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ABSTRACT

The beta decay of Pa^{233} was studied by means of high resolution permanent-magnet electron spectrographs, an iron-free beta spectrometer, and a curved-crystal gamma ray spectrometer. Measured conversion electron and photon relative intensities are used to determine conversion coefficients and to assign multipolarities and multipole mixing ratios for the transitions in U^{233}. The quantum assignments of the levels in U^{233} are considered, by comparisons of observed beta and photon branching ratios to those predicted by theory. Several new transitions were observed and some of these are used to postulate new levels in U^{233}.

THE ENERGY LEVELS OF U^{233}†

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INTRODUCTION

The energy levels of U^{233} have been studied by a number of workers, and the general features of the level scheme are well known. In their comprehensive review of the single particle levels of spheroidally deformed nuclei, Mottelson and Nilsson[1] have discussed these levels in terms of four intrinsic states, excited either by Coulomb excitation of U^{233}, alpha decay of Pu^{237}, or beta decay of Pa^{233}. The scheme as summarized by Mottelson and Nilsson is shown in Figure 1.

The electron and photon spectra of Pa^{233} were first seriously investigated by Hok et al.,[2] Keller and Cork,[3] and Brodie,[4] and, as a result of these studies the general features of the Pa^{233} decay scheme became known. A discussion of the U^{233} levels has been given by Newton,[5] who observed the Coulomb excitation of two rotational levels in U^{233}. More recently, and concurrently with this study, two other investigations of Pa^{233} decay have been reported, by Albouy and Valadares[6] and by Bisgård, Dahl, and Olesen.[7] The results of all these studies form a generally consistent picture of Pa^{233} decay.

A primary aim of this work was to obtain accurate measurements with high-resolution equipment of both the energies and intensities of the conversion electron and photon lines, in order that multipolarities, mixing ratios,

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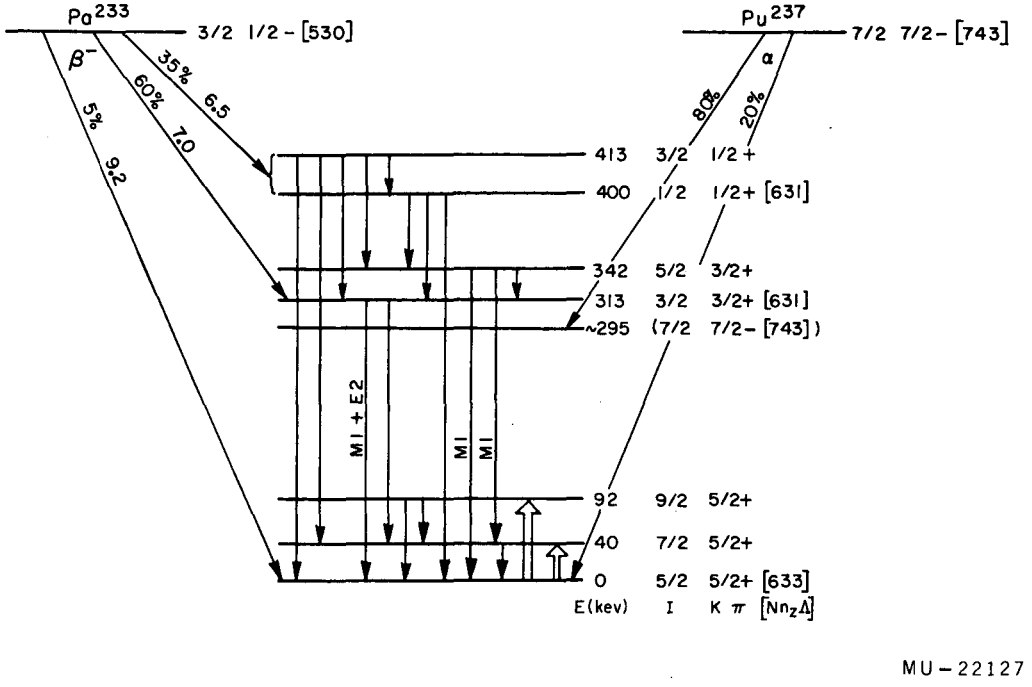

Fig. 1. Basic level scheme of U^{233} as summarized by Mottelson and Nilsson.[1]

and transition intensities could be obtained. Correlation of these data with the transition intensities predicted by the theory of Bohr and Mottelson[8] serves as a test of the quantum assignments of the nuclear energy levels of U^{233}. In addition, the ability to produce very intense sources of Pa^{233} by the neutron irradiation of Th^{232} and to study these sources with high-resolution equipment offered the hope of discovering weak, previously unobserved, transitions.

2. EXPERIMENTAL EQUIPMENT-ELECTRONS

The internal conversion spectrum was measured with several types of instruments: (a) Permanent-magnet 180° spectrographs with field strengths 50, 100, 215 and 340 gauss. The resolution obtained with these spectrographs is $\Delta\rho/\rho \sim 0.1\%$.

The relative intensities of the conversion lines recorded photographically by the permanent-magnet spectrographs on Eastman no-screen X-ray emulsion were obtained by two different means — densitometer tracings and visual estimates. The densitometer tracings were analyzed by the method of Mladjenović and Slätis.[9]

In some instances the ratio of background to line intensity was too high to permit an accurate analysis by means of densitometry. In these cases relative intensities were obtained from visual comparisons of plates exposed for different periods of time. Two photographic plates differing in exposure by a known factor were placed one on-top-of the other with emulsions touching, and were viewed over a diffuse source of light. Two lines that were to be analyzed were lined up beside each other and their relative intensities compared. If, under these conditions, the intensities of the lines appeared to be equal, then the absolute intensities of the lines were assumed to differ by the same factor as the exposures. By superimposing the plates in this manner differences in the backgrounds of the plates tend to cancel because both lines are viewed through the same background. This method proved so useful that a set of standard-intensity plates was prepared by making many exposures of a Pa^{233} source, the exposure time varying from 2 to 80 hours. In those cases in which comparison could be made the agreement between intensities obtained by densitometry and visual estimates was good to within 10%. In all cases corrections were made for instrument geometry (by multiplying by the radius of curvature of the electron path.[9]) for film efficiency, and for decay during exposure.

(b) A permanent-magnet pre-accelerating spectrograph, used to measure the low-energy conversion and Auger electron spectrum. The field strength of this instrument is 50 gauss, and it has been described by Albridge.[10]

(c) The Berkeley 25-cm. double-focusing spectrometer, with a G-M counter. Resolution of 0.3% was obtained.

(d) The 30-cm. iron-free double-focusing spectrometer located at

the Physics Institute, University of Uppsala, Sweden.[11] A resolution equal to or better than 0.14% was obtained with conversion lines of energy $\geq$ 65 kev, but because of source thickness, the resolution became poorer at lower energies (e.g., 0.24% at 23 kev). This instrument was used primarily for determinations of the relative intensities of the stronger internal conversion lines, as a check on the photographically determined intensities. In most cases the areas of the lines were assumed to be proportional to the peak heights. Recording was by a G-M counter with a 2-kev window cutoff.

3. EXPERIMENTAL EQUIPMENT-PHOTONS

The DuMond bent-crystal spectrometer Mark I,[12] located at the California Instiute of Technology, Pasadena, was used for precision measurements of the energies and intensities of the X-ray and gamma-ray spectra. Two different detector arrangements were used. The initial experiment employed a 3-inch diameter by 2-inch cylindrical sodium iodide crystal connected to a single-channel pulse-height analyzer with chart recorder. Later, a 5-inch diameter by a 3-inch cylindrical sodium iodide crystal was used with the single-channel analyzer for energy determinations and with a 100-channel Penco Gamma Analyzer for intensity measurements.

The instrument is such that the width at half maximum of the recorded peak ($\Delta\lambda$) is constant over the wave length range; $\Delta\lambda$ is of the order of 0.28 x-unit. The resolution, ($\Delta\lambda/\lambda$) varies with λ. The resolution is of order 0.2% at 100 kev and 0.9% at 400 kev. The transmission is approximately the solid angle subtended by an 0.008-inch source at 2 meters.

The gamma ray spectrum was also examined by use of a 100-channel Penco pulse-height analyzer with a 3 x 3-inch NaI(Tℓ) crystal. The resolution was 8% at 560 kev and 10% at 280 kev.

4. PREPARATION OF SOURCES

For the measurements performed in Berkeley, the Pa^{233} was prepared by neutron irradiation of 0.5-to 1.0 gm. quantities of Th^{232} metal foil in the Materials Testing Reactor at Arco, Idaho. The Uppsala sample was irradiated at the reactor in Kjeller, Norway.

The purification procedure for carrier-free protactinium was typically the following:

The thorium was dissolved in 10 M HCl and $\approx$ 0.1 M HF and the sample

passed through a Dowex A-1 column after the fluoride had been complexed with H_3BO_3. The protactinium was eluted with 3 M HCl, extracted from 6.9 M HCl into di-isopropyl ketone, and back-extracted into 2 M HCl. Again the protactinium was adsorbed onto a Dowex A-1 column from 10 M HCl and possible zirconium impurities eluted with 6.0 M HCl. The protactinium was then eluted in 9.0 M HCl and 0.1 M HF.

Sources used in the permanent-magnet spectrographs and in the Berkeley double-focusing spectrometer were prepared by electrodeposition onto 0.010-in.-diameter platinum wires; the Uppsala sample was electrodeposited onto a 0.2 mm tin wire. An ammonium fluoride electrolyte (pH 6.3) was used with a plating current of 100 to 150 ma. These sources varied in strength from 0.02 to 50 r/hr as measured by a beta-gamma survey meter at a distance of approximately 3 inches.

Two sources were prepared for the Pasadena bent-crystal spectrometer. The first was electroplated onto a 0.005-in.-diameter platinum wire in the manner described above. This wire was threaded into a 0.008-in. i.d. quartz capillary which was then sealed with a torch. The source was measured as greater than 100 r/hr of gamma activity at a distance of approximately 4 inches. Because x-ray emission of the platinum wire (induced by the intense beta source) proved troublesome, a second source was prepared without the wire. Approximately 3.5 mg of ThO_2 in a 0.008-in.-diameter quartz capillary was neutron-irradiated for two months in the Materials Testing Reactor, at a flux of $\sim 3 \times 10^{14}$ neutrons/cm^2/sec. The irradiated ThO_2 in the capillary was itself used as the spectrometer source without chemical treatment.

