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SOVIET PHYSICS JETP VOLUME 5, NUMBER 4 NOVEMBER, 1957

Internal Conversion Electron Spectrum of Radiothorium II

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(Submitted to JETP editor September 24, 1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 682-689 (April, 1957)

The internal conversion electron spectrum of a sample of RaTh has been investigated in the $H\rho$ range from 500 to 1380 gauss-cm. The energies and relative intensities of the conversion lines have been determined. It is shown that spectrometers can be calibrated with an accuracy of 5×10^{-4} through the use of Auger electrons.

1. CALIBRATION OF THE SPECTROMETER

AN INVESTIGATION OF A CONVERSION spectrum has been carried out using a magnetic spectrometer with improved focusing[1] with an instrument line width of 0.25%. The aperture angle of the spectrometer in the horizontal plane is 40° and the height of the diaphragms 16 mm. The source and counter slits measure 0.3×16 mm. The magnetic field is measured by the proton-resonance method.[2] The electrons are detected in two self-quenching Geiger counters, connected in coincidence; the count at the first counter is also recorded.

The calibration of the instrument was carried out with the most accurate presently available values of $H\rho$ for the conversion lines for radiothorium. These values are given in the second column of Table 1.

The values of $H\rho$ for the A, B, F, I and J-lines were taken from the work of Siegbahn and Edvardson.[3] These values have an uncertainty of approximately 7×10^{-5}. The value of $H\rho$ for the L-line was taken from the work of Lindstrom[4] which has an uncertainty of approximately 1.2×10^{-4}. The values of $H\rho$ for the Aa and Ab-lines were calculated by using the values of $H\rho$ for the A-line given by Siegbahn. In this calculation we have used the fact that the A, Aa and Ab lines are produced by the conversion of the same 39.85-kev γ-quanta in the Tl atom in the L_I, L_{II} and L_{III}-subshells respectively. In these calculations, as in all similar calculations in this work, we have used the binding energies given by Hill[5] and the tables given by Gerholm for the conversion of $H\rho$ to energy.[6] The Hill tables are apparently the most accurate; by the author's estimate the accuracy is of order of ± 10 ev for the absolute values of the binding energy and of the order ± 1 ev for the differences in binding energy.

The value of $H\rho$ for the E-line was calculated starting from the fact that this line is obtained in the conversion of 115.14-kev γ-quanta in the L_I-subshell of the bismuth atom. The energy of these quanta was determined using the fact that the A-line is complex and consists of two lines, one of which is obtained in the conversion of 39.85-kev γ-quanta in the L_I-subshell of the Tl atom and the other in the conversion in the K-shell of those γ-quanta which yield the E-line. The spacing between these lines is 110 ev.[7]

Column 3 of Table 1 lists the nuclear-resonance frequencies f corresponding to the maxima of the lines, while column 4 gives the value of k, which is the ratio of $H\rho$ to the frequency f. From Table 1 and Fig. 1 it is obvious that $H\rho$ is not linear with f for $H\rho < 2600$ gauss-cm. The departure from linearity for the A-line is approximately 0.2%. This departure from linearity may be explained qualitatively by the change in the magnetic-field configuration in the low-field region. Because measurements of the magnetic field by the nuclear resonance method require the placement of the pick-up coil in

TABLE I. Conversion lines used in calibrating the instrument.

Line	$H\rho$	E, MeV	kc/sec	$k = H\rho/f$
A	534.21	24.510	284.248	1.87938
Aa	541.40	25.159	287.975	1.87980
Ab	563.50	27.201	299.748	1.87992
B	652.40	36.153	346.955	1.88036
E	1109.71	98.756	589.765	1.88162
F	1388.44	148.08	737.494	1.88266
I	1753.91	222.22	931.254	1.88338
J	1811.11	234.60	961.586	1.88346
L	2607.17	422.84	1383.04	1.88510

