The L X-Ray Spectra from Radioactive Decay of Transuranium Elements*

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A bent crystal x-ray spectrometer is described, and some results are given on the analysis of L-series x-rays produced in radioactive decay processes of transuranium elements. There is generally good agreement between measured energy values of L-series lines and those predicted by the Moseley relationship. The relative intensities of the various lines produced in this case from γ-ray internal conversion, are compared with those emitted from uranium excited by electron bombardment and values reported of internal conversion excited x-rays in the region of lead.

I. INTRODUCTION

THE x-rays accompanying radioactive decay processes are capable of yielding a considerable amount of information on the nature of these processes. For some purposes simple detection may be adequate, but much potential information can come to light only if the x-ray spectra are resolved. As an example, spectrometry of x-rays enables one to distinguish between electron capture and isomeric transition processes and, in particular, to aid in the resolution of decay schemes for nuclei which undergo more than one mode of decay. In another study[1] the identification of x-rays has revealed an unsuspected electron-capture branching in the decay of Am^{242m}.

In many transitions the K-electron levels are "excited" and for these considerable information can be obtained from weak sources by absorption methods because of the simplicity of the K x-ray spectra. However, the complexity of L x-ray spectra renders absorption techniques largely ineffective; and a method capable of greater discrimination is needed. Among the heaviest elements, for which K-electron binding energies are around 100 kev, it would seem from the scanty data so far available that many of the decay processes do not excite the K level and that only L x-rays are observable.

It is with the measurement of the L x-ray spectra from the decay of heavy nuclei that the present communication is concerned. The method used is capable of a moderately high degree of precision and consists of diffraction separation using an oriented thin bent crystal. Since the x-rays examined were those of transuranium elements, the x-ray energies obtained are of interest in themselves, since it may be seen whether or not they agree with extrapolations from lower elements.

The x-rays with which the present report is concerned have their origin in the internal conversion of gamma-rays. In addition to the goals of x-ray spectrometry already mentioned, the measurement of relative intensities of various transitions as they are related to the relative conversion coefficients in the various levels are of obvious importance in understanding the process of γ-ray internal conversion. Kinsey[2] has reviewed the problem in the heavy element region, and in a second paper[3] gives data on ThC and RaD taken by absorption and coincidence counting methods. The data to be reported here are in some details at variance with the generalizations made from the observations on ThC and RaD.

The possibility of making a focusing x-ray spectrometer was examined originally by de Broglie[4] and by Darbord.[5] Later a more complete study of the practical aspects of the problem was made by DuMond and Kirkpatrick.[6] Shortly after this the first generally satisfactory instrument was devised by Cauchois,[7] and her approach is that which has been adopted by a number of others. The essential feature of a Cauchois instrument is the use of an elastically bent crystal to permit focusing of radiation with high resolution and without structural complications.

Abelson[8] was the first to use a bent crystal spectrograph to observe x-rays from a radioactive decay process, and among other measurements he identified molybdenum x-rays from the electron-capture decay of element 43 (technetium). Pool and co-workers[9] have made extensive use of this technique in their identification of radioactive species, as has the group at Zurich.[10] A large radius spectrometer has been built and used by DuMond[11] for precision measurement of photon energies from the conventional x-ray region into the range of a Mev.

The present report describes a bent crystal spectrometer and its use in determining the L x-ray spectra of two of the transuranium elements, neptunium, and

