

FIG. 11. Conversion peak of electrons from the K- and L-shells of the atom generated by γ-rays of 220-kev energy.

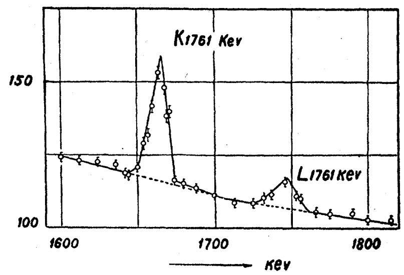

FIG. 12. Conversion peak of electrons from the K- and L-shells of the atom generated by γ-rays of 1761-kev energy. Comparison of the areas of the K and L peaks shows that the ratio of the probability of conversion on the K-shell to the probability of conversion on the L-shell equals 4.3:1.

curve of dipole transitions; according to our data, however, it lies on the curve of quadrupole transitions, which is in complete agreement with the data of the positron spectrum. Column 9 of Table I gives the multipolarity of the γ-lines, obtained by comparing the γ-line intensities which follow from the spectrum of recoil electrons and the spectrum of internal conversion electrons. The agreement with column 6 is complete.

Our measurements permitted us to determine conversion on the L-shell for a number of γ-lines. We refrain from going into the details of this question in the present paper, observing merely that absorption in the K-shell comprises approximately 80 percent of the total absorption in all the shells of the atom for hard γ-rays.

6. THE PHOTO-EFFECT FROM HARD γ-RAYS

The photo-effect from hard γ-rays has been studied least of all. The quantum theory of the photo-effect brings, in the general case, integrals which cannot be expressed in terms of known functions. Approximate formulas have been deduced for several particular cases. As for experimental investigations, there are no direct measurements of the effective cross section of the photo-effect. All determinations of the effective cross section were made by measuring the cross section of total absorption and then subtracting the theoretically computed effective cross sections of Compton scattering and pair formation. This method of investigating the photo-effect has the following shortcomings:

1. In the case of hard photons, where but a very small portion of the absorption is caused by the photo-effect, the accuracy of the determination of the photoelectric absorption coefficient is very small.

2. The results of this method depend greatly on the accuracy of the Bethe-Heitler formula for the effective cross section of pair formation; the direct verification of this formula, however, has been effected with comparatively small accuracy.

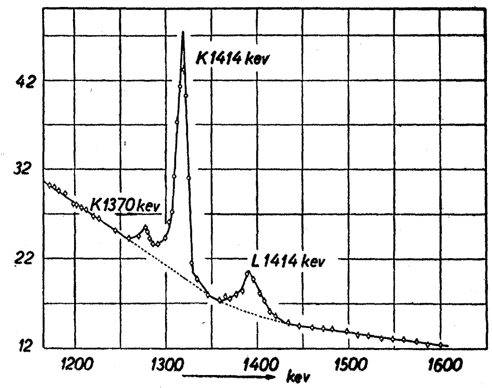

FIG. 13. Conversion peaks of electrons: K1370 kev, K1414 kev, and L1414 kev. For the energy level 1414 kev it is only possible to determine the ratio of the probability of conversion on the K-shell to the probability of conversion on the $L+M+\cdots$ shells, which is equal to 4.1:1; since the conversion peak L cannot be separated from the conversion peak M because of the superposition of electrons generated by the conversion of the γ-line 1520 kev on the L-shell. A correction was made for these electrons in the above ratio.

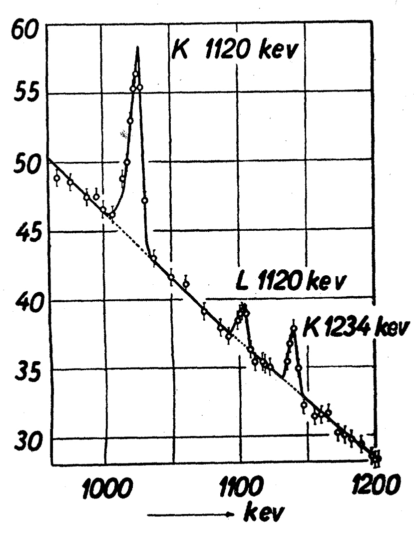

FIG. 14. Conversion peaks of electrons: K1120 kev, L1120 kev, and K1234 kev. Comparison of the areas of the peaks K1120 kev and L1120 kev shows that the ratio of the probability of conversion on the K-shell to the probability of conversion on the L-shell equals 5.2:1.