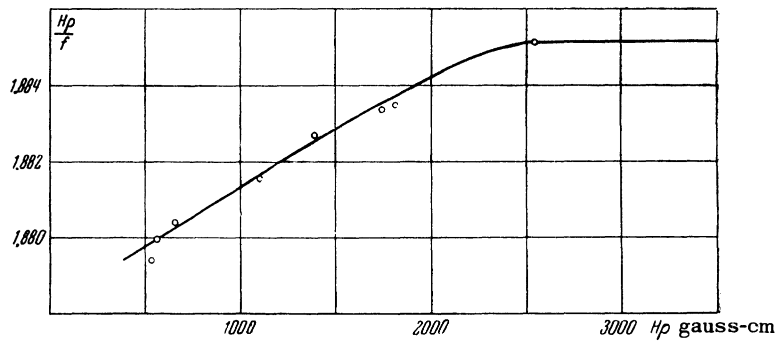

FIG. 1. Calibration curve for the ketron at low energies.

a homogeneous region of the field, we measured the field not directly at the electron trajectories, but in the region of maximum homogeneity. Hence, a change in the magnetic field configuration will lead to nonlinear effects in the instrument.

It should be noted that the value of k for the A-line departs from the smooth curve more than for the other points; this situation may be due to the complex structure of the A-line. Hence, in plotting the curve this point was not included. As has been shown earlier,[8] for $H\rho > 2600$ gauss-cm, the instrument is linear within the limits of accuracy of the experiment.

The nonlinearity of the instrument reduces strongly the accuracy in the determination of the energies of the lines in our instrument. Whereas in the region $H\rho > 2600$ gauss-cm, in which the instrument is linear, the accuracy of the relative measurements of $H\rho$, according to our estimates,[8] reaches 10^{-4}, the uncertainty in $H\rho$ for strong lines is approximately 3×10^{-4} in the nonlinear region.

2. AUGER ELECTRONS FROM Bi^{212} (ThC)

The calibration of the instrument can be checked by a measurement of the energies of Auger electrons. We have used the following series of Auger electrons: KL_pL_q, KL_pM_q, KL_pN_q and KL_pO_q. The series KL_pM_q, KL_pN_q, KL_pO_q contain a large number of components which are located close to one another. Fig. 2 shows the composite curve for these series. We did not attempt to resolve these lines graphically but only determined the total intensity of the group with respect to the I-line. This ratio was found to be 0.0782. The arrows denote the positions of the maxima of the individual lines, calculated under the assumption that the absence of electrons in the L-shell reduces the shielding of the nucleus by an amount corresponding to an increment in the charge of the nucleus of $\Delta Z = 1$. It is apparent from Fig. 2 that this assumption, within the limits of the accuracy, does not contradict the experimental result. The series KM_pM_q, KM_pN_q etc. were not observed because of their low intensity.

The KL_pL_q Auger electron series consists of six rather closely spaced lines. In our work and in Refs. 9 and 10 these have been partially resolved (Fig. 3). Table 2 shows the positions and intensities of the Auger electrons of this series. Our data are compared with the results of Ellis[11] and Mladjenovic and Slätis,[10] who investigated Auger

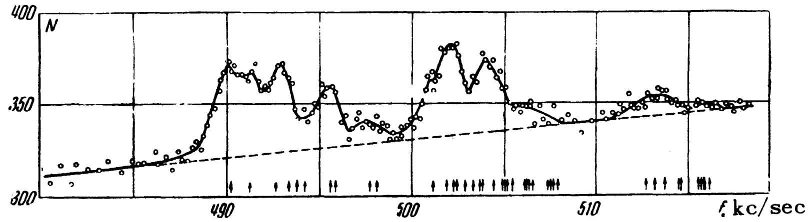

FIG. 2. Auger electrons from Bi[212] (ThC) of the series KL_pM_q, KL_pN_q and KL_pO_q. The arrows indicate the positions of the maxima of the individual lines computed under the assumption that $\Delta Z = 1$.