* This work was performed under the auspices of the AEC.
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[1] O'Kelley, Barton, Crane, and Perlman, Phys. Rev. **80**, 293 (1950).
[2] B. B. Kinsey, Can. J. Research **26A**, 404 (1948).
[3] Reference 2, p. 421.
[4] L. de Broglie, Compt. rend. **158**, 944 (1914).
[5] R. Darbord, J. phys. radium **3**, 212 (1922).
[6] J. W. M. DuMond and H. A. Kirkpatrick, Rev. Sci. Instr. **1**, 88 (1930).
[7] Y. Cauchois, J. phys. radium **3**, 320 (1932); **4**, 61 (1933).
[8] P. Abelson, Phys. Rev. **56**, 753 (1939).
[9] Edwards, Pool, and Blake, Phys. Rev. **67**, 151 (1945); J. E. Edwards and M. L. Pool, Phys. Rev. **72**, 384 (1947); K. D. Coleman and M. L. Pool, Phys. Rev. **72**, 1070 (1947).
[10] Marmier, Blaser, Preiswerk, and Scherrer, Helv. Phys. Acta. **22**, 155 (1949); **21**, 198 (1948).
[11] J. W. M. DuMond, Rev. Sci. Instr. **18**, 626 (1947).

plutonium. These x-rays arise from internal conversion of gamma-rays accompanying the alpha-decay of isotopes of americium and curium, respectively.

II. METHODS

The spectrometer used in the present studies was designed as a monochromator using a counter tube as detector. A scale drawing of the essential parts may be seen in Fig. 1 in which the sample (2), its collimator (4), the crystal (1), and the counter (9) with its collimator (8) are shown in line. The sample holder is mounted on an arm which rotates it on the focal circle of 5-inch radius facing the concave side of the crystal. As pointed out by DuMond,[11] if the counter is placed on the convex side and the source on the concave side, there is a considerable increase in efficiency over the opposite arrangement, since all x-rays from the source are incident upon the crystal at the appropriate angle for diffraction. The crystal used for the measurements to be reported was quartz 0.008 inch thick cut perpendicular to the 310 planes. A tool steel holder with an aperture $\frac{3}{4}$ in. long$\times\frac{1}{4}$ in. high and surfaces machined to a radius of 10 inches clamps the crystal so that its center is tangent to the focal circle and all crystal planes are directed at a point on the opposite side of the focal circle.

In operation on continuous sweep the motor (5) rotates the sample holder arm and at the same time rotates the detector arm so that the angles between crystal planes and sample and between crystal planes and detector are equal. An arrangement of metal bands turns the sample holder so that the sample and its defining slit always face the crystal aperture. The gear changing box (6), operating through the worm gear (7), permits selection of angular speeds of the sample arm of 1, 1/5, 1/20, and 1/100 degree per minute. The position of the sample arm is read on the scale by means of a vernier.

The counter is protected from stray radiation in several ways. The fine lead collimator (8) protects the counter tube from undiffracted x-rays passing through the crystal; in addition, the tube is placed in a lead cylinder and the fixed shield (10) gives still more protection against direct radiation from the sample. The counter used in the measurements to be reported was an end window proportional counter filled with xenon at a pressure of 55 cm Hg and methane at 15 cm. With no sample in place, the background counting rate was in the range 3 to 10 per minute, depending on the amount of activity in the adjacent laboratory. Incoherent scattering contributed an additional background of about $\frac{1}{2}$ percent of the total x-radiation observed. This low background counting rate was made possible by operating the tube in a pulse height selection circuit to discriminate against radiation not in the energy range of the x-rays under measurement.

Figure 2 shows a block diagram of the counting circuits. The tube is operated with the copper cathode