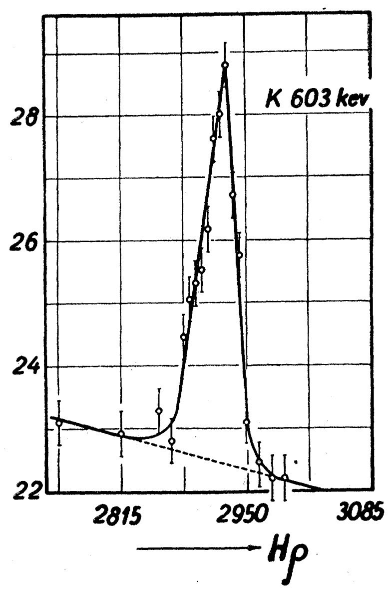

FIG. 15. Conversion peak of electrons generated in the K-shell of the atom by γ-rays of 603-kev energy.

3. The results of the measurements, especially for the rays from RaC, depend to a great extent on the preliminary filtration of the γ-rays.

4. Finally, this method does not permit investigation of photoelectric absorption on the K- and L-shells of the atom, or the angular distribution of the photoelectrons.

For this reason, the direct investigation of photoelectric absorption is highly important. Such a method would make it possible to solve a wide range of problems:

1. To verify accurately the theory of the photo-effect from hard γ-rays.

2. A solution of this problem would, in turn, make it possible to verify more exactly the Bethe-Heitler formula for pair formation.

3. The method worked out for determining the number of photoelectrons from individual γ-lines would permit the method under discussion to be applied to the investigation of the spectral composition of radiation from radioactive nuclei, especially in the region of energy $h\nu < 2mc^2$, where the coefficients of photoelectric absorption and internal conversion are large. By observing the number of photoelectrons and internal conversion electrons from individual γ-lines, it is possible to solve completely the problem of γ-line intensities and multipolarity in the region of γ-radiation from radioactive nuclei of energy $h\nu < 2mc^2$.

The method of investigating recoil electrons from hard photons by means of a magnetic spectrograph, which has been developed by G. D. Latyshev and co-workers,[6,13] is also applicable to the investigation of photoelectrons ejected by individual γ-lines.

The method is as follows: a lamina of the material under investigation is placed in the focus of the magnetic spectrograph (see Fig. 1) and irradiated by γ-rays. Upon the passage of the γ-rays through the lamina, Compton electrons, photoelectrons, and pairs are generated in it. By varying the strength of the magnetic field it is possible to analyze the velocities of the charged particles formed, the Compton electrons, photoelectrons, and electron components of the pairs separating from each other.

Indeed, the maximum energy of Compton electrons emerging at an angle of 0° to the initial direction of the γ-quanta equals:

$$E_k = h\nu 2\alpha/(1+2\alpha)$$

where $\alpha = h\nu/mc^2$. For the γ-line 2620 kev which we investigated $\alpha = 5.13$. Hence