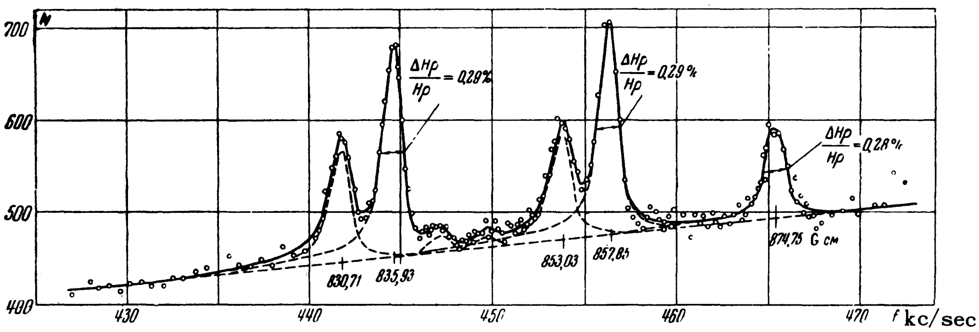

FIG. 3. Auger electrons from B[212] (ThC) KL_pL_q series.

TABLE II. Spectrum for Auger electrons; KL_pL_q series.

Transition	Present data				Ref. 10		Ref. 11	
	$H\rho$	E	I	I_1	I	$H\rho$	I	$H\rho$
$KL_I\ L_I$	830.71	57.458	1.00	0.0247	1.0	830.77	1	826.6
$KL_I\ L_{II}$	835.93	58.147	1.72	0.0425	1.8	836.17	1.8	832.3
$KL_{II}\ L_{II}$	840.75	58.783	0.17	0.0043	<0.2	—	0.2	—
$KL_I\ L_{III}$	853.03	60.423	0.91	0.0224	1.1	853.00	1.3	849.5
$KL_{II}\ L_{III}$	857.85	61.070	1.64	0.0404	1.6	858.01	2.3	854.5
$KL_{III}L_{III}$	874.75	63.367	0.69	0.0170	0.8	875.04	1.3	871.5

electrons of this series for the same Z. It is apparent from the table that our date are in good agreement with the results of Mladjenovic and Slätis. The average discrepance in the magnitude of $H\rho$ in our work and in Ref. 10 is approximately 2×10^{-4} while the error in both papers is approximately 3×10^{-4}. The relative line intensities are also found to be in good agreement with the data of Mladjenovic and Slätis if it is assumed that the errors in both papers are on the order of 10%. The quantity I_I given in the table is the intensity with respect to the I line.

The energy of Auger electrons can be calculated from the formula:

$$E_{KL_pL_q} = E_K^Z - E_{L_p}^Z - E_{L_q}^{Z+\Delta Z},$$

where E_K^Z and $E_{L_p}^Z$ are the binding energies for K and L-electrons respectively in the normal atom while $E_{L_8}^{Z+\Delta Z}$ is the binding energy of the L_q-electrons in the atom with the L_p-electron absent. The binding energy of the L_q-electron is increased because of the reduction in the shielding of the nuclear charge due to the absence of the L_p-electron. Quantitatively the reduction in the shielding can be written in terms of an effective increase in the charge as in Refs. 9 and 10:

$$\Delta Z = (E_{L_q}^{Z+\Delta Z} - E_{L_q}^{Z})/(E_{L_q}^{Z+1} - E_{L_q}^{Z}).$$

A theoretical calculation of the quantity ΔZ is extremely complicated and has not been carried out at the present time. The best experimental determination is that given in Refs. 9 and 10. Table 3 lists the calculated values of ΔZ and also the results of Mladjenovic and Slätis[10] for $Z = 83$ and those of Bergström and Hill[9] for $Z = 80$. These quantities are found to be in agreement within the error limits.