5. CONVERSION-ELECTRONS — EXPERIMENTAL DATA

The Pa^{233} conversion-electron data, taken on the Berkeley permanent-magnet spectrographs and the Uppsala iron-free spectrometer, are summarized in Table I. The unassigned lines, listed in Table IX, are discussed separately. Most of the electron lines listed in Table I were detected by means of the conventional permanent-magnet spectrographs; however, the lines of the 17-kev transition and the L lines of the 28-kev transition were detected with the pre-accelerator spectrograph.[10] The relative precision of measurement of the energies of lines taken on a single spectrograph is within 0.1% except for extremely weak or extremely strong lines. The selected transition energies listed in Table I were chosen as most representative of the data; they are

Table I

Pa^{233} conversion-electron data

Electron energy (kev)	Conversion shell	Transition energy[a] (kev)	Selected transition energy[b] (kev)	Conversion-electron intensities[c] (percent beta decay) Berkeley P.M.	Uppsala Iron-Free	Selected value	Remarks
11.72	M_I	17.27					
12.07	M_{II}	17.25					
12.96	M_{III}	17.26					
15.78	N_I	17.22					
15.97	N_{II}	17.24					
			17.26				
6.76	L_I	28.52					
7.57	L_{II}	28.51					
11.37	L_{III}	28.53					
23.01	M_I	23.56		1.9	1.7	1.7	
23.37	M_{II}	28.55		0.94	0.47	0.47	
24.26	M_{III}	28.56		1.0	--	0.52	
27.06	N_I	28.50					
27.22	N_{II}	28.49					
27.50	N_{III}	28.54					
28.25	O_I	28.57					
			28.54				
18.62	L_I	40.38		1.1	--	0.96	
19.42	L_{II}	40.36		4.2	--	3.7	
23.15	L_{III}	40.31		3.1	2.7	2.7	
34.73	M_I	40.28					
35.10	M_{II}	40.28		0.70	--	0.70	
35.96	M_{III}	40.26		0.78	--	0.78	Masks 58-L_I
38.99	N_{II}	40.26					
39.24	N_{III}	40.28					
40.06	O_{II}	40.31					
			40.29				
36.92	L_{II}	57.86					L_I line masked by 40-M_{III}

Table I (continued)

Electron energy (kev)	Conversion shell	Transition energy[a] (kev)	Selected transition energy[b] (kev)	Conversion-electron intensities[c] (percent beta decay) Berkeley P.M.	Uppsala Iron-Free	Selected value	Remarks
40.74	L_{III}	57.90					M_{III} line
			57.90				masked by 75-L_I
53.37	L_I	75.13		8.2	8.6	8.6	Masks 58-M_{III}
54.14	L_{II}	75.08		1.1	1.2	1.2	
58.01	L_{III}	75.17		0.12	--	0.13	
69.57	M_I	75.12		2.5	2.1	2.1	Masks 87-L_{III}
69.90	M_{II}	75.08					
70.81	M_{III}	75.11					
73.65	N_I	75.09		0.78	--	0.78	
73.82	N_{II}	75.09					
74.77	O_I	75.09		0.31	--	0.31	
75.06	P_I	~75.1					
			75.13				
64.75	L_I	86.51		9.6	9.4	9.4	
65.50	L_{II}	86.44		1.2	1.3	1.3	
	L_{III}			--	0.26	0.26	Masked by 75-M_I
80.85	M_I	86.40		2.8	2.6	2.6	
81.14	M_{II}	86.32		0.47	0.58	0.58	
	M_{III}			--	0.13	0.13	Masked by 103-L_I
84.93	N_I	86.37		0.73	--	0.73	
86.05	O_I	86.37		0.18	--	0.18	
			86.45				
81.91	L_I	103.7		2.7	2.6	2.6	Masks 86-M_{III}
82.68	L_{II}	103.6		0.39	0.47	0.47	
86.37	L_{III}	103.5		0.11	0.10	0.10	
98.11	M_I	103.7		0.81	--	0.81	
98.39	M_{II}	103.6					
99.36	M_{III}	103.7					

Table I (continued)

Electron energy (kev)	Conversion shell	Transition energy[a] (kev)	Selected transition energy[b] (kev)	Conversion-electron intensities[c] (percent beta decay) Berkeley P.M.	Uppsala Iron-Free	Selected value	Remarks
102.2	N_I	103.7		0.36	--	0.36	
103.3	O_I	103.7					
			103.6				
155.8	K	271.4		0.057	--	0.057	
250.6	L_I, L_{II}	271.5		0.055	--	0.055	
254.4	L_{III}	271.5		≦ 0.042	--	≦0.042	
266.0	M_I, M_{II}	271.6					
269.9	N_I, N_{II}	271.3					
			271.5				
184.4	K	300.0		5.5	5.2	5.2	
278.1	L_I	299.9		1.3	1.1	1.1	
278.5	L_{II}	299.4		0.14	0.16	0.16	
	L_{III}			(est. 0.014)	--	--	Masked by 398-K
294.4	M_I	299.9		0.31	0.32	0.32	Masks 311-L_{III}
298.3	N_I	299.7		0.083	--	0.083	
300.0	O_I	300.3		(est. 0.024)	--	--	Masked by 416-K
			299.8				
196.2	K	311.8		22	27	27	
289.7	L_I	311.4		4.8	6.3	6.3	
290.7	L_{II}	311.6		0.57	0.59	0.59	
	L_{III}			(est. 0.021)	--	--	Masked by 300-M_I
306.3	M_I	311.9		1.5	1.5	1.5	
306.9	M_{II}	312.1		--	--	--	
310.0	N_I	311.4		0.52	--	0.52	
311.4	O_I	311.8		0.13	--	0.13	
			311.7				
224.9	K	340.5		2.6	2.6	2.6	
318.5	L_I	340.3		0.57	--	0.57	
319.5	L_{II}	340.5		0.073	--	0.073	
323.0	L_{III}	340.1		--	--	--	

Table I (continued)

Electron energy (kev)	Conversion shell	Transition energy[a] (kev)	Selected transition energy[b] (kev)	Conversion-electron intensities[c] (percent beta decay) Berkeley P.M.	Uppsala Iron-Free	Selected value	Remarks
334.8	M_I	340.3		0.18	--	0.18	
339.5	N_I	340.9		0.073	--	0.073	
340.1	O_I	340.4					
			340.3				
259.9	K	375.5		0.078(0.055)[e]	0.043	0.043	
353.6	L_I	375.3		[0.023][f]	--	0.012	
354.2	L_{II}	375.2		[0.047]	--	0.025	
358.4	L_{III}	375.5		[0.023]	--	0.012	
369.8	M_I	375.4					
			375.5				
282.7	K	398.3		0.10(0.073)[e]	--	0.073	Masks 300-L_{III}
376.6	L_I	398.3		[0.044][f]	--	0.022	M_{III} line masked by 416-L_I,L_{II}
377.3	L_{II}	398.3		[0.075]	--	0.039	
381.3	L_{III}	398.4		[0.024]	--	0.012	
			398.3				
300.0	K	415.6		0.26(0.18)[e]	0.18	0.18	Masks 300-O_I
393.7	L_I	415.5		[0.078][f]	--	0.036	Masks 398-M_{III}
394.4	L_{II}	415.3		[0.055]	--	0.025	Masks 398-M_{III}
398.3	L_{III}	415.4		[0.015]	--	0.0068	
410.0	M_I	415.5					
413.8	N_I	415.3					
			415.6				

a. Electron binding energies were taken from Hill et al., Reference 13.

b. Selected values are weighted averages of the experimental values.

c. Measured relative intensities have been converted to absolute values by a method described in the text.

e. Normalized to K(416) = 0.18. See text.

f. Square brackets indicate an uncertainty in the normalization factor used for these values. See text.

weighted averages of several determinations.

Only relative conversion-electron intensities were determined directly in this work. The absolute intensities listed in Table I are obtained by a normalization procedure described in Section 9. The intensities listed from permanent-magnet spectrograph plates are averages of from two to seven visual estimates and, when possible, two or three densitometer traces.

In a few cases two different conversion lines arising from different transitions overlap. In these cases the intensities of the two lines were estimated from the assigned multipolarities of the transitions. The estimated intensity of the weaker component was then subtracted from the total measured intensity to give the final intensity for the stronger component. Estimated values are listed in Table I in parentheses. The electron intensities reported here are probably accurate within ~15% for the strong and medium lines and within a factor of two for the weak lines.

Relative conversion-electron intensities were also obtained with the Berkeley double-focusing spectrometer. These data are listed in Table II along with the results of other measurements. The relative intensities in Table II have been normalized to absolute intensities by the method described in Section 9. Column 1 lists the energies of the peaks recorded by the double-focusing spectrometer and column 2 the conversion lines which, on the basis of energy and resolution considerations, are included in the peak. For the low-energy electron lines window-absorption corrections were made by use of the curves of Saxon for nylon films.[15] No corrections were made for source absorption which, for the low-energy lines, might have been appreciable, since the source used in the spectrometer was not entirely mass-free. Most values in column 6 of Table II are the averages of from one to four separate determinations; parentheses indicate the value is that of a single determination only or that the value is uncertain for some reason.