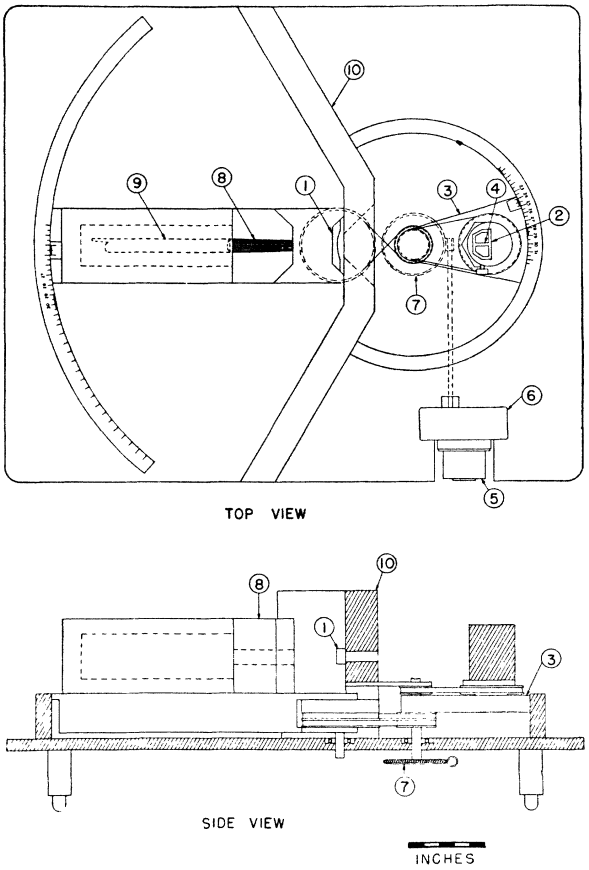

FIG. 1. Scale drawing of x-ray spectrometer.

shell at high voltage in order to simplify the coupling of the small pulses from the proportional counter to the preamplifier. The preamplifier is mounted on the counter housing and amplifies the counter pulse about one hundred fold. The pulse height discriminator which follows the second amplifier can be adjusted both in band width and pass band; and, as mentioned, it is used to eliminate pulses which are not in the range of those produced by the x-rays under measurement. The recording system following the third amplifier includes a scaling circuit, which actuates a recording Streeter-Amet Traficounter, and a counting rate meter connected to an Esterline-Angus graphic milliammeter. The diffraction angle is read and recorded manually on the Traficounter tape at intervals. Points on the milliammeter record chart and on the Traficounter tape are related reliably to the angular position of the sample since all three are driven by synchronous motors.

The method of converting the counting data to x-ray energies is based on the grating spacing of the 310 planes of quartz which was taken to be 1.178A. From the measured diffraction angle and Bragg's law, the wavelength is determined in Angstrom units; and this is converted to energy in kev units by the relation $E=12.395/\lambda$. An internal check on the value of the

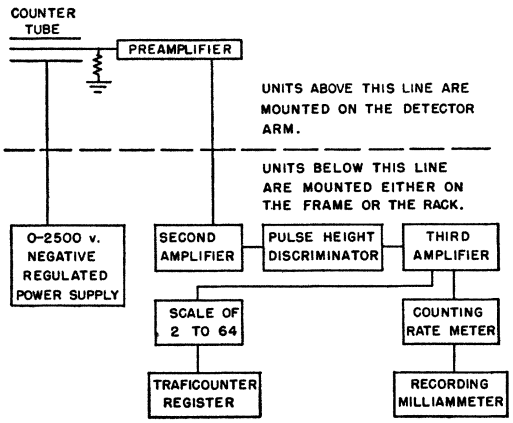

FIG. 2. Block diagram of electronic circuits for proportional counter detector of the x-ray spectrometer.

diffraction angle is obtained by observing it on both sides of the spectrometer zero point. Errors caused by inaccuracies in location of the sample or orientation of the crystal planes are eliminated in this manner. Other details of the methods will be found under discussion of the particular measurements.

III. RESULTS

It will be necessary to refer to the different components of the L x-ray spectra, and Fig. 3 shows a term diagram with the transitions observed in these studies designated according to the Siegbahn convention.[12] The particular levels shown are those for plutonium x-rays with energy values obtained by use of the Moseley relation:[13]

$$E^{\frac{1}{2}}=K(Z-\sigma).$$

The values for K and σ were calculated from the level energies of Th and U as given by Siegbahn.[14] The transition energies obtained in this manner have been used to identify the observed x-ray lines. The energies predicted for the major transitions from elements in the atomic number range 90 to 96 are listed in Table I.