In the first approximation it follows from our results, as has already been noted,[9,10] that the binding energy of the L_q-electron is independent of which of the L-subshells has a missing electron. Hence, as in Refs. 9 and 10, we have determined ΔZ from the average value of $E_{L_q}^{Z+\Delta Z}$ (averaging three values of $L_{L_q}^{Z+\Delta Z}$ corresponding to the absence of L_I, L_{II} and L_{III} electrons). However, if one takes into account the departure from the average for the case of a missing L_I electron and for a missing L_{III} electron, it turns out that both our data as well as those of Mladjenovic and Slätis should show a difference between the binding energy of the L_q-electrons when there is an electron missing in the L_I subshell and the energy when an electron is missing in the L_{III} subshell; on the average this difference is approximately 20 ev. This corresponds to a quantity of the order of 4×10^{-4} of the electron energy, whereas the error in both investigations is approximately 3×10^{-4}. The binding energy of the L_q-electrons for a missing L_{III}-electron is greater than in the case of a missing L_I electron. The results of Bergström and Hill[9] have not been taken into account in this connection since the relative error in their work is approximately 10^{-3}. As regards the case in which an L_{II} electron is ejected, the results of the present work and those of Ref. 10, indicate only that the binding energy of the L_q-electron when an electron is absent in the L_{II} shell lies between the values which apply for electrons missing in the L_I and L_{III} subshells.

The results of the measurements of the spectrum for Auger electron indicate that our data are in gôod agreement with the results of Mladjenovic and Slätis and those of Bergström and Hill; this fact verifies the calibration of the spectrometer and also indicates, that at the present time, the energy of Auger electrons is known with an accuracy of approximately 5×10^{-4} or better and can be used for calibrating spectrometers in the soft region.

3. INTERNAL CONVERSION ELECTRONS

The spectrum of internal conversion electrons from radiothorium has been investigated earlier by Ellis,[12,13] Surugue,[14,15] and Arnoult.[16] In all these papers photographic detection of the electrons was employed. The shortcoming of this method lies in the large error in the determination of the relative line intensities. This error is due chiefly to the necessity of introducing corrections for the spectral sensitivity of photographic plates and the nonlinear dependence of the blackening density on radiation intensity. In work performed by Flammersfield[17] electron detection was carried out with a Geiger counter; however, the resolving power in this work was rather low (approximately 1 percent) and since it was not possible to resolve many of the lines, total intensities were given in many cases.

We have found it worthwhile to repeat the measurements of the spectrum of internal conversion electrons from radiothorium with an instrument half-width of 0.25%. With this half-width, the majority of lines in the soft region are resolved an the instrument has good transmission factor, thus making it

TABLE III.

Transition	$E_{KL_pL_q}$	$E_{L_q}^{83+\Delta Z}$	$E_{L_q}^{83+\Delta Z}$	$E_{L_q}^{83}$	$E_{L_q}^{84}$	ΔZ Present work	ΔZ Ref. 9	ΔZ Ref. 10
$KL_I\ L_I$	57.458	16.677						
$KL_{II}\ L_I$	58.147	16.665	16.674	16.386	16.93	0.53	0.51	0.54
$KL_{III}L_I$	60.423	16.681						
$KL_I\ L_{II}$	58.147	15.988						
$KL_{II}\ L_{II}$	58.783	16.029	16.012	15.709	16.23	0.58	0.52	0.55
$KL_{III}L_{II}$	61.070	16.034						
$KL_I\ L_{III}$	60.423	13.712						
$KL_{II}\ L_{III}$	61.07	13.742	13.730	13 417	13.81	0.80	0.76	0.76
$KL_{II'}L_{III}$	63.36	13.737						

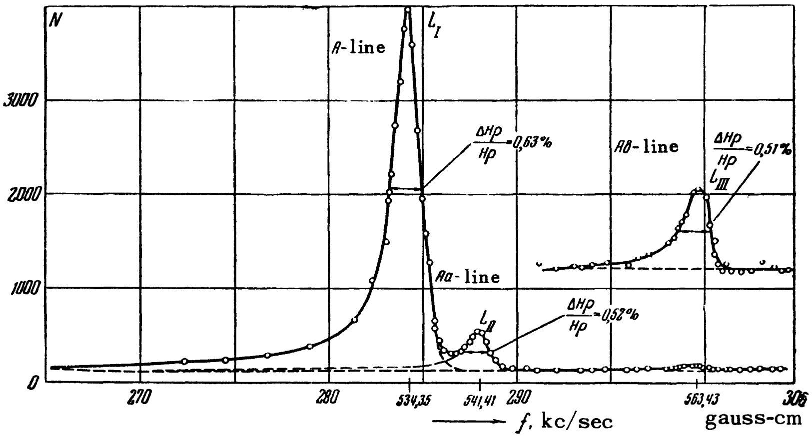

FIG. 4. A, Aa and Ab lines. The Ab lines is given separately with a magnification of 16.