$$E_k = 2620(2\times 5.13/1+2\times 5.13) = 2390 \text{ kev}.$$

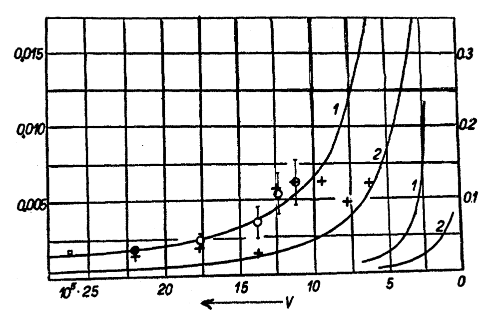

FIG. 16. Theoretical curves giving the relation between the coefficient of internal conversion and the energy of the γ-rays. Curve 1, computed by Taylor, corresponds to quadrupole transitions in the nucleus. Curve 2, computed by Hulme, corresponds to the case of dipole transitions in the nucleus. The circles denote points plotted from the experimental data of Table I, columns 5 and 7. Since we lacked the absolute values of the intensities of the γ-lines, the point corresponding to the line 2200 kev, was placed on the theoretical curve of quadrupole transitions. The crosses denote the absolute values of the internal conversion coefficients according to Ellis and Aston.[4] The square denotes the value of the internal conversion coefficient for the γ-line 2620 kev according to the data of A. I. Alichanov and S. Y. Nikitin.[20]

Compton electrons which emerge at other angles have lesser energies.

All the photoelectrons possess the same energy

$$E_\phi = h\nu - W$$

where W, the work function for the K- and L-shells, equals 87.6 kev and 15.8 kev, respectively, for lead. Hence the energy of the photoelectrons from the K- and L-shells of lead are equal, respectively, to

$$E_k = 2620 - 87.6 = 2532 \text{ kev}, \quad E_L = 2604 \text{ kev}.$$

This energy is even greater for the lighter elements where the work function is less. As for the electron components of the pairs, their energy is less than that of the photoelectrons and Compton electrons by 1020 kev.

With a spectrograph of sufficiently high resolving power it is possible to separate not only Compton and photoelectrons but also (for the heavy elements) photoelectrons from the K- and L-shells. Figure 17 shows the spectrum of Compton and photoelectrons in lead, investigated with the apparatus represented in Fig. 1.

We subsequently constructed a spectrograph with larger focal length. In order to investigate the dependence of the probability of the photo-effect on Z we measured the photo-effect in lead, tantalum, silver, and copper.

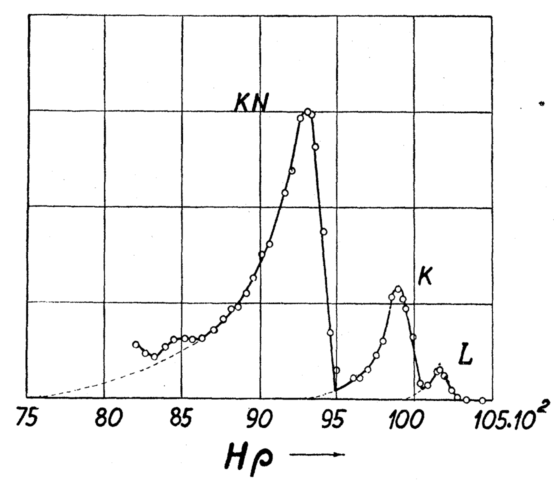

FIG. 17. Spectrum of Compton and photoelectrons generated in a lead lamina upon the passage through it of 2620-kev γ-rays. Peak KN corresponds to recoil electrons, peaks K and L—to photoelectrons from the K- and L-shells of the lead atoms. The spectrum was recorded with the apparatus depicted in Fig. 1.

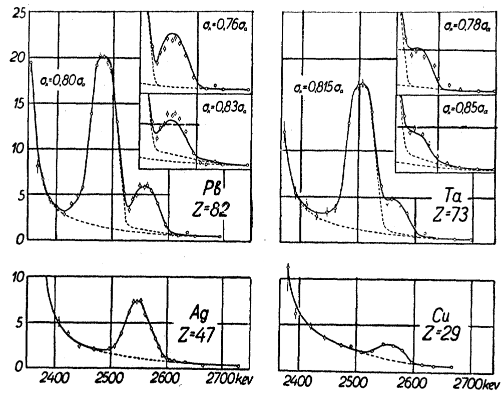

FIG. 18. Results of measurements of the photo-effect from the 2620-kev γ-line in Pb, Ta, Ag, and Cu. The dotted lines on the curves for Pb and Ta separate the photoelectrons generated in the K- and L-shells of the atom. The upper right-hand corner of the drawing shows how the curve would lie with respect to the experimental points if the two limiting values of the ratio σ_k/σ_a were taken.