A. Plutonium X-Rays from Decay of Cm^{242}

The isotope Cm^{242} is an alpha-particle emitter with 162-day half-life, prepared for the present study by the neutron irradiation of the 475-yr Am^{241} according to the following reactions:

$$Am^{241}(n,\gamma)Am^{242m}, \quad Am^{242m}\xrightarrow[16\text{ hr}]{\beta^-}Cm^{242}.$$

The alpha-decay of Cm^{242} includes fine structure in which roughly 20 percent of the disintegrations go to an excited state of Pu^{238} about 50 kev above the ground state.[15] The accompanying γ-ray transition is largely internally converted in the L-shell and the x-rays measured in this study are those resulting from the refilling of these L-orbit vacancies. The uncertainties in x-ray counting efficiencies allow an estimation of their number only between wide limits, but which for the present we take to be 10 L x-ray quanta per 100 alpha-disintegrations.

A sample[15a] of CmF_3 emitting about 3×10^8 x-rays per second was mounted in a quartz capillary tube making a line source about 1 cm long. This capillary tube was held vertically in a lucite holder in the sample housing. No sample collimator was necessary because of the good definition of the source.

Even so, it is likely that the resolution is limited by the sample width, since with similar samples not so homogeneous in their geometrical distribution, identical "fine structure" appeared in each line, which is interpreted as an image of the sample distribution.

The spectrometer was adjusted to sweep at a rate of 1/20 degree per minute and the counts in each 0.8-min interval were recorded. Figure 4 shows one segment of the spectrum including the $L\alpha_1$ and $L\alpha_2$ lines, in which both the spectrometer scale reading and the energy calibration are indicated. One unit of the spectrometer

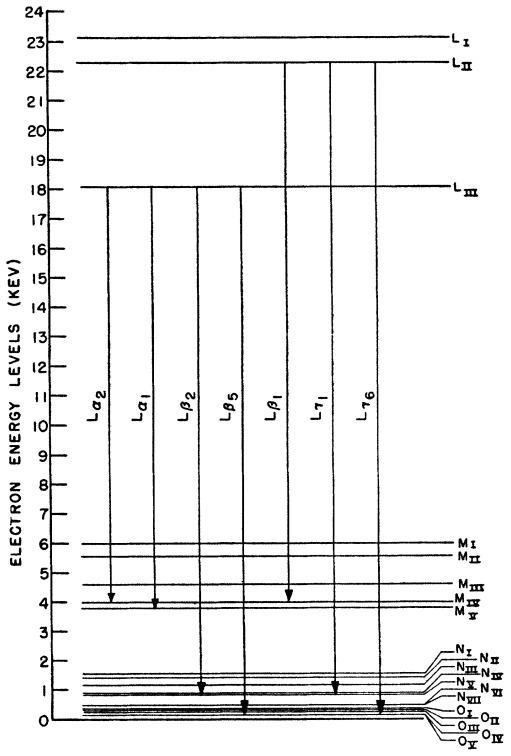

FIG. 3. Term diagram, in which x-ray energy levels in the plutonium transitions observed in this study are indicated.

[12] Compton and Allison, *X-rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935), p. 596.
[13] H. G. J. Moseley, Phil. Mag. 27, 703 (1914).
[14] M. Siegbahn, *Spektroskopie der Röntgenstrahlen* (Verlag. Julius Springer, Berlin, 1931).
[15] G. D. O'Kelley and W. W. T. Crane, unpublished work.
[15a] We are grateful to Mr. W. W. T. Crane for placing this sample of curium at our disposal.

TABLE I. Calculated *L*-series x-ray energies.