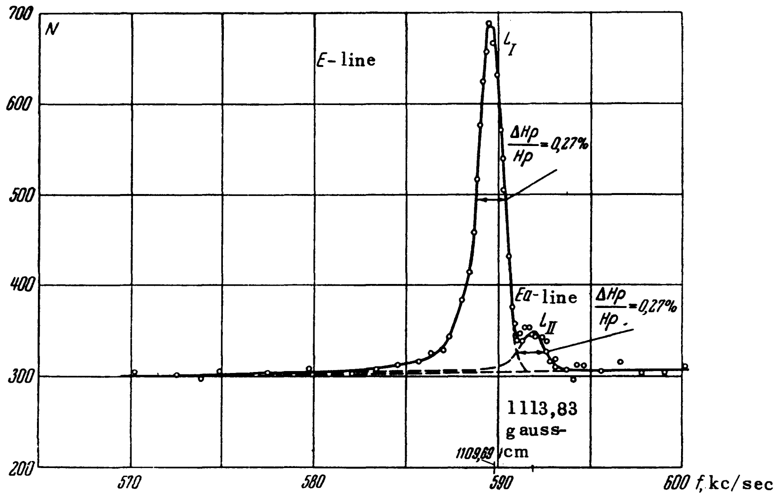

FIG. 5. E and Ea lines.

possible to detect rather weak lines.

High stability in the counter efficiency is required in making an accurate determination of line intensities. We have taken a number of measures to obtain good stability. The voltage for the counter was obtained from a rectifier with high stability (VS-16). The change in the supply voltage in the course of a day (after a three-hour warm-up period) was less than 1 volt. The voltage at the counters monitored with a kilovoltmeter, connected in parallel with a galvanometer having a scale which made it possible to measure counter voltage to 1 volt. The source was introduced into the instrument without disturbing the vacuum; hence it was not necessary to pump out the mixture from the counter on changing sources. This feature also improved the counter stability. The counter plateau did not shift by more than 3 – 5 volts in six hours of operation. These variations were checked periodically and appropriate adjustments made in the counter voltage.

The relative intensities were determined with respect to the l-line of ThB. Three series of measurements were performed. Several conversion lines are shown in Figs. 4–5. The relative half-width depends on the $H\rho$ of the line up to $H\rho$ = 1000 gauss-cm. This effect may be due to scattering of electrons in the source and to a change in the magnetic field configuration.

The average values of $H\rho$ and the line intensities are shown in Table 4 (the lines for the Auger electrons are not included in the table). For comparison purposes, the same table shows the results of Ellis, Surugue, Arnoult, and Flammersfeld. It is apparent from the table that there is a marked difference in the relative intensities as compared with the work in which the photographic method for detecting elec-

TABLE IV. Spectrum of internal conversion electrons from radiothorium. $H\rho = 500 - 1380$ gauss-cm.