In order to avoid distortion of the results caused by scattering of the photoelectrons in the targets, the thicknesses of the laminae of the materials under investigation were chosen so that the mean scattering angle was the same in all of them. The results of the measurements are shown in Fig. 18. Comparison of the areas of the photoelectron curves for Pb, Ta, Ag, and Cu shows that the effective cross sections of the photo-effect per atom in these elements are in the ratio:

$$\sigma a_{\mathrm{Cu}} : \sigma a_{\mathrm{Ag}} : \sigma a_{\mathrm{Ta}} : \sigma a_{\mathrm{Pb}} = (1 \pm 0.2) : (9.5 \pm 1.1) : (74 \pm 8) : (120 \pm 11).$$

Figure 19 represents the results of the experiments in the logarithmic scale. As is evident from the figure, in the interval from $Z = 29$ to $Z = 82$, the dependence on Z of the effective cross section of the photo-effect for the investigated γ-line can be exactly represented by the formula:

$$\sigma_a = k \cdot Z^n; \quad \text{where} \quad n = 4.6 \pm 0.25.$$

Figure 18 shows that for Pb and Ta the curves of photoelectrons from the K- and L-shells can be separated. The separation depicted in the figure by the dotted line was effected on the assumption that the form of the curve must be the same for the photoelectrons from the K- and the L-shells. Hence, if all the ordinates of the curve of photoelectrons from the K-shell are decreased by a factor σ_K/σ_L and the curve is shifted to the

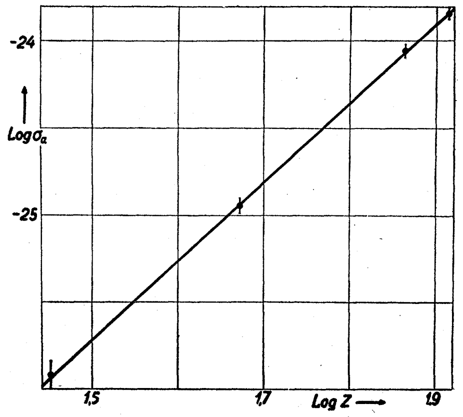

FIG. 19. Dependence of σ_a on Z.

right a distance equal to the difference of the work functions of the K- and L-shells, the curve of photoelectrons from the L-shell is obtained. The ratio was chosen so that the sum of the L-curve thus obtained plus the K-curve should coincide with the experimental curve. The photoelectrons from the M-shell were also taken into account here. It was assumed that $\sigma_M/\sigma_L=\frac{1}{4}$. Because of the small number of M-photoelectrons, the error in the estimate of σ_M/σ_L will not affect the accuracy of our separation.

It appeared that $\sigma_K/\sigma_L=4.9$ for lead, and $\sigma_K/\sigma_L=5.4$ for tantalum. Hence, if we assume $\sigma_M/\sigma_L=\frac{1}{4}$, we obtain: for Pb—$\sigma_K/\sigma_a=0.80\pm0.035$ and for Ta—$\sigma_K/\sigma_a=0.815\pm0.035$, where σ_a is the effective cross section per atom. The error in the value found for σ_K/σ_a does not exceed 3–4 percent. With a small change in the ratio σ_K/σ_a the right-hand section of the summary curve passes outside the limits of the experimental points, as is clearly evident in Fig. 18.

In order to determine the absolute value of the effective cross section for the photo-effect, it is necessary to determine the total number of photoelectrons emerging from the lamina under investigation. Such determinations were made for a lead lamina 9.4 mg/cm² thick, for which the angular distribution of the photoelectrons was investigated. Measurements were taken of the number of photoelectrons emerging from the lamina at angles of 0.8°, 6.2°, 11°, 16°, 21°, and −9° to the initial direction of the quanta (Fig. 20).