Line	Transition	Energy (kev) 90Th	91Pa	92U	93Np	94Pu	95Am	96Cm
1	$L_{III}-M_I$	11.14	11.39	11.64	11.90	12.16	12.42	12.69
α_2	$L_{III}-M_{IV}$	12.84	13.15	13.47	13.79	14.11	14.45	14.78
α_1	$L_{III}-M_V$	13.00	13.32	13.65	13.98	14.31	14.66	15.00
η	$L_{II}-M_I$	14.54	14.99	15.43	15.89	16.35	16.81	17.29
β_6	$L_{III}-N_I$	15.00	15.37	15.76	16.14	16.53	16.92	17.32
β_2	$L_{III}-N_{IV}$	15.62	16.01	16.42	16.82	17.29	17.66	18.08
β_4	L_I-M_{II}	15.67	16.14	16.61	17.09	17.58	18.07	18.57
β_5	$L_{III}-O_{II}$	16.24	16.67	17.10	17.54	17.98	18.44	18.89
β_1	$L_{II}-M_{IV}$	16.24	16.75	17.26	17.78	18.30	18.84	19.38
β_3	L_I-M_{III}	16.46	16.97	17.49	18.02	18.56	19.10	19.65
γ_1	$L_{II}-N_{IV}$	19.02	19.61	20.21	20.81	21.43	22.05	22.68
γ_2	L_I-N_{II}	19.34	19.93	20.53	21.13	21.75	22.37	23.00
γ_3	L_I-N_{III}	19.54	20.15	20.76	21.38	22.01	22.65	23.29
γ_6	$L_{II}-O_{IV}$	19.64	20.27	20.89	21.53	22.17	22.83	23.49

scale corresponds to 4 degrees displacement of the sample arm; therefore, the angle traversed between the two peaks shown is only about 0.6 degree.

Figure 5 shows curves obtained for the spectrum in the interval of approximately 14 to 22 kev, in which the two sections represent data taken on the two sides of the zero position. As mentioned, the mean diffraction angle obtained from scale readings on both sides of the zero position is the true value, even though misalignment of the sample or the crystal planes would introduce an error in each of the single position readings. In obtaining these curves a system of curve smoothing was employed which averaged over each five adjacent points and plotted the number so obtained at the center of the smoothing interval. The relative heights of the peaks do not reproduce faithfully the abundances of the emitted x-ray lines, because no corrections have yet been made for the differences in reflection coefficients, counter efficiencies, and several sources of absorption. These will be discussed further below.

Table II lists in the second and third columns the spectrometer scale readings corresponding to the lines of Fig. 5 for some of which there were two measurements. Another series of measurements has been made on a different curium sample and the results agree with those reported here both in energy of the lines and intensities. The last two columns of Table II give the angles of diffraction obtained from these readings and the corresponding energies. The level transition assignments of the lines were made by comparing with the calculated values listed in Table I. Table III compares our measured energy values for the *L*-series x-rays of plutonium (Table II) with those obtained by extrapolation and shown in Table I and with a set calculated by Monk and Allison,[16] who used a formula of Sommerfeld[17] derived by the old quantum theory.

Of interest are the intensity values listed in the last three columns of Table III. The column headed "uranium" gives relative intensities measured by Allison[18] from the electron bombardment of uranium. Comparing these values for uranium with similar measured ones for thorium indicates no gross changes with atomic number. The next column lists the observed intensities according to Fig. 5, and the last column, the corrected values normalized to the $L\alpha_1$ intensity taken to be 100. The corrections involved the following. The sample mounting, quartz crystal, and counter window were estimated to be equivalent to 150 mg/cm² alumi-

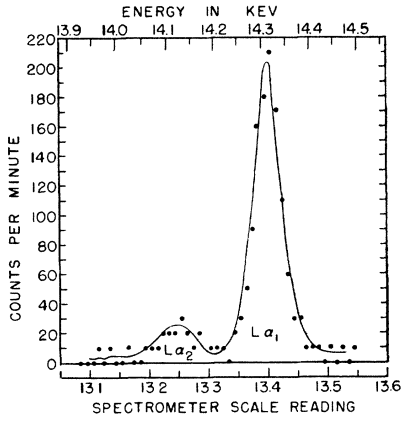

FIG. 4. $L\alpha_1$ and $L\alpha_2$ lines of plutonium from decay of Cm^{242}.