	Present work								Ellis		Surugue		Arnoult		Flammersfeld
Ellis designation	f, kc/sec	$H\rho$	E, keV	Transition	Z	Level	E_γ, keV	I	$H\rho$	I	$H\rho$	I	$H\rho$	I	I
A	284.25	534.21	24.510	CC''	81	L_I	39.854	4.31	536.50	—	534	0.27	534	0.55	
A_1	—	—	—	BC	83	K	115.14	—	538.95	—	536	0.009	538	0.023	4.07
Aa	288.00	541.40	25.159	CC''	81	L_{II}	39.854	0.395	542	—	541	0.027	541	0.055	
Ab	299.70	563.50	27.201	CC''	81	L_{III}	39.854	0.0343	564.53	—	563	0.005	563	0.009	—
B	346.97	652.40	36.153	CC''	81	M_I	39.854	0.997	652.57	—	652	0.18	652	0.37	0.69
Ba	—	—	—	CC''	81	M_{II}	—	—	655.45	—	655	0.005	655	0.009	
Bb	360.86	678.62	39.012	CC''	81	N	39.854	0.244	678.33	—	678	0.05	678	0.09	
Bb_1	—	—	—	—	—	—	—	—	—	—	680	—	—	—	0.171
Bc	364.26	685.05	39.728	CC''	81	O	39.854	0.0542	685.00	—	684	0.009	686	0.018	
$C2$	449.52	845.46	59.411	CC''	81	K	144.94	0.0029	841.5	0.013	845	0.009	841	0.015	—
Dg	547.79	1030.63	86.150	BC	83	K	176.671	0.0184	1027.1	0.017	1030	0.027	1021	0.073	—
Dh	—	—	—	—	—	—	—	—	—	—	1096	0.005	1060	0.009	—
E	589.74	1109.71	98.756	BC	83	L_I	115.142	0.1004	1106.6	0.099	1110	0.15	1101	0.12	0.123
Ea	591.93	1113.83	99.430	BC	83	L_{II}	115.139	0.0123	1110.4	0.009	1114	0.009	1105	0.009	
$Ea1$	—	—	—	—	—	—	—	—	—	—	1170	—	1144	0.009	
Eb	629.00	1183.72	111.139	BC	83	M	115.139	0.0224	1180.5	0.032	1183	0.027	1177	0.027	0.037
Eb_1	638.46	1201.55	114.204	BC	83	N	115.142	0.0070	1199.1	0.009	1202	0.009	1195	0.009	
	640.86	1206.08	114.986	BC	83	O	115.143	0.0027	—	—	—	—	—	—	—
$Et2$	—	—	—	—	—	—	—	—	1226.2	0.002	1226	—	1235	0.009	—
Ec	666.23	1253.92	123.380	$C''D$	82	K	211.38	0.0125	1251.1	0.013	1253	0.018	1247	0.018	—
Ec_1	—	—	—	—	—	—	—	—	1273.8	—	1295	—	1281	0.009	—
Ec_2	—	—	—	—	—	—	—	—	—	—	1323	—	—	—	—
E_d	730	1374	145.4	$C''D$	82	K	233.4	0.009	1370.8	0.009	1372	0.009	1364	0.009	—

trons was used. The differences between our data and the result of Flammersfeld are smaller. A number of lines which were detected in the photographic work were not seen in the present work since the sensitivity of the photographic method is higher.

The relative intensities of the conversion lines have been computed from the reading of the first counter. Since the cutoff energy of the film in the first counter was 4 kev, no corrections for absorption were introduced. According to Ref. 18, this effect is less than one percent for electron energies four or five times greater than the cutoff energy.

The accuracy in the relative intensity measurements for the conversion lines is 3–5 percent for the strong lines and 20–30 percent for the weak lines.

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SOVIET PHYSICS JETP VOLUME 5, NUMBER 3 NOVEMBER, 1957

Generation of Slow π-Mesons by Cosmic Ray Particles

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(Submitted to JETP editor July 20, 1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 690-696 (April, 1957)

Results of experiments on the transition effect of π-mesons are presented and discussed. The results presented allow one to conclude that low energy mesons are abundant in the spectrum of the generated mesons and that the plural mechanism of meson creation is correct. Most of the generating particles are probably cosmic ray neutrons.

1. SOURCES OF THE π-MESONS OBSERVED IN PHOTOGRAPHIC PLATES EXPOSED TO COSMIC RAYS

IN EXPERIMENTS, reported in Refs. 1-3, investigating the transition curve of π-mesons and the intensity of their generation as a function of the atomic weight of the target, no account was taken of the current of slow π-mesons from extraneous dense materials situated near the photographic plate or of the presence of π-mesons in the air. Both of these factors can influence the form of the transition curve.

Before embarking on an investigation of the transition effect of π-mesons and the intensity of their generation as a function of the atomic weight of the target, it is necessary to study the current of π-mesons coming from the air and from nearby extraneous dense absorbers. We set up special experiments for this purpose on a mountain top (altitude 4000 m).
A pair of photographic plates were exposed during the course of two months on a mast 10 m high, with