The intensity values listed in columns 7 and 8 were obtained by summing the intensities obtained by means of the high-resolution instruments (Table I, columns 5 and 6) for the conversion lines comprising the peaks. Columns 3, 4, and 5 are relative intensities reported previously by other investigators, normalized to a value of 26 for the K line of the 312-kev transition. The intensity of the K line of the strong 312-kev transition was difficult to determine in many of our experiments because of the intense sources used; therefore columns 6, 7, and 8 are normalized to a value of 2.6 for the K line

Table II

The decay of Pa^{233} – comparison of experimental conversion line intensities

E(e)[a] (kev)	Conversion lines[b]	Intensities (normalized to percent beta decay)[c]					
		Elliott and Underhill[d]	Brodie[e]	Hok and Kramer[f]	This work (Berkeley double-focusing spectrometer)[g]	This work (Berkeley P.M. spectrographs)[h]	This work (Uppsala iron-free spectrometer)[h]
18.3	40-L_I,L_{II}	--	1.3	--	1.9	5.3	--
21.5	40-L_{III}; 28-M	--	2.6	--	4.2	6.9	4.9
25.9	28-N	--	0.39	--	0.79	--	--
34.8	40-M	--	--	--	2.5	1.5	--
39.2	40-N,0;(58-L_{III}?)	--	--	--	0.89	--	--
53.3	75-L_I,L_{II}	5.2	5.5	5.2	12	9.3	9.8
64.7	86-L_I,L_{II}	6.2	4.6	(7.5)	(15)	11	11
69.7	75-M	1.3	0.26	(1.8)	2.4	2.5	2.1
74.0	75-N, 0	--	--	0.078	(1.2)	1.1	--
81.9	86-M;103-L_I,L_{II}	--	--	3.5	6.3	6.4	6.4
84.5	86-N, 0;103-L_{III}	--	--	0.78	0.78	1.0	--
98.8	103-M	0.78	0.52	0.78	0.86	0.81	--
102	103-N, 0	--	--	0.21	0.36	0.36	--
186	300-K	2.6	1.0	5.7±0.52	(6.0)	5.5	5.2
197	312-K	[26]	[26]	[26]	--	22	27
225	340-K	2.6	2.1	2.6	[2.6]	[2.6]	[2.6]
260	375-K	--	--	--	(0.039)	0.078	0.043
278	300-L_I,L_{II}	--	--	0.91	1.1	1.4	1.3

Table II (continued)

Ee^- [a] (kev)	Conversion lines [b]	Intensities (normalized to percent beta decay) [c]					
		Elliott and Underhill [d]	Brodie [e]	Hok and Kramer [f]	This work (Berkeley double-focusing spectrometer) [g]	This work (Berkeley P.M. spectrographs) [h]	This work (Uppsala iron-free spectrometer) [h]
281	300-L_{III}; 398-K	--	--	--	(0.31)	0.10	--
291	312-L_I, L_{II}	6.5	6.5	5.2	(6.0)	5.4	6.9
293	300-M; 312-L_{III}	--	--	--	0.29	0.33	0.32
300	415-K; 300-N, O	--	--	--	0.29	0.37	--
306	312-M	--	--	1.2	1.2	1.5	1.5
310	312-N, O	0.65	<1.0	0.39	0.44	0.65	--
320	340-L_I, L_{II}			0.47	0.49	0.64	--
335	340-M	--	--	0.13	0.12	0.18	--
342	340-N, O	--	--	--	0.065	0.073	--
357	375-L	--	--	0.026	0.049	0.093	--
378	398-L	--	--	0.039	(0.034)	0.14	--
399	416-L	--	--	0.065	0.065	0.15	--
411	416-M	--	--	0.026	(0.020)	--	--

a. Ee^- is the approximate energy of the peak shown in the double-focusing-spectrometer spectrum. Only peaks whose intensities were measured by the spectrometer of this work have been listed for comparison.

b. The conversion lines listed are those whose energies (as determined by the permanent-magnet spectrographs) fall within the limits of the spectrometer peak.

c. The intensities are normalized to a value of 26 for the K line of the 312-kev transition with the exception of the Berkeley and Uppsala work, whichare normalized to a value of 2.6 for the K line of 340-kev transition. This normalization converts the relative intensities to percent beta decay, as discussed in the text.

Table II (continued)

d. Reference 14.

e. Reference 4.

f. Reference 2.

g. These values are the averages of from one to four determinations with the double-focusing spectrometer. Lines for which only one determination was made or which are uncertain for some other reason are enclosed in parentheses.

h. These values are the intensities determined from the higher-resolution equipment. They are the sums of the intensities of the individual conversion lines appearing in the peak.

of the 340-kev transition. In most cases the agreement between the intensity values obtained in this work by the spectrometers and the photographic spectrographs is within 30%; however, the agreement between these values and those of previous investigations is in general poor.

In general, the intensity data of the Berkeley double-focusing spectrometer have been used only as a check on the precision of the spectrographically determined intensities. The high resolving power of the spectrographs makes possible the individual determination of the intensities of many lines that are unresolved by this double-focusing spectrometer.

The intensities of the stronger conversion lines were measured with the iron-free double-focusing spectrometer[11] at the University of Uppsala, Sweden. Because of the extremely thin G-M counter window used, there was no necessity for window absorption corrections; however source absorption effects might not have been negligible, as evidenced by the poorer resolution obtained with the low-energy lines. These intensities, which are normalized to a value of 2.6 for the K-line of the 340-kev transition, agree within 10% in most cases with the photographic plate data (Table I and II). This agreement speaks well for the comparative visual method of intensity measurement used with the photographic plates and lends confidence to the intensities of those lines which were measured only in the permanent-magnet spectrographs. Thus, although the iron-free spectrometer intensity values were chosen as the "final values" in most cases, there would be no appreciable difference in the interpretation of the decay scheme were the photographic intensity data used exclusively.

More than half of the conversion lines were not measured in the iron-free spectrometer; for example, the weaker members of L and M subshell groups. In these cases the relative subshell intensities obtained from the photographic plates were taken as "final" with a normalization of the intensity of the strongest subshell line to the iron-free spectrometer value.

The interpretation of the two highest energy levels in U^{233} depends strongly on the assignments of multipolarities to the 375-, 398-, and 415-kev transitions. These multipole assignments in turn depend upon the measured intensities of the conversion lines of these transitions. Because of the importance of these intensity values and of the difficulty in obtaining them, the following special comments are made:

The intensity of the 416-kev K line has been well established by the

Uppsala iron-free spectrometer and the Berkeley double-focusing spectrometer. In the Berkeley double-focusing spectrum this line is not resolved from the N and O lines of the 300-kev transition; however, corrections were made for the intensity of these interfering lines by means of the spectrographic data. A corrected average of 0.18 was obtained from four spectrometer measurements. The value is probably accurate to within 15%, and coincides with the iron-free value of 0.18.

In obtaining the intensities of the three high-energy K lines by means of the photographic spectrum, a special effort was made to insure that the measured intensities of the lines relative to one another were as precise as possible so that a normalization of these intensities to a value of 0.18 for the 416-kev K line would be justified. The values so normalized are given in parentheses in Table I next to the measured values. It is seen that for the K-line of the 375-kev transition there is reasonable agreement between the normalized value and the iron-free spectrometer value. For this reason, the normalized intensity value for the K line of the 398-kev transition (not measured at Uppsala) is taken as the final value. The intensity of this line as measured by the Berkeley spectrometer is highly uncertain because in the lower-resolution spectrum the line lies between two fairly intense conversion lines.

The intensities of the L lines of the 375-, 398-, and 416-kev transitions were determined from the photographic spectrographs but were not measured in the Uppsala iron-free spectrometer. The intensities of these nine lines relative to one another are probably fairly precise; however, there was difficulty in normalizing these values to the intensity scale used for reporting the data (i.e., to a value of 2.6 for the 340-kev K line). This difficulty arises from the fact that the lines in question are quite weak, so that the lower-energy portion of the photographic plate on which the lines are seen is extremely dark, hence it was difficult to observe a line of known intensity so that the normalization could be effected. Because of these uncertainties the intensities of these lines listed in Table I are enclosed in square brackets. The L-subshell ratios of these lines are not affected by this normalization uncertainty.

Fortunately, it was possible to bring about a normalization of these lines in an indirect manner. The values of the total intensities of the L lines of the 375- and 416-kev transitions measured by the Berkeley double-

focusing spectrometer (Table II) are fairly precise (i.e., in each case three individual measurements agree with their average to within 20%). The values (0.049 and 0.065, respectively) indicate that the spectrographically determined values are too large by a factor of approximately two; hence the spectrographically determined intensity values for the 375- and 416-kev L lines have been normalized to bring about agreement with the total L values measured by means of the Berkeley double-focusing spectrometer. The spectrographically measured intensities of the 398- kev L lines have likewise been corrected by dividing by a factor of two. (The value of 0.034 for the intensity of the 398-kev L line, as measured by the Berkeley spectrometer, is uncertain.) These corrected values are listed as the selected values in Table I.

The intensities of the conversion lines of the 40-kev transition are also of special importance in the interpretation of the decay scheme (see Section 10). For this reason it is worth while to mention the accuracy with which the intensities of the low-energy electron lines have been determined. For the intensities of the conversion lines of the 28- and 40-kev transitions the spectrographically determined values of this work are subject to large errors due to film efficiency corrections and to line broadening which makes visual estimates difficult; hence these values are probably not accurate to better than a factor of two. The values obtained with the Berkeley double-focusing spectrometer could also be in error by a factor of two.

The intensities of the low-energy electron lines as measured in the Uppsala spectrometer from the peak heights of the lines are probably the most accurate; however, these values, too, are subject to large uncertainties. These uncertainties are evidenced by the fact that the resolutions obtained for the 40-kev L_{II} and L_{III} lines were 0.42% and 0.24%, respectively, as compared with a typical 0.1% for lines of higher energy. Such line broadening at low energies was undoubtedly due to absorption effects. For these reasons we believe that the selected values of the intensities of the conversion lines with energies less than approximately 50 kev may be too small by as much as a factor of two.

6. PHOTONS — EXPERIMENTAL DATA

The gamma-ray and x-ray data taken on the Pasadena bent-crystal spectrometer are listed in Table III. The method of determining the energy of an observed photon is described fully by DuMond.[12] The limits of error quoted

Table III

Pa^{233}: photons measured with the Pasadena bent-crystal spectrometer

Gamma rays

Energy (kev)		Intensity (percent beta decay)			
This work	Browne[a]	Pt wire source	ThO_2 source	Average	Browne[a]
	28.67 ± 0.02				0.060
40.35 ± 0.01	40.47 ± 0.1	0.015		0.015	0.048
41.65 ± 0.02		(weak)			
75.28 ± 0.01	75.4 ± 0.2		0.82	0.82	1.3
86.59 ± 0.01	87.0 ± 0.3	2.0	1.5	1.7	[1.7]
103.86 ± 0.02		0.62	0.70	0.66	
145.42 ± 0.05			0.44	0.44	
271.62 ± 0.23		0.33	0.25	0.29	
300.20 ± 0.24		6.0	6.5	6.3	
311.91 ± 0.13		[34]	[34]	[34]	
340.51 ± 0.18		3.9	3.8	3.9	
375.35 ± 0.32		0.51	0.61	0.56	
398.57 ± 0.40		1.1	1.0	1.1	
415.87 ± 0.42		1.4	1.6	1.5	

X-rays

Energy (kev)		Intensity (percent beta decay)					Transition
This work	Accepted[b]	Pt wire source	ThO_2 source	Average	Browne[a]	Beckman[c]	
Uranium							
94.655	94.664	9.5	8.3	[8.8]	[8.8]	8.8	$K\text{-}L_{II}(K\ \alpha_2)$
98.441	98.442	18	14	16	17	16	$K\text{-}L_{III}(K\ \alpha_1)$
110.421	110.428	2.3	1.1	1.7		2.3	$K\text{-}M_{II}(K\ \beta_3)$
111.297	111.307	4.1	3.4	3.8		4.4	$K\text{-}M_{III}(K\ \beta_1)$
114.502	114.568	1.5	2.0	1.7		2.0	$K\text{-}N_{II}, N_{III}$ $(K\ \beta_2)$
115.405	115.412	0.42	0.42	0.42		0.48	$K\text{-}O_{II}, O_{III}$

Table III (continued)

X-rays						
Energy (kev)		Intensity (percent beta decay)				Transition
This work	Accepted[b]	Pt wire source	ThO_2 source	Average	Browne[a]	Beckman[c]	
Platinum							
65.127	65.122						$K\text{-}L_{II}$ ($K\alpha_2$)
66.861	66.831						$K\text{-}L_{III}$ ($K\alpha_1$)
75.292							75-kevγ+ $K\beta_3$
75.754	75.749						$K\text{-}M_{III}$ ($K\beta_1$)

a. Reference 16.

b. Reference 17.

c. Reference 18.

are based upon estimates of the precision with which the center positions of the line profiles were determined. The agreement between the measured and accepted energies of the uranium and platinum K x-rays[17] indicates that the accuracy of the energy measurements is good.