num for x-rays in this energy region, and absorption losses were calculated from the compilation of absorption coefficients by Allen.[19] The counting efficiency of the xenon tube for the different energy x-rays was estimated from calibrations by Crane and Ghiorso[20]

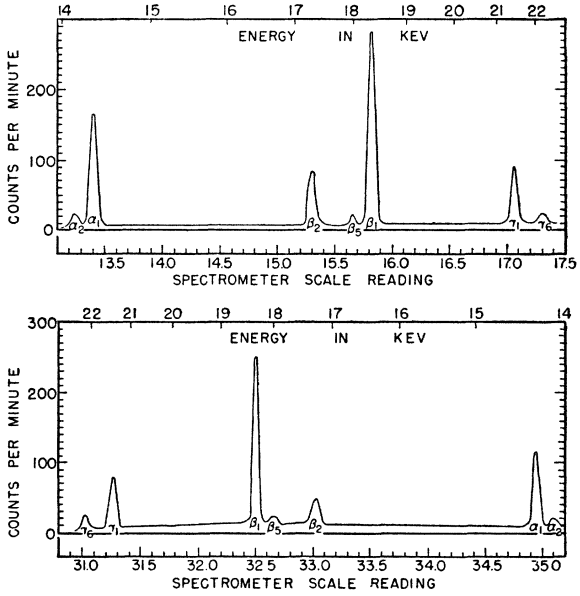

FIG. 5. *L*-series x-ray spectrum of plutonium following decay of Cm^{242}. (Upper and lower plots show identical spectra taken on two sides of spectrometer zero position.)

[16] A. T. Monk and S. K. Allison, Manhattan Project Metallurgical Laboratory Report CP-2120 (September, 1944) (unpublished).
[17] Compton and Allison, reference 12, p. 610.
[18] S. K. Allison, Phys. Rev. **30**, 245 (1927); **32**, 1 (1928).
[19] S. J. M. Allen, reference 12, p. 800.
[20] W. W. T. Crane and A. Ghiorso, unpublished work.

TABLE II. Plutonium L x-rays from Cm^{242} decay.

X-ray designation	Spectrometer scale reading First position	Second position	Angle of diffraction θ (degrees)	Energy (kev)
$L\alpha_1$		34.932 34.947		
	13.404	34.940	21.536±0.02	14.31±0.01
$L\alpha_2$	13.244	35.090	21.846±0.02	14.14±0.01
$L\beta_1$		32.500 32.495		
	15.830	32.497	16.667±0.02	18.35±0.02
$L\beta_5$		32.650 32.660		
	15.665	32.655	16.990±0.02	17.91±0.02
$L\beta_2$	15.305	33.020	17.725±0.02	17.28±0.02
$L\gamma_1$	17.065 17.067	31.262 31.250		
	17.066	31.256	14.190±0.02	21.46±0.04
$L\gamma_6$	17.315	31.025	13.710±0.02	22.20±0.04

and the reflection coefficient of the crystal is assumed to vary[21] as $1/E^2$.

It would not be expected that there should be agreement between all of the relative intensities of x-rays resulting from electron bombardment as compared with those from γ-ray internal conversion because of differences in the relative excitation of different L-levels. However, there should be agreement in the ratios of the different transitions arising from the same L-vacancy. If we normalize the α_1 intensities as in Table III, there is excellent agreement between uranium and plutonium intensities for the α_1, β_2, α_2, and β_5 lines, all of which are transitions involving the L_{III} level. However, those resulting from transitions to the L_{II} level (β_1, γ_1, and γ_6) are relatively twice as abundant for the internal conversion spectrum as for the electron bombardment spectrum. Furthermore, certain transitions involving the L_I level seen in moderate abundance in the electron bombardment source are missing, and therefore lower by at least a factor of 5 in the internal conversion source. From electron bombardment of uranium the ratio $L\beta_3/L\beta_1=0.085$, while the same ratio in our source is <0.016. Similar limits can be set for other lines representing L_I and L_{III} vacancies.