The angular distribution of the photoelectrons is shown in Fig. 21. The ordinates of the curve divided by the solid angle subtended by the counters (0.0074) give the number of photoelectrons per unit solid angle in the given direction; if these numbers are then multiplied by $2n\sin\theta$, the area of the resulting curve gives the total number of photoelectrons emerging from the lamina per unit of time. Denote this area by S_ϕ, and the number of photoelectrons generated in the target by N_ϕ. Then $S_\phi=KN_\phi$, where K is a coefficient depending on the scale of the curves and the energy interval recorded by the counters.

If N_ϕ is divided by the number of quanta striking the target per unit time (N_γ) and by the number of atoms (n_a) per cm² of this target, the effective cross section of the photo-effect in lead is obtained:

$$\sigma_{a\,\mathrm{Pb}}=N_\phi/N_\gamma n_a=S_\phi/KN_\gamma n_a.$$

N_γ can be determined by measuring the number of Compton electrons ejected from the lamina by the same source. Since the effective cross section of the Compton effect is known exactly, N_γ can thus be determined. It is convenient thus to measure the number of Compton electrons formed, not in a lead lamina, but rather in a lamina made of some light substance where

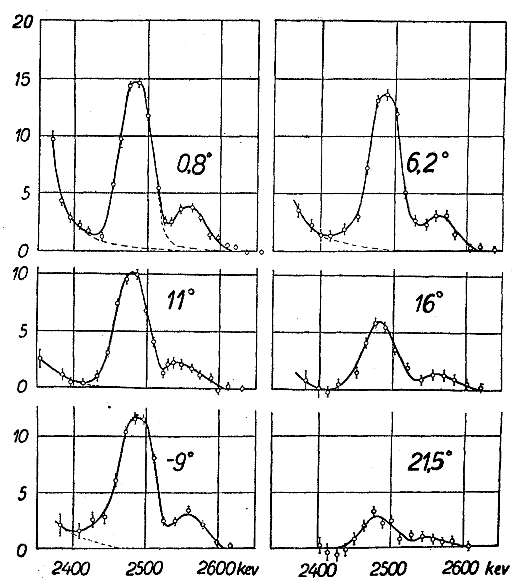

FIG. 20. Curves of photoelectrons, emerging from a lead lamina at different angles to the initial direction of the γ-quanta.

multiple scattering of the Compton electrons can be accurately estimated.

Denote the area of the curve of Compton electrons by S_k, and the number of Compton electrons entering the counter by N_k; then[13]

$$S_k = KN_k = K \times 20.8 \times 10^{-6} \times N_\gamma,$$

where N_γ is the number of quanta, and the coefficient K has the same value as in the formula for photoelectrons. Hence we obtain:

$$\sigma_{a\mathrm{Pb}} = \frac{S_\phi}{KN_\gamma n_a} = 20.8 \times 10^{-6} \frac{S_\phi}{S_k} \frac{1}{n_a} N_\gamma.$$

The value of $\sigma_{a\mathrm{Pb}}$ thus obtained was equal to $(1.3 \pm 0.41) \times 10^{-24}$ which is in excellent agreement with the theoretical values given by Hulme[14] and co-workers.

As for the true angular distribution of the photoelectrons in an elementary act of the photo-effect, it cannot be determined from the curve in Fig. 21, since this distribution is distorted by the scattering of the photoelectrons in the lamina itself. An investigation of the true angular distribution of the electrons in an elementary act of the photo-effect for γ-rays of the given energy would necessitate the utilization of exceedingly thin laminae and small divergences of the magnetic spectrograph, and hence is practically impossible. We therefore made an approximate estimate of the angle of scattering of the electrons in the photo-effect from the curve in Fig. 21. (It should be observed that this is the only case, in which it is possible to estimate the angle of scattering of the photoelectrons in this energy range.)

Indeed, a rough estimate of the most probable scattering angle for electrons of 2550 kev in the lamina under investigation yields a value of 2–3°, on consideration that the electrons are generated in different layers of the target and hence different electrons must traverse different thicknesses of material. But the most probable angle for the experimental curve in Fig. 21 equals 11°. Hence the greater part of the photoelectrons must emerge at an angle of 8–9°, which is in good agreement with the predictions of the theory of relativistic effects.