The photon relative-intensity values listed were obtained by positioning the source at the angular position determined during the energy measurements as the profile center, and recording the photon peak with the pulse-height analyzer. The pulse-height analyzer is used in order to reduce the background counting rate. The values obtained by means of the wire source and the single-channel analyzer, and those obtained with the ThO_2 source and the 100-channel analyzer are listed in Table III.

These intensities have been corrected for detector efficiency and the photopeak-to-total ratio.[19] Corrections were made for absorption in the source, SiO_2 capsule, air between source and detector, and the aluminum cover of the detector crystal. With the exception of the source absorption these corrections were made by the direct use of the exponential attenuation equation and the attenuation coefficients of Grodstein.[20] A graphical integration method was used to calculate the source absorption.[10]

The largest correction applied to the gamma-intensity data arises from the energy dependence of the reflectivity of the quartz crystal. When the spectrometer is adjusted to accept photons of a given energy, not all the

photons of this energy that strike the bent crystal are diffracted toward the detector. Lind et al.[21] have reported that for a bent quartz crystal the ratio of the diffracted beam to the incident beam (the reflection coefficient) is proportional to $1/E^2$. This energy-dependent correction was applied to the data in Table III by multiplying each photon intensity by $(E_\gamma/E_{340})^2$ in order to normalize the intensity to that of the 340-kev transition. The 340-kev transition was chosen as the norm because it is near the middle of the energy range investigated and because the majority of the gamma rays observed were of energies close to 340 kev. The magnitude of the correction factor varies from 0.014 for the 40-kev transition to 1.49 for the 416-kev transition.

The averages of two intensity determinations (listed in Table III) have been chosen as the final values. All the intensity data listed in Table III have been normalized to the conversion-electron relative-intensity data by means of the theoretical K-conversion coefficient of the 312-kev transition (see Section 8). The photon intensities have also been placed on an absolute basis of percent beta decay by a means described in Section 9.

Gamma-ray data published by Browne[16] are also presented in Table III. The energy data of Browne are in reasonably good agreement with the data of this work; however, the relative intensities of the low-energy gamma rays are not in agreement. For the purpose of comparison the intensity data of Browne were normalized by means of the 87-kev photon intensity. The values of this work and of Browne, so normalized, deviate considerably at lower energies. This deviation is such that the ratio of Browne's intensities to those of this work, for photons of lower energy than 87 kev, varies linearly with energy, suggesting a systematic error in one of the sets of data. The cause of the deviation is unknown.

In Table III uranium K-x-ray relative-intensity data of Beckman[18] and of Browne[16] are also listed, normalized to a value of 8.8 for the K α_2 line. The relative intensities of this work are seen to be in close agreement with those of the previous workers.

Since the intrinsic line widths of X-rays are greater than those of gamma rays, it is necessary to normalize differently X-ray and gamma ray intensities determined by peak heights. The normalization of the K X-ray intensities was done so as to make the total intensity equal to 34% of the beta disintegrations. This value for the total X-ray intensity was measured independently, as follows.

(a) The total K-conversion line intesity is 35.1%. Correcting for the fluorescence yield (0.963), the total K x-ray intensity becomes 34%.

(b) The total intensities of the KLL Auger lines were measured[10] as 0.68% per beta disintegration (including estimates of 0.02% and 0.08% for the unobserved $KL_{II}L_{II}$ and $KL_{III}L_{III}$ lines). From the tables of Wapstra et al.[17] we take the ratio KLY/KLL and KXY/KLL to be 0.7 and 0.05, respectively, for Z=90, and calculate the total K-Auger intensity to be 1.2%. The K x-ray intensity is therefore 1.2/(1-0.963) = 32%.

7. THE 312-KEV MAGNETIC DIPOLE TRANSITION

From a measurement of L-subshell conversion ratios and K-conversion coefficient, the multipolarity of the 312-kev transition is determined to be essentially pure magnetic dipole. These data are: The L_I/L_{II} ratio, determined with the iron-free spectrometer, is 10.5 ± 1. The theoretical value[22] (Table IV) for M1 radiation is 10. E2 admixture would lower the observed L_I/L_{II} ratio markedly, because E2 radiation favors L_{II} conversion. The error limit as given would indicate a maximum of 3% E2 admixture in this transition.

A more sensitive indication of the extent of E2 admixture should be given by the L_I/L_{III} ratio, but here unfortunately the L_{III} line is unresolved from the much stronger 300-kev M_I line. We find that the intensity ratio $(300\ L_I)/(300\ M_I + 312\ L_{III})$ is 3.4, which is about the value expected for the L_I/M_I ratio of the 300 kev transition alone; thus the contribution of the 312-kev L_{III} line to the composite line must be quite small. A quantitative estimate of the amount of 312-L_{III} in the composite line yields the result that E2 admixture in the 312-kev transition lies between zero and 5%.

An experimental measurement of the K-conversion coefficient of this transition was also made, with four samples of varying strengths, by use of a thick-lens spectrometer and a 100-channel scintillation spectrometer. The photon spectrum is shown in Fig. 2. Normalization between the two instruments was effected with the 570-kev transition of Bi^{207}, whose conversion coefficient is known (α_K=0.017).[23] Our experimental value, 0.8 ± 0.3, is consistent with the interpretation of this transition as pure M1, but is not accurate enough for use in any quantitative way. The theoretical M1 conversion coefficient for a 312-kev transition in Z=92 is given as 0.79 by Rose[22] and as 0.72 by Sliv and Band[24].

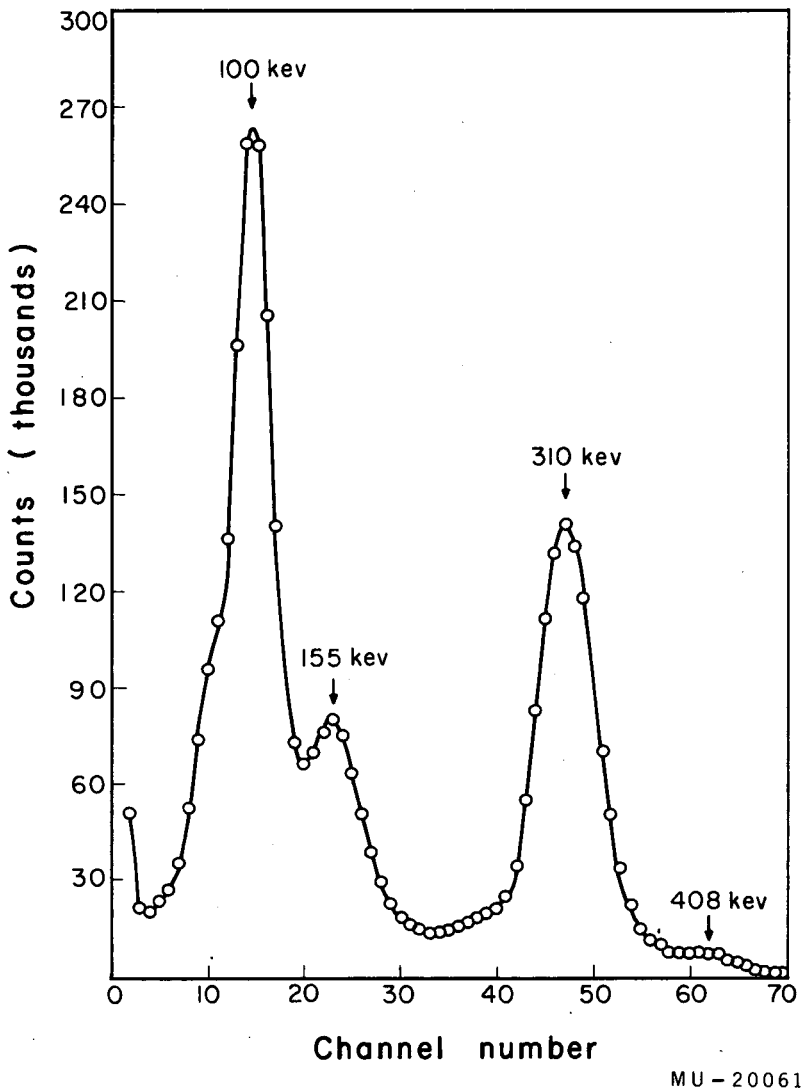

Fig. 2. Gamma-ray spectrum of Pa^{233}.