Kinsey[3] has used absorption methods to determine the L_{III} transitions as related to the sum of L_{II} and L_I transitions for internal conversion processes in RaD and ThC. The present results on the internal conversion of a γ-ray of an excited state of Pu^{238} show the ratio of L_{II} to L_{III} x-rays to be in the range reported by Kinsey; but the L_I x-rays were not detected, and a limit of *20 percent* of the number of L_I vacancies formed by electron bombardment could be set. This observation is not consistent with the assumption[2,3] that the L_I level is always most strongly excited in internal conversion. Almost certainly the relative incidence of vacancies is dependent upon both the energy of the γ-emission process and the selection rules, and differences are to be expected for different nuclei.

[21] Lind, West, and DuMond, Phys. Rev. **77**, 475 (1950).

B. Neptunium X-Rays from the Decay of Am^{241}

Through a mechanism similar to that in which plutonium x-rays are present following Cm^{242} alpha-decay, x-rays of neptunium result from the internal conversion of a gamma-ray from an excited state of Np^{237} following the alpha-decay of Am^{241}. The isotope Am^{241} has a half-life of somewhat less than 500 years, emitting alpha-particles measured as 5.45 Mev, a large fraction or all of which go to an excited state[22] of Np^{237}.

TABLE III. Comparison of predicted and observed energies and abundances in L-series x-rays of plutonium from alpha-decay of Cm^{242}.

Line	Transition	Energy (kev) Monk and Allison (ref. 16)	Calc. (this paper)[a]	Measured[b]	Intensity In uranium (ref. 18)	Observed here[c]	Corrected here[d]
α_1	$L_{III}-M_V$	14.30	14.31	14.31	100	160	100
β_1	$L_{II}-M_{IV}$	18.27	18.30	18.35	49.4	276	91
β_2	$L_{III}-N_V$		17.29	17.28	28	78	28
γ_1	$L_{II}-N_{IV}$		21.43	21.46	12	80	23
α_2	$L_{III}-M_{IV}$	14.11	14.11	14.14	11	20	13
β_5	$L_{III}-O_V$		17.98	17.91	6.4	16	6
β_3	L_I-M_{III}	18.55	18.56		4.2		
β_4	L_I-M_{II}	17.60	17.58		4.1		
1	$L_{III}-M_I$	12.12	12.16		3.4		
γ_6	$L_{II}-O_{IV}$		22.17	22.20	2.2	14	4
β_6	$L_{III}-N_I$		16.53		1.6		
γ_2	L_I-N_{II}		21.75		1.5		
γ_3	L_I-N_{III}		22.01		1.4		
η	$L_{II}-M_I$	16.28	16.35		1.0		
β_7	$L_{III}-O_I$		17.73		0.4		

[a] Calculated as explained for Table I and as listed there.
[b] Measured in this work. See Table II.
[c] See Fig. 5.
[d] Corrected as explained in text.

TABLE IV. Neptunium L x-rays from Am^{241} decay.

Line designation	Spectrometer scale reading First setting	Second setting	Angle of diffraction	Energy (kev) (Measured)	(Extrap.)
$L\alpha_1$	35.15	13.05	22.10±0.05	13.98±0.03	13.98
$L\beta_2$	33.12 33.15				
	33.14	15.05	18.09±0.06	16.94±0.05	16.82
$L\beta_1$	32.69 32.71				
	32.70	15.50	17.20±0.04	17.79±0.03	17.78

[22] Seaborg, James, and Morgan, National Nuclear Energy Series, Plutonium Project Record **14B**, *The Transuranium Elements: Research Papers*, paper No. 22.1 (McGraw-Hill Book Co., Inc., New York, 1949).