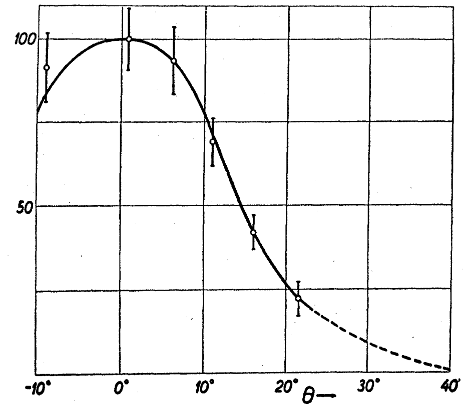

FIG. 21. Angular distribution of the photoelectrons. The points are plotted from the data of Fig. 20.

TABLE III. Long range α-particles from ThC′→ThD.

Energy of the group in kev	Disintegration energy in kev
10,520	10,720
9,600	9,780
9,450	9,780
8,770	8,940

7. DIAGRAM OF LEVELS OF THE ThC′ NUCLEUS

In the radioactive disintegration ThC′→ThD, the ThC′ nucleus emits groups of long range α-particles. Table III gives these groups according to the measurements of Rosenblum and Valadres.[15] The system of levels of the ThC′ nucleus should contain levels determined by these four groups of long range α-particles.

The γ-ray spectrum of the active thorium deposit reveals γ-lines of energy 1600 and 2200 kev which do not correspond to the levels determined by the groups of long-range α-particles from ThC′. However, the excited levels corresponding to these γ-lines (2200 and 1600 kev) undoubtedly belong to the ThC′ nucleus. This follows from an analysis of the system of levels of the disintegration products of ThA proposed by Ellis.[16]

The system of levels of the ThC′ nucleus (Fig. 22), which we suggest, fully explains all the γ-lines found in the recoil electron spectrum of the active thorium deposit. Moreover, this system is borne out by the circumstance that the low energy lines (150, 690, 840 kev) which follow from it appear in the natural β-spectrum of Th(B+C+C″) published by Ellis in 1932. The

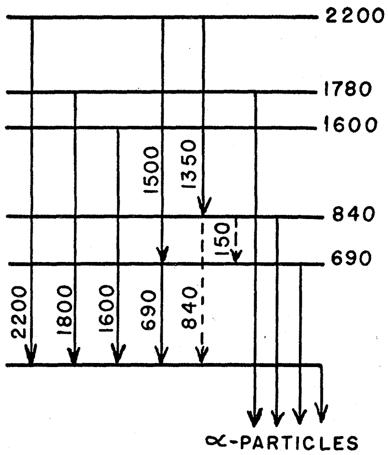

FIG. 22. Diagram of levels of the ThC′ nucleus.

slight difference between the energies of the levels and the energies of the observed γ-lines is to be accounted for by our experimental errors and those of Rosenblum and Valadres in determining the energy of the α-particles.

8. RATIO OF THE PROBABILITY OF EMITTING A LONG-RANGE α-PARTICLE TO THE PROBABILITY OF EMITTING A γ-QUANTUM FROM THE 1800-kev LEVEL OF THE ThC′ NUCLEUS

When the 1800-kev level of the ThC′ nucleus is excited, disintegration can proceed in one of two ways: either the excited nucleus may emit a long-range α-particle, or it may first emit an 1800-kev γ-quantum (the ThC′ nucleus passes to the ground state) and then an α-particle from the ground level. This is the only case in which it is possible to estimate the ratio of the probability of emitting a γ-quantum to the probability of emitting an α-particle. Our data permit such an estimate to be made fairly accurately.