TABLE IV

Experimentally determined conversion coefficients of transitions in U^{233}

Experimental values													Theoretical values[c]											
													M1						E2					
ENERGY (kev)	α_K	α_{L_I}	$\alpha_{L_{II}}$	$\alpha_{L_{III}}$	α_{M_I}	$\alpha_{M_{II}}$	$\alpha_{M_{III}}$	α_{N_I}	α_{O_I}	$\alpha^a_{\Sigma L_i}$	$\frac{\alpha_K}{\alpha_{\Sigma L_i}}^a$	Multipole assignment	α_K	α_{L_I}	$\alpha_{L_{II}}$	$\alpha_{L_{III}}$	$\alpha_{\Sigma L_I}^a$	$\frac{\alpha_K}{\alpha_{\Sigma L_i}}^a$	α_K	α_{L_I}	$\alpha_{L_{II}}$	$\alpha_{L_{III}}$	$\alpha_{\Sigma L_i}^a$	$\frac{\alpha_K}{\alpha_{\Sigma L_i}}^a$
28	--	--	--	--	$M_I/M_{II}/M_{III}$=1.0/0.27/0.30			--		--	--	98% M1 2% E2	--	$M_I/M_{II}/M_{III}$=1.0/0.1/0.0047				--	--	$M_I/M_{II}/M_{III}$=1.0/28/28				--
40	--	64	230	180	--	47	52	--	--	470	--	70% M1 30%E2	--	50	4.2	0.29	54	--	--	16	400	390	806	--
75	--	11	1.5	0.16	2.6	--	--	0.95	0.38	13	--	98% M1 2% E2	--	8.9	0.75	0.043	9.7	--	--	1.2	23	17	41	--
87	--	5.5	0.76	0.15	1.5	0.34	0.076	0.43	0.11	6.4	--	97% M1 3% E2	--	5.8	0.49	0.027	6.3	--	--	0.60	11	8.0	20	--
104	--	3.9	0.71	0.15	1.2	--	--	0.55	--	4.8	--	95% M1 5% E2	--	3.5	0.30	0.016	3.8	--	--	0.30	4.9	3.2	8.0	--
272	0.20		0.19	≤0.14	--	--	--	--	--	≤0.33	≥0.59	E2	1.2	0.23	0.023	0.00093	0.25	4.7	0.089	0.023	0.082	0.033	0.138	0.65
300	0.83	0.17	0.025	--	0.051	--	--	0.013	--	0.20	4.1	90% M1 10% E2	0.86	0.17	0.017	0.00068	0.19	4.6	0.075	0.018	0.055	0.020	0.073	1.0
312	0.79[b]	0.19	0.018	--	0.044	--	--	0.015	0.0038	0.21	3.9	M1	0.79	0.16	0.016	0.00062	0.18	4.5	0.070	0.017	0.048	0.017	0.065	1.1
341	0.67	0.15	0.019	--	0.046	--	--	0.019	--	0.17	4.0	95% M1 5% E2	0.60	0.12	0.012	0.00046	0.13	4.5	0.059	0.014	0.033	0.011	0.047	1.3
375	0.077	0.021	0.045	0.021	--	--	--	--	--	0.087	0.90	E2	0.48	0.098	0.0099	0.00036	0.11	4.4	0.051	0.012	0.024	0.0076	0.044	1.2
399	0.066	0.020	0.035	0.011	--	--	--	--	--	0.066	1.0	E2	0.40	0.081	0.0082	0.00030	0.089	4.5	0.045	0.010	0.018	0.0055	0.034	1.3
416	0.12	0.024	0.017	0.0045	--	--	--	--	--	0.046	2.7	22% M1 78% E2	0.36	0.074	0.0076	0.00027	0.082	4.4	0.043	0.0094	0.016	0.0047	0.030	1.4

a. α_{L_i} refers to the sum of the L-conversion coefficients determined in this work. α_{L_i} differs from α_L (total L-conversion coefficient) in those cases in which not all of the L-subshell electron intensities were measured.

b. Relative photon intensities were normalized to relative electron intensities by means of the theoretical α_K^{312}, which is 0.79 (see text).

c. Reference 22.

8. CONVERSION COEFFICIENTS AND MULTIPOLE ASSIGNMENTS

In order to calculate from the relative electron and gamma intensities the conversion coefficients of the observed transitions, the gamma intensities were normalized to the electron intensities by means of Rose's theoretical K-conversion coefficient for the 312-kev M1 transition.[22] (Subsequently both the electron and photon intensities were normalized to "percent beta decay" as explained in Section 9.) This means of normalization was chosen because the large limits of error on the experimental value of α_k^{312} made this value undesirable as a normalization factor. If the 312-kev transition should have the 3% E2 admixture which we set as an upper limit, then the use of the theorectical α_k^{312} for a pure M1 transition would introduce a 3% error in the normalization and in the calculated conversion coefficients.

The conversion coefficients so calculated are listed in Table IV. From the limits of error placed on the electron and gamma intensities, one can estimate limits of error of about 35% for most of the experimental conversion coefficients listed in Table IV. The values for the weak transitions may be in error by as much as a factor of two.

The experimental L-subshell ratios, $\alpha_k/\alpha_{\Sigma L_i}$ ratios,[25] and absolute conversion coefficients are compared with the theoretical values of Rose[22] in order to assign transition multipolarities. Rose's theoretical values for M1 and E2 transitions are listed in Table IV along with the experimental values and the assigned multipolarities.

Some general observations can be made about the data and assignments presented in Table IV. In most cases the major multipole component of each transition is clearly indicated. The percentages of admixed multipoles are calculated from the conversion coefficient data; and although the listed percentages of the less intense multipole components are approximate, they are quantitative.

In making these quantitative estimates of multipole admixtures most weight was given to the L-subshell ratio data. In most cases the experimental absolute conversion coefficients are larger than expected from these assignments and the theoretical conversion coefficients. This is especially evident in the pure E2 assignments. These differences are probably due to experimental errors in the electron- and photon-intensity data and to the means of normalizing the photon intensities to the electron intensities. If it were assumed that the K-conversion coefficient of the 312-kev transition were less than 0.79 because of a few percent of E2 admixture, then the photon-intensity normalization

would make all calculated conversion coefficients several percent lower. The discrepancies cannot be eliminated entirely by adjustment of the normalization factor, however.

Finally, it is noted that the experimental $\alpha_K/\alpha_{\Sigma L}$ values of the 300-, 312-, and 340-kev transitions are approximately 10% smaller than would be predicted by the assigned multipolarities and theoretical values. It has been mentioned that the iron-free spectrometer electron intensities are the measured peak heights of the conversion lines. However, the intensities of the 312-kev K and L_I lines were also measured by integrating the area under the peaks. The K/L ratio of the 312-kev transition obtained in this manner is 4.2±0.4 and is more accurate than the value of 3.9 obtained from the peak heights; thus there is no discrepancy between the experimental and theoretical K/L ratios for this transition. The K/L ratios of the 300-kev transition (measured in the iron-free spectrometer from peak heights) and the 340-kev transition (measured in the photographic spectrographs) are known less accurately than that of the 312-kev transition, but it is reasonable to infer from the above that they would be approximately 6% larger if they had been measured from integrated areas rather than from peak heights. The experimental K/L ratios of the 300- and 340-kev transitions, therefore, most likely agree with the theoretical values within the experimental errors. It should be noted that Bisgård et al. report values of approximately 5 for the K/L ratios of the 300-, and 312-, and 340-kev transitions.[7]

Table V gives a comparison of the multipolarity assignments made by Bisgård et al.[7], by Albouy and Valadares[6], and in this study. The agreement between the data of Bisgård et al.[7] and this work is not good, the differences being by a factor of two in many cases. Their qualitative multipole assignments are, however, essentially the same as ours, with the following exception. Bisgård et al. assign the 416-kev transition as magnetic dipole, whereas we interpret the transition as an M1-E2 mixture, predominantly E2. It is encouraging that the data of Bisgård et al. and of this work for the 375- and 399-kev transitions are in reasonably close agreement. The multipole assignments of these transitions are quite important in the interpretation of the decay scheme, and this agreement supports the assignments of these transitions as electric quadrupole.

The multipole assignments by Albouy and Valadares[6] are also in essential agreement with those of this work, with the exception of the 40-kev transition.

TABLE V

The decay of Pa^{233} - multipolarity assignments of various workers

E_γ (kev)	Conversion ratio	Experimental values Bisgard et al.[a]	This work	Multipolarity: Bisgard et al.[a]	Multipolarity: Albouy and Valadares[b]	Multipolarity: This work
28.5	$\frac{M_I + M_{II}}{M_{III}}$	~ 9	4.3	M1 + E2	96% M1 4% E2	98% M1 2% E2
40.4	$\frac{L_I + L_{II}}{L_{III}}$	1.0	1.7	M1 + E2	40% M1 60% E2	70% M1 30% E2
	$\frac{L_I}{L_{II}}$	~0.4	0.26			
75.3	$\frac{L_I + L_{II}}{L_{III}}$	> 130	74	M1	M1(<1% E2)	98% M1 2% E2
	$\frac{L_I}{L_{II}}$	~ 13	7.1			
86.6	$\frac{L_I + L_{II}}{L_{III}}$	> 20	40	M1	M1(<1% E2)	97% M1 3% E2
	$\frac{L_I}{L_{II}}$	~ 9	7.4			
103.9	$\frac{L_I + L_{II}}{L_{III}}$	> 30	30	M1	M1(<1% E2)	95% M1 5% E2
	$\frac{L_I}{L_{II}}$	~9	5.6			
271.6	K/L	0.55	≧ 0.59	E2	E3,E4, or E5 or M1+E2	E2
	$\frac{L_I + L_{II}}{L_{III}}$	2.8	≧ 1.3			
300.2	K/L	5.0	4.1	M1	M1	90% M1 10% E2
311.9	K/L	5.1	3.9	M1	M1	M1
340.5	K/L	5.0	4.0	M1	M1	95% M1 5% E2
	$\frac{L_I + L_{II}}{L_{III}}$	> 100				
375.4	K/L	1.2	0.90	E2	--	E2
	$\frac{L_I + L_{II}}{L_{III}}$	3.1	3.0			
398.6	K/L	~2.4	1.0	E2	--	E2
	$\frac{L_I + L_{II}}{L_{III}}$	4.0	5.1			
415.9	K/L	3.9	2.8	M1	--	22% M1 78% E22
	$\frac{L_I + L_{II}}{L_{III}}$	> 20	9.0			

a. Reference 7; b. Reference 6.

These authors report this transition as an M1-E2 admixture with approximately 20% M1, whereas we interpret the transition as M1-E2 with approximately 70% M1.

9. ABSOLUTE TRANSITION INTENSITIES AND LOG FT VALUES

From the data of previous investigators,[2,4,14] it is apparent that approximate 95% of the beta decay populates the upper four levels in U^{233}. The measured relative intensities in Tables I, II, and III have been placed on an absolute basis of percent beta decay by requiring that the sum of the intensities of the transitions depopulating the upper four levels be 95% of the total beta decay. The transition intensities (the sums of the electron and gamma-ray intensities) are listed in Table VI.