The resulting 62-kev transition is highly converted in the L-shell, giving rise to the L x-ray spectrum. The Am^{241} was prepared by neutron capture in plutonium resulting in the β^--emitter Pu^{241}, which decays to the desired product.[23]

[23] Ghiorso, James, Morgan, and Seaborg, Phys. Rev. 78, 472 (1950).

The measurements of the x-rays were made in a manner similar to that already described for the curium sample. However, the americium source was some ten-fold weaker, so that not so many lines could be seen, and relative intensities could not be estimated. The data for the three most intense lines ($L\alpha_1$, $L\beta_1$, and $L\beta_2$) are given in Table IV and energies compared with the estimated values as listed in Table I.

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The X-Ray Spectrum Produced by 322-Mev Electrons Striking a Platinum Target*

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(Received September 25, 1950)

The differential energy spectrum of the photons produced by 322-Mev electrons striking a 20-mil platinum target was measured by observing the energy of 3467 pairs produced in a one-mil thick lead foil in a Wilson cloud chamber in a magnetic field of 10,000 gauss. The spectrum is found to agree with that predicted by the Bethe-Heitler bremsstrahlung theory using a Thomas-Fermi model with suitable corrections for the thickness of the target. The energy of the 322-Mev electrons was determined by the spectrum of the photons observed in this experiment.

I. INTRODUCTION

THE Berkeley synchrotron produces 322-Mev electrons as estimated from the results of this experiment. These electrons make x-rays by striking a 20-mil thick platinum target inside the quartz vacuum chamber of the machine. The x-rays pass through 1.5 to 2 cm of quartz before reaching the air where practically all experiments are performed. This paper gives the energy distribution of the x-rays as obtained from the measurement of the energy of 3467 pairs produced in a 1-mil thick lead plate placed in the x-ray beam from the synchrotron.

II. APPARATUS

A 16-in. diameter Wilson cloud chamber with a magnetic field of 10,000 gauss was placed in the x-ray beam from the synchrotron, with its center 88.5 ft from the 20-mil thick platinum target of the synchrotron. A six-in. thick lead collimator, 35 ft from the target, collimated the x-rays so that they formed a beam at the chamber approximately 6.5 in. wide and 1 in. high. The beam entered the chamber through a 5-mil aluminum window and passed through a vertical lead plate 1-mil thick across the center of the cloud chamber. Electron-positron pairs were produced in the lead and the gas (a mixture of half argon and half helium with water and ethyl alcohol for the vapor) of the chamber. Only those pairs produced in the lead plate were used in the data given below.

The synchrotron gives a pulse of x-rays six times per sec which can be interrupted at suitable intervals by changing the timing of the high voltage on the synchrotron injector so that it fires too late to produce a beam. The procedure is to monitor the beam by means of a Zeus meter placed just out of the main beam. The beam is run steadily at some low value, interrupted for about a second before and after the pulse used by the cloud chamber. The timing sequence of the cloud chamber is synchronized with the x-ray signal in the following way. First the cloud chamber magnet is energized, reaching full field in 2.3 sec, at which time a ready signal is given so that the next pulse of the synchrotron magnet sends a signal to expand the chamber. The expansion is delayed so that the x-rays from the following pulse reach the chamber just after the expansion. The lights are flashed 0.035 to 0.045 sec after the arrival of the beam. Two General Electric FT-22 flash tubes charged to 1700 v with 250 μf of capacity each are used for illumination and the 127-mm focal length camera lenses were set at f:8 using Eastman Orthochromatic Linagraph film. Because of the early timing of the lights, it was necessary to open the lenses so as to give about four times the light usually required. This early timing and control of the temperature of the chamber to 0.1°C resulted in turbulence free pictures where the spurious radius of curvature was greater than 50 m.

T. C. Merkle, Jr., suggested that a mixture of argon and helium be used in the chamber for the following reasons. Argon gives a larger number of ion pairs per cm length of track than does helium but has the disadvantage of a low heat conductivity and, therefore, takes a long time to reach thermal equilibrium. By mixing in equal amounts of helium, which has a heat

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