Let N be the number of γ-quanta of 2620-kev energy emitted by our source per unit time. It is well known that a 2620-kev quantum is emitted in every radioactive disintegration ThC″→ThD. Hence N is equal to the number of disintegrations on the branch ThC→ThC″→ThD, which comprises 35 percent of the disintegrations of the Th nuclei. It is evident that the number of disintegrations on the branch ThC→ThC′→ThD will be equal to $65/35N$. If n denotes the number of 1800-kev γ-quanta emitted by our source, then the number of these γ-quanta (1800 kev) per disintegrated Th nucleus will be equal to:

$$(n/N)(35/65)=6.2\times10^{-2}(35/65),$$

since n/N is the intensity of the 1800-kev γ-line relative to the 2620-kev line, which on the basis of the data of Table II, column 2, equals 6.2×10^{-2}.

According to the data of Rutherford-Ellis, the number of α-particles emitted from the 1800-kev level is equal to 190 per 10^6 particles emitted from the ground level of the ThC′ nucleus. If W_α denotes the probability of emission of an α-particle from the 1800-kev level and W_γ—the probability of radiation of a γ-quantum from the same level, then their ratio is equal to

$$\frac{W_\alpha}{W_\gamma}=(190/10^6)6.2\times10^{-2}(35/65)=5.7\times10^{-3}.$$

Utilizing the less accurate data of D. V. Skobeltzyn,[18] Ellis[17] estimated the ratio of the probabilities of these two processes at 3.6×10^{-3}.

9. CONCLUSIONS

The investigations described in our paper are concerned with the experimental verification of the fundamental conclusions of the modern relativistic quantum mechanics of Dirac. These investigations were carried out in our laboratory by different methods in the course of a number of years. We succeeded in making exceedingly accurate measurements of all the effects by the same method, in all cases directly measuring the effect itself.

It follows from the results of the experiments described that:

1. The conclusions of the Dirac relativistic quantum mechanics in the region of several million electron-volt energies are fully and sufficiently accurately borne out by experiment;
2. In the process of studying the interaction of hard γ-radiation with matter, spectrographic methods of γ-radiation were evolved.

In the region of energies $h\nu>2mc^2$ the combined study of the spectra of internal conversion positrons and of recoil electrons makes it possible to find a complete solution of all the problems connected with the γ-ray spectrum in this region; that is, to determine the intensities and multipolarity of the γ-lines.

In the region of energies $h\nu < 2mc^2$ the familiar method of the internal conversion of γ-rays on the electron shells of the atom, in conjunction with the study of recoil electron or photoelectron spectra also, leads to a solution of all the problems of nuclear γ-spectroscopy.

3. The results of the present paper show that our data on the spectral composition of the hard γ-rays of RaC (Table I, column 5) and Th(C+C″) (Table II, column 3) are the most accurate and have made possible a solution of the entire group of fundamental problems connected with the interaction of hard γ-rays with atoms.

We express our sincere gratitude to A. I. Alichanov for the general formulation of the problem and for consultation on the present paper.

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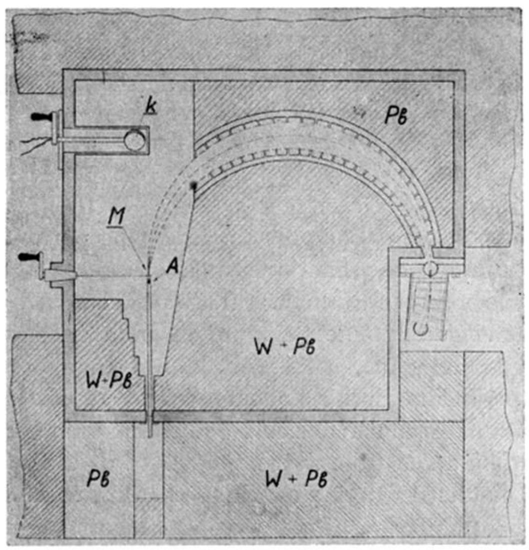

FIG. 1. Diagram of magnetic spectrograph. Cross section in the plane perpendicular to the magnetic field. A—radioactive source; M—target; K—coil for measuring the magnetic field; W+Pb—tungsten screen to shield the counter from the γ-rays of the source.