Since no gamma-ray data and only limited electron-intensity data are available for the 28-kev transition, its intensity was estimated in the following manner: The multipolarity of the 28-kev transition was deduced from the relative M-subshell ratios by comparing the experimental values to Rose's theoretical values.[22] The transition was found to be M1 with approximately 2% E2 admixture. The theoretical M-conversion coefficients for a gamma ray of this multipole admixture were taken from Rose's M1 and E2 conversion coefficients, then the measured M electron intensities and the deduced conversion coefficients were used to estimate the 28-kev photon intensity. Since the conversion coefficients are large, this estimated gamma intensity is a small fraction (0.2%) of the total intensity. The total L-electron intensity was then approximated as 3.6 times the total M electron intensity. The factor 3.6 is an average of the ratio of total L to total M intensities for other M1 transitions observed here. Finally, the N and O electron intensities were assumed to be smaller than the M-electron intensity by factors 3 and 9, respectively. (This latter assumption was made also in estimating the total intensities of other transitions whose N and O intensities had not been measured.)

The percent beta population to each level in U^{233} was deduced from the absolute transition intensities; these are listed in Table VII. Hok's measured intensity values for the low- and medium-energy beta components are 37% and 58%, respectively.[2] The corresponding values deduced from the values in Table VII are 40% and 54%; thus there is close agreement in the values of these beta-decay groups determined in two independent ways.

Table VI

The decay of Pa^{233} –
Total absolute transition intensities

Transition energy (kev)	Transition intensity (percent beta decay)
17.26	--
28.54	~12
40.35	9.4
75.28	14
86.59	17
103.86	5.1
271.62	0.48
300.20	13
311.91	70
340.51	7.3
375.35	0.66
398.57	1.3
415.87	1.7

Table VII

Beta-component intensities and log ft values in the decay of Pa^{233}

Final state (kev)	Beta-group Intensity (percent)	log ft
415.80	$\gtrsim$ 22	$\lesssim$ 6.72
398.55	$\lesssim$ 18	$\gtrsim$ 6.93
340.52	18	7.32
311.93	36	7.20
40.35, 0.00	5	9.16

The value of 5% decay to the ground state listed in Table VII is that measured by previous workers.[2,4,14] The log ft values in Table VII were calculated from the curves of Moszkowski[26] by use of the beta intensities listed.

10. DISCUSSION OF DECAY SCHEME

The above data have been used to construct the decay scheme shown in Fig. 3. The general features of the scheme are the same as proposed by Brodie[4] and supported by Hok and Kramer.[2] The quantum assignments of the U^{233} levels suggested by Newton[5] are confirmed. Some Coulomb-excitation data of Newton are included in the scheme for completeness. The energies of the levels have been assigned so as to give good agreement between the sums and differences of the energies of the gamma rays connecting the levels. In all cases the different possible energy values of a level as computed by different sums and differences agree within 0.04%.

The ground-state spin of U^{233} has been measured as 5/2 by a number of investigators.[27-31] As pointed out by Newton,[5] the ground state is most probably the 5/2+ [633] Nilsson level. The ground state spin of Pa^{233} was measured as 3/2 by Hubbs and Winocur.[32] Evidence that the ground state of Pa^{233} has odd parity was obtained by a beta-gamma angular correlation experiment performed at Uppsala by Hamilton, Hollander, and Pettersson.[33] An anisotropy observed between the 250-kev beta group and the 312-kev photon establishes that the beta transition to the 312-kev level cannot be purely allowed. Thus, the parity of Pa^{233} is odd if that of the 312-kev level is even. The Pa^{233} ground state has been interpreted[34] as the 3/2 member of a K = 1/2 band based on the Nilsson level 1/2 - [530]. With this basic information and the data at hand it is possible to analyze the scheme with respect to beta branchings, photon branchings, and log ft values. It will be convenient to discuss each of the rotational bands separately.

a. Ground-State Band

The assigned quantum states indicate that the ground-state beta transition proceeds largely by the "unique" $\Delta I = 2$, yes, type of decay, since $\Delta I = 1$ transitions are K-forbidden ($\Delta K = 2$). In addition, the first-forbidden transition to the ground state is "hindered", in the notation of Alaga,[35] since a selection rule on the asymptotic quantum number Λ is violated. The calculated log ft of 9.16 for the ground-state transition is consistent with "unique" 1st forbidden decay and hence with the assigned quantum states.[36]

The rotational constant ($\hbar^2/2\mathfrak{J}$) for the ground-state band was calculated from the energy of the first excited state (40.35 kev) by means of the equation[8]

$$E_{rot} = \hbar^2/2\,\mathfrak{J}\,[I\,(I+1) - I_o\,(I_o+1)].$$

The result is $\hbar^2/2\,\mathfrak{J} = 5.76$ kev. With this constant the energy of the second excited state is calculated to be 92.22 kev. Newton's measured value is 92.0 kev.[5]

The recent results of Albouy and Valadares[6] indicated a serious discrepancy in the Pa^{233} decay scheme: they reported that the total feeding of the 40-kev level is stronger than the measured intensity of the 40-kev transition by a factor of 3 or 4. We do not confirm this large discrepancy, but find instead the 40-kev transition to be too weak by only 30%. The predominant decay to the 40-kev state occurs via the 300, 270, and 375-kev transitions (total intensity 14%) whereas our measured intensity of the 40-kev transition is 9.4%. An examination of the sources of error associated with our measured intensities easily accounts for this imbalance, as follows: The consistency of the measured intensities of both the photon and electrons of the 300-kev transition among the several independent determinations is very good, so it is probably reasonable to assign an error of about 15% to the relative intensities of this transition. Of course, errors in the normalization of the relative gamma intensities to the relative electron intensities result in errors in the absolute transition intensities; if the possible error in the normalization is ± 10% and the error limits of the relative gamma and electron intensities are ± 15%, then the overall error limits of the 300-kev transition intensity are about ± 20%. The errors associated with the very weak 270- and 375-kev transitions are unimportant.

The discussion in Section 5 shows that the electron-line peak heights of the 40-kev transition may have been substantially attenuated by source absorption effects. This could easily amount to 20%. Thus, the 30% imbalance which we note in the population-depopulation of the 40-kev level is not only within the experimental uncertainty but is in the direction and of the magnitude that should be expected.

We have assigned the 40-kev transition as 70% M1 and 30% E2; Albouy and Valadares[6] report this mixture as 40% M1 and 60% E2. In addition, these workers[6] have calculated a value of 20% M1 and 80% E2 based upon the data of Newton.[5] The mixing ratio of this transition is important because it can be

used along with the experimental values of the the magnetic and quadrupole moments to calculate the gyromagnetic ratios for the particle ($g\Omega$) and core (gR) for the ground state rotational band. The calculation is based on the fact that the reduced transition probability for collective M1 transitions is proportional to $(g\Omega - gR)^2$, and that of collective E2 transitions is proportional to Q_o^2,[8] where Q_o is the intrinsic quadrupole moment. Also, the magnetic moment is related to $g\Omega$ and gR by the equation[8]

$$\mu = \frac{I^2}{I+1} g\Omega + \frac{I}{I+1} gR \quad \text{for } I=K=\Omega \geq 3/2.$$

The values of $g\Omega$ and gR cannot be determined uniquely unless the signs as well as the values of Q_o and μ are known. Newton[5] discusses this calculation in more detail.

For U^{233} μ has been measured as $\pm$ 0.51 nuclear magnetons[36] and q, the measured quadrupole moment, is $\pm$ 3.4 barns.[36] From the latter we deduce a value of $\pm$ 9.5 barns for Q_o.[8] Using the mixing ratio of 70% M1 and 30% E2 for the 40-kev transition, and assuming that Q_o and gR are both positive we calculate the following choices:

$$g\Omega = 0.157, \; gR = 0.320$$

or

$$g\Omega = 0.250, \; gR = 0.087$$

The second choice is not acceptable since gR is expected to have a value of approximately[8] $+ Z/A = 0.4$.

The mixing ratio of 40% M1 and 60% E2 reported by the French[6] workers leads to values of

$$g\Omega = 0.228, \; gR = 0.142$$

or

$$g\Omega = 0.178, \; gR = 0.267$$

Newton[5] has previously reported calculated values of

$$g\Omega = 0.25, \; gR = 0.17$$

or

$$g\Omega = 0.20, \; gR = 0.28$$

In Newton's calculation, however, a value of Q_o of ~ 14 barns was used.

b. K = 3/2 Band

The levels at 311 kev and 340 kev have been interpreted as the 3/2 and 5/2 members of rotational band based on the Nilsson level 3/2 + [631].[5]

The calculated log ft values listed in Table VII for beta decay to these levels are consistent[37] with first-forbidden nonunique decay (ΔI=0 or 1, yes) and hence in agreement with the assigned spins and parities. The experimental beta branching to these two levels, however, differs by a factor of two

from the theoretical value predicted from vector-addition coefficients. The theoretical value for L = 1 decay is $\frac{B\ (3/2 \rightarrow 5/2)}{B\ (3/2 \rightarrow 3/2)} = 1.5$, whereas the experimental value (inverse ratio of ft values) is 0.76. We here compare only L = 1 beta decay because L = 0 decay to the 3/2 level is K forbidden. To explain this disagreement in terms of experimental error, one must assume an error of about 75% in the estimated intensity of the 28-kev transition. To bring about agreement the intensity would have to be about 21 instead of the assigned value of 12; this is not impossible in view of the absorption effects on these low-energy conversion lines (as discussed earlier) and because the intensities of the L lines of the 28-kev transition were not measured but only estimated from the measured M-electron intensities.

As an alternative explanation for this disagreement in beta decay branching, admixture of K = 3/2 in the ground state of Pa^{233} or of K = 1/2 in the 311- and 340-kev levels in U^{233} would affect the beta transition ratio for L = 1 decay and would allow beta decay to the 312-kev state by L = 0. If the theoretical ratio were corrected for such effects, the first named could either raise or lower the ratio depending upon what admixtures were assumed; whereas the last named effect would lower the theoretical ratio.

It is possible to test the quantum assignments of the 340-kev level also by a comparison of the relative reduced photon transition probabilities of both the M1 and E2 components of the 300- and 340-kev transitions with those predicted theoretically for states pure in K. The experimental and t heoretical values are listed in Table VIII. The theoretical values are the ratios of the squares of vector-addition coefficients; the experimental ones were calculated by two nearly independent means. The experimental values in the first set are the ratios of the measured gamma-ray relative intensities corrected for the $E^{2\ell+1}$ energy dependence and for multipole admixtures. Those in the second set were determined in like manner except that the relative photon intensities were deduced from the measured conversion-electron intensities and the theoretical conversion coefficients. The values calculated by these two means are nearly the same. Also listed are experimental values deduced from the data of Albouy and Valadares.[6]

TABLE VIII

The decay of Pa^{233} — experimental and theoretical relative reduced photon transition probabilities

E_γ/E_γ'	K_i/K_f	$\frac{L: B(I_i \to I_f)}{L: B(I_i \to I_f')}$	Theoretical values	Experimental values: Albouy and Valadares[a]	Experimental values: From photon intensities	Experimental values: From electron intensities
75/103	1/2/3/2	$\frac{M1: B(3/2 \to 5/2)}{M1: B(3/2 \to 3/2)}$	1.5	1.3→1.7	3.3	3.2
416/375	1/2/5/2	$\frac{E2: B(3/2 \to 5/2)}{E2: B(3/2 \to 7/2)}$	1.3	> 2.4	1.2	1.2
300/340	3/2/5/2	$\frac{M1: B(5/2 \to 7/2)}{M1: B(5/2 \to 5/2)}$	2.5	1.3	2.3	2.1
300/340	5/2/5/2	$\frac{M1: B(5/2 \to 7/2)}{M1: B(5/2 \to 5/2)}$	0.4			
300/340	3/2/5/2	$\frac{E2: B(5/2 \to 7/2)}{E2: B(5/2 \to 5/2)}$	0.037	---	6.6	6.0

[a] These values were deduced from data presented in Ref. 6.

A comparison of the experimental and theoretical ratios for the M1 radiation should best indicate the major K- component of the 340-kev level, since the amount of E2 mixing in the 300 and 340 kev transitions is small and inaccurately known. For the M1 components our experimental values agree well with the theoretical value for K = 3/2, and support the assignment of the 340 kev state as the first rotational member of the band based on the 3/2+[631] intrinsic state. From the energy difference between 3/2+ and 5/2+ members of this band (28.59 kev) one calculates a rotational constant of 5.72 kev. The calculated energy of the 7/2+ members is, then, 380.6 kev. No evidence for a state of this energy was found in this work.

There is large disagreement between our experimental and theoretical ratios for the E2 components of the 300 and 340 kev radiation. This disagreement is perhaps in part due to errors in the experimental determination of the mixing ratios and perhaps in part due to an admixture of K = 1/2 in the 340-kev level. Such an admixture would not affect the branching ratio of the M1 components since for K = 1/2 → K = 5/2 dipole radiation is K-forbidden.

c. K = 1/2 Band

According to the multipole assignments listed in Table V the levels at 398 and 415 kev must have spins and parities of 1/2+ and 3/2+, respectively. These assignments are in agreement with the interpretation that these levels are the first two members of a K = 1/2 rotational band with the Nilsson level 1/2 + [631] as the base state.[5] The division of the primary beta population between these two levels cannot be estimated accurately because the intensity of the 17-kev transition is not known. In Table VII the log ft values listed for these two levels were calculated for the intensity of 0% for the 17-kev transition, and the uncertainties indicated by (<) and (>) signs. These approximate log ft values are in agreement with the postulated spin and parity assignments.

The theoretical branching ratio for beta decay to these levels cannot be calculated from vector-addition coefficients without knowledge of the relative amounts of L = 0 and L = 1 types of decay to the 416-kev level; however, if the quantum assignments of the 399- and 416-kev levels are assumed to be correct it is possible to make an indirect test of the assignment K = 1/2 to the ground state of Pa^{233}. The only other K value consistent with the measured spin for Pa^{233} is K = 3/2. If this value is assumed, it is possible to make

branching-ratio comparisons for decay to the 416- and 399-kev levels because L = 0 transitions are then K-forbidden. With this assumption the theoretical ratio for L = 1 decay to the two highest levels is $\frac{B(3/2 \rightarrow 1/2)}{B(3/2 \rightarrow 3/2)} = 1.25$; the experimental value is 0.62, calculated by assuming the intensity of the 17-kev transition to be negligible. (The experimental ratio would be smaller if a finite value were assumed for the intensity of the 17-kev transition.) Thus, the theoretical and experimental values differ by at least a factor of two. This in itself is not conclusive evidence against an assignment of K = 3/2 for the ground state of Pa^{233} because such deviations can be caused by admixtures of K values in the initial or final states. Additional evidence that the ground state of Pa^{233} has K = 1/2 comes from the work of Stephens, Asaro, and Perlman[38] on the alpha decay of Np^{237}, which populates several excited states in Pa^{233} whose spacings appear to be characteristic of a K = 1/2 band.

The theoretical and experimental values of the reduced photon branching ratio $\frac{416\text{-E2}}{375\text{-E2}}$ are compared in Table VIII. The agreement between the theoretical value and our experimental values is quite good and supports the quantum assignment of (3/2+, 1/2) for the 416-kev level. Note that M1 transitions from the K = 1/2 band to the ground-state band are K-forbidden. This accounts for the predominantly E2 character of the 416-kev transition.

The theoretical and experimental reduced photon branching ratios $\frac{75\text{-M1}}{103\text{-M1}}$ also are compared in Table VIII. Our experimental value is more than a factor of two larger than the theoretical value, a discrepancy certainly outside the assigned limits of error.

If the multipolarities of the gamma rays depopulating the 416-kev level have been correctly deduced, the only choice of spin for this level is 3/2; and thus the only possible K values are 1/2 and 3/2. The alternative choice of K = 3/2 leads to a theoretical value of $\frac{\text{M1: } B(3/2 \rightarrow 5/2)}{\text{M1: } B(3/2 \rightarrow 3/2)} = 0.67$, which differs from the experimental value by a factor of 4.5, in worse disagreement than the result for K = 1/2.

The difference between the experimental and theoretical values may be due to admixtures in the initial or final states of K values differing from the principal one by ± 1. Approximate calculations show that although interaction between the observed K = 3/2 and K = 1/2 band is probably not large enough to explain the discrepancy, the Nilsson state 1/2 + [640] may mix with the K = 1/2 and/or K = 3/2 band to a degree large enough to affect the relative reduced transition probabilities appreciably. Thus, the evidence indicates that the major component of the 399- and 416-kev states is K = 1/2.

11. OTHER TRANSITIONS AND NEW STATES

It is possible that transitions from the previously unobserved 5/2 member of the K = 1/2 band were seen in this study. These transitions, of 62.61 and 45.36 kev, are shown in Fig. 3 depopulating a level at 461.16 kev. The evidence for these transitions is two weak electron lines of energies 41.67 and 23.60 kev listed in Table IX. It was assumed that the first of these lines is the L_{II} line of a 63-kev/transition, and that the second is the L_I line of a 45-kev M1-E2 transition. The fact that no other electron lines associated with these transitions were observed is consistent with the very weak intensities of the observed lines and the multipole assignments of the transitions. This evidence is tenuous, since in the energy region of these lines there are many unassigned lines among which one might expect some coincidental agreement. Some support is given the postulate by the very close agreement between the differences of the postulated transitions (17.25 kev) and themeasured energy (17.26) of the 3/2+→ 1/2+ transition.

TABLE IX

Unassigned electron lines in the decay of Pa^{233}

Ee^- (kev)	Possible assignments
Relatively certain lines	
1.90	(a)
4.08	(a)
108.3	130-L_I
112.7	130-L_{III}
166.5	
172.4	(a)
226.6	
229.5	250-L_{II}
232.1	
232.3	
233.5	250-L_{III}
262.7	
281.1	
292.0	314-L_I
293.0	314-L_{II}
445.4	

TABLE IX (Con't)

Ee^-(kev)	Possible assignments
Questionable lines	
6.84	
9.31	
9.44	
19.86	
20.25	
20.49	
21.30	
21.75	
22.08	
23.60	
23.84	
24.68	
25.70	
28.52	
30.64	
35.53	
37.77	$58.8\text{-}L_{II}$
41.67	$58.8\text{-}L_{III}$
47.59	
53.86	
54.16	(b)
63.91	
65.15	
65.83	
67.23	
69.42	
72.21	
74.46	
81.73	

TABLE IX (Con't)

Ee^- (kev)	Possible assignments
Questionable lines	
105.6	KM_IM_{III} Auger line
217.7	
219.5	
221.5	
227.2	
396.7	$415\text{-}L_{III}$

a. Much stronger than others listed in this table.

b. This line is the low-energy side of the 75-kev L_{II} line, which appeared split on this film. This may indicate two-close lying lines or may be an instrumental effect.

With the assignment of the 5/2 member, it is possible to calculate the rotational constant $\hbar^2/2\mathfrak{J}$ and the decoupling parameter "a" for this K = 1/2 band. These constants are defined by the equation[8]

$$E_{rot} = \hbar^2/2\mathfrak{J}\ [I\ (I + 1) + a\ (-)^{I + 1/2}\ (I + 1/2)\ ]\ .$$

Substitution of the measured energies gives $\hbar^2/2\mathfrak{J}$ = 7.41 kev and a = - 0.22.

It is interesting to compare these values with those of the same rotational band occurring in other nuclei. In U^{235} the 1/2 + [631] level is a low-lying isomeric state. Albridge and Hollander,[39] using permanent-magnet spectrographs, have determined the energies of the 3/2+ and 5/2+ members of this band in U^{235} by measuring the 5/2+ → 1/2+ and 5/2+ → 3/2+ transition energies from the alpha decay of Pu^{239}. The energies of the 5/2+ and 3/2+ levels were found to be 51.67 kev and 13.00 kev, respectively. These energies lead to values of $\hbar^2/2\mathfrak{J}$ = 6.04 kev and a = - 0.28. The 1/2+ [631] level is the ground state of Pu^{239}. In a study of the decay of Np^{239} Hollander et al.[40,41] Ewan et al.[42] determined values of $\hbar^2/2\mathfrak{J}$ and a for the K = 1/2 band in Pu^{239} as 6.25 kev and - 0.58, respectively.

In Table I are listed two lines assigned as the L_{II} and L_{III} lines of a 57.90-kev transition. In Fig. 3 this transition is placed between the

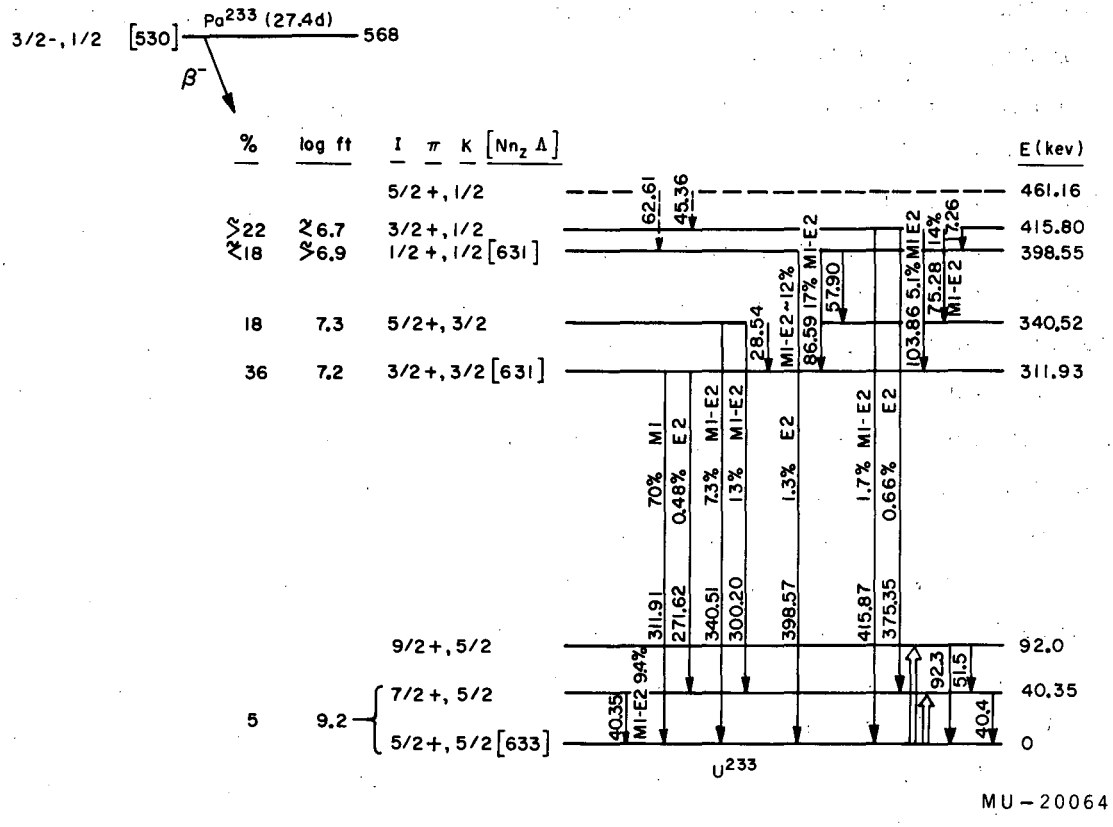

Fig. 3. The energy levels of U^{233}.

399- and 341-kev levels. The electron line of about 41 kev, assigned as the 58-kev L_{III} line, was seen by means of the 50- and 100-gauss spectrographs and by means of the accelerator camera both with and without pre-acceleration. The ~37-kev line, assigned as the 58-kev L_{II} line, was seen by means of the 50-gauss instrument and perhaps with the 100-gauss spectrograph. That this line was not observed in the accelerator camera is explained by the fact that it is weaker than the ~41-kev line, and this stronger line was just visible on the plates exposed in the accelerator camera. The line of ~36 kev reported by Hok and Kramer[2] as the 58-kev L_I line was most likely the 40-kev M_{III} line.

The 58-kev L lines assigned in this work were too weak to be given a numerical intensity. This weakness, in addition to the fact that the transition is thought to be E2 and, therefore, highly converted, is consistent with the fact that Browne[16] failed to detect the gamma ray of this transition. That a 58-kev photon was not detected with the Pasadena spectrometer may not be significant since it is possible that during the sweep of this energy region the discriminator of the detector was set so as not to accept pulses corresponding to this energy. This fact was not discovered until the source had been returned from Pasadena to Berkeley.

The position of the 58-kev transition in the proposed decay scheme requires that this transition be electric quadrupole. The L-conversion coefficients of a 58-kev electric quadrupole transition are given by Rose[22] as 3.3, 70, and 56 for the L_I, L_{II}, and L_{III} shells, respectively. That the L_{III} line is observed as somewhat more intense than the L_{II} line is not necessarily in contradiction to an assignment of E2, since source-absorption and film-efficiency corrections would increase the intensity of the L_{II} line relative to that of the L_{III} line.

There is evidence for the existence of other gamma transitions in the Pa^{233} decay. This evidence is a number of unassigned electron lines (Table IX) detected with the permanent-magnet spectrographs and two photon lines (Table III) of energies 41.65 and 145.42 kev detected with the Pasadena bent-crystal spectrometer. These new data and possible interpretations are discussed in this section.

The electron lines listed in Table IX are divided into two groups. Those in the first group are lines whose existence are considered relatively certain because of their intensities or because of their detection on more than one photographic plate. The second group contains lines whose existences are questionable or doubtful.

Bisgård et al.[7] have reported weak electron lines of energies approximately 5 kev less than those of the 300-, 312-, and 341-kev K lines (i.e., at ~180, ~185, and ~220 kev). With the exception of a questionable line at approximately 220 kev, lines of these energies were not observed in this work, although they would most likely have been visible had they been present in the intensities reported by the Danish workers.

Fairly large error limits have been placed on the measured energies of the 42- and 145-kev photons (Table III) because in the spectrum the photon lines were not well defined and the energies were difficult to determine. The 41.65-kev gamma was observed only with the platinum wire source because the line was of too low intensity to be seen with the weaker ThO_2 source. The 145-kev line was observed only with the ThO_2 source because this region of the energy spectrum was not scanned with the platinum wire source.

In Table IX there is no definite evidence of conversion electrons corresponding to transitions of 42 or 145 kev. One extremely weak line, seen at an energy of 19.86 kev, could be the L_I line of a 41.62-kev transition; however, this line is of doubtful existence. The fact that there is no definite evidence of conversion electrons of these two transitions raises the question whether the recorded gamma rays have arisen from impurities in the particular sources used for gamma spectroscopy. The source with which the 41-kev gamma was detected underwent the same chemistry as used for the permanent-magnet spectrograph sources; and although the source used for the detection of the 145-kev gamma underwent no chemistry, it is likely that very few fission products were formed, owing to the low thermal-neutron fission cross section of Th^{232}. At any rate, no gamma ray of 145 kev has been reported as being associated with a fission product. Thus, these photons are considered to arise in Pa^{233} decay. The most probable reason for the failure to observe conversion electrons from these transitions is that they have small conversion coefficients. For example, if the transitions were electric dipole it is reasonable that the conversion-electron intensities would have been too small to be detected.

The difference between the energies of the 42- and 145-kev photons is 103.77 ± 0.05 kev. This difference agrees with the energy of the 103.86 ± 0.02-kev transition to within 0.1%, but the agreement is not within the assigned limits of errors. Probably the error limits have been underestimated and the close agreement is a significant one; but a definite answer to this

point must await a more precise redetermination of the photon energies. With the assumption that this energy difference is significant, the two new photons can be used to define a level at either 270.3 kev or 457.4 kev, as shown in Fig. 4. Thomas et al.[43] have reported a level in U^{233} of approximately 290 ± 28-kev populated by the alpha decay of Pu^{237}, and this may possibly be identified with our 270.3 kev alternative.

Stephens et al.[34] and Mottelson and Nilsson[1] have discussed the possible Nilsson assignments of the ~290 kev level. The former workers favor the assignment 5/2 - [752], the latter, 7/2 - [743]. Of the two possibilities, our data allow only the 5/2 - [752] assignment to be made to the new state, regardless of its energy. The 7/2 - assignment would demand that the 42- and 145-kev transitions be M2, which would be inconsistent with our failure to see conversion lines. On the other hand, with the 5/2 - assignment the transitions would be electric dipoles with small conversion coefficients. (The 145-kev transition would, however, be K-forbidden.) Because of its high resolution, the bent-crystal spectrometer was not used to sweep the entire energy spectrum; thus it is not known whether photons associated with this level other than the two reported here are observable. The existence of a 270.3-kev state would of course pose the additional demand that there be an E1 transition to ground. It would be of value to search for the 270.3-kev photon, which would have to be at least as intense as the 145-kev photon (0.44%), with which it would be in coincidence.

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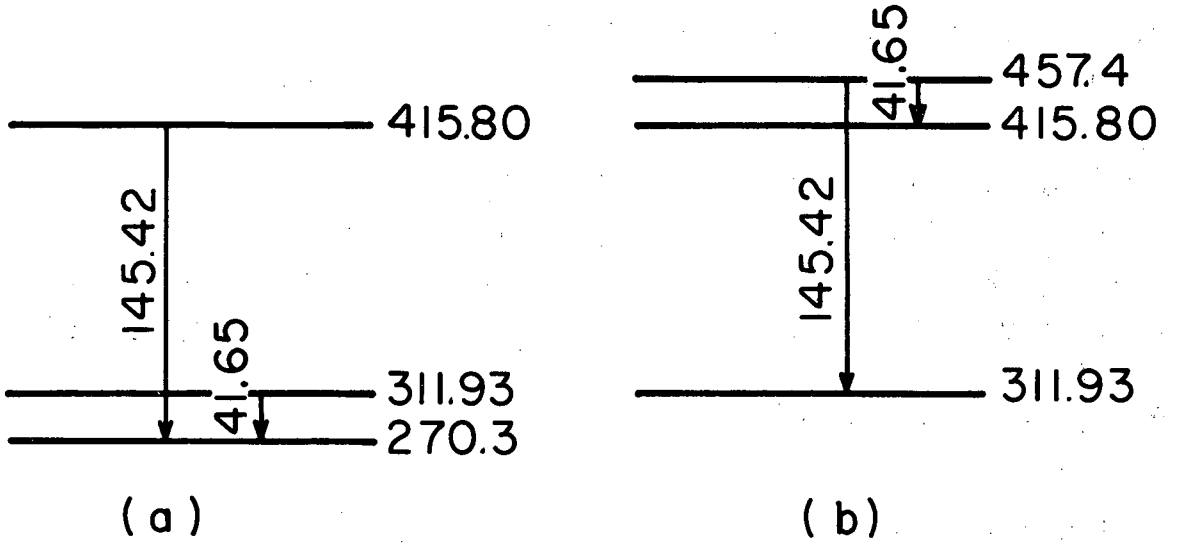

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Fig. 4. (a and b) Possible assignments of two new transitions in the the decay of Pa^{233}.

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