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THE DECAY OF ^{140}La

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Abstract: The beta-ray and internal-conversion spectra from the decay of ^{140}La to ^{140}Ce have been investigated using double-focussing spectrometers. Beta branches with end-point energies 2166±7, 1674±10, 1354±15 and 1244±20 keV have been established, giving a Q-value of 3762±8 keV. In the internal conversion spectrum, 26 transitions have been found ranging in energy from a previously not reported 24.595±0.004 keV transition up to a very weak transition at 3322±4 keV.

The gamma-ray spectrum following the decay of ^{140}La has been studied using a Ge(Li) detector. The theoretical K-conversion coefficient for the 1596 keV E2 transition has been used to calculate conversion coefficients. From these coefficients together with K/ΣL and L-subshell ratios, probable multipolarity assignments have been obtained for most of the transitions. All transitions observed have been fitted into a tentative decay scheme.

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RADIOACTIVITY ^{140}La [from ^{139}La(n, γ)]; measured $T_{\frac{1}{2}}$, E_β, E_γ, I_β, I_γ, I_{ce}, Q_β. ^{140}Ce deduced levels, J, π, cc, log ft. Natural target, Ge(Li) detector.

1. Introduction

Several investigations [1-6]) have been performed on the disintegration of the nucleus ^{140}La and the main features of the decay scheme must now be regarded as fairly well established.

However, despite the great number of investigations performed, there still exist many inconcistencies in the decay scheme, especially concerning energies and intensities of the beta branches and the low-energy transitions. Consequently the present work was initiated with high-resolution magnetic spectrometers in order to search for additional weak transitions and to perform accurate energy determinations.

When the measurements described in this paper were nearly completed, the works of El-Nesr *et al.* [7]) and Baer *et al.* [8]) appeared. El-Nesr *et al.* [7]) studied the internal conversion electron spectrum by means of magnetic spectrometers of good resolution. However, their results seem to be too erroneous from several points of view to be further discussed. Some of the strong new conversion lines reported by them were specially sought for in this investigation, but no indications for their existence were found. Furthermore, their energy determinations of some previously well-established transitions disagree markedly with the results of Baer *et al.* [8]) and those of this work. Baer *et al.* [8]) made precision energy determinations of 24 gamma rays with a curved-crystal spectrometer and a Ge(Li) detector. They reported most of the weak transitions found in our experiments and the results of the two investigations are in good agreement.

2. Source preparation and instrumentation

The lanthanum activity was produced by irradiating La metal or the compound [†] La_2O_3 in a neutron flux of about 1.5×10^{14} neutrons/cm^2 · s. The irradiation periods ranged from 2 to 12 d.

The sources for the beta spectrometers were prepared either by evaporating the inactive metal or oxide onto an aluminium foil prior to irradiation or by irradiating oxide powder and afterwards placing the active deposit on the source backing by molecular plating [9]). The different techniques were required because of contamination of the first sources prepared. The La metal used was found to contain Sm, giving 47 h ^{153}Sm as a weak impurity activity. Also, 24 h ^{187}W activity was found in some evaporated sources emanating from the evaporation procedure. Sources obtained by molecular plating of active La_2O_3 were, however, found to have no detectable contamination from other isotopes. The backing material used was aluminium foils of thickness 1.3 mg/cm^2. The strength of the sources varied from 100 mR/h to 5 R/h gamma dose at a distance of 10 cm. A total number of 33 sources were used.

The beta spectrometers used in this investigation were the two, 50 cm, double-focussing instruments at Uppsala. The iron-yoke spectrometer [10]) was used to scan the internal conversion spectrum from 60 keV to 3.5 MeV, to measure the higher energy conversion lines and to determine the branches of the continuous beta spectrum and the half-life of the decay. The type of source used in this instrument was an active strip 2-4 mm wide and 20 mm high mounted on an aluminium source holder ring. The detector was a twin GM counter with a 0.5 mg/cm^2 mylar window, which was totally transparent to the electrons measured with the instrument.

The iron-free spectrometer [11]) was used to scan and measure the lines in the low-energy internal conversion spectrum from 10 keV to 70 keV electron energy. Most of the lines throughout the entire spectrum were also measured with this instrument, thereby obtaining an independent determination of energies and intensities. In the iron-free spectrometer, two different source arrangements were used. The single-source arrangement used for precise energy determinations consisted of an active narrow strip ($\approx$ 1 mm) mounted on an aluminium source holder ring. A multi-strip source arrangement [12]) was used in most of the measurements. This extended source consisted of 15 active vertical strips 1×16 mm^2 glued on a plexiglass backing with a separation of 0.5 mm and kept at different potentials. By this source arrangement it was possible to measure low-energy lines from very thin, active deposits and still

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[†] Of "specpure" quality, obtained from Johnson, Matthey & Co., Ltd, London.

obtain a considerable intensity because of the large source area. Detection was provided by a GM counter or a multi-detector arrangement [12]). The multi-detector consisted of an array of 10 surface-barrier semiconductor detectors. The GM counter with a formvar window of thickness ≈ 0.15 mg/cm^2 was used in the lowest energy region.

The gamma spectrum was taken in Buenos Aires with a Ge(Li) detector having a sensitive volume of 0.5 cm × 4 cm^2 connected to a RIDL 1600-channel analyser.

3. Half-life determination

In order to check the decay rate of ^{140}La, a determination of the half-life was performed. The sources used in this part of the investigation were carefully checked to insure that they were not contaminated by any other radioactive isotope. Negatons with a constant energy of 550 keV were counted in the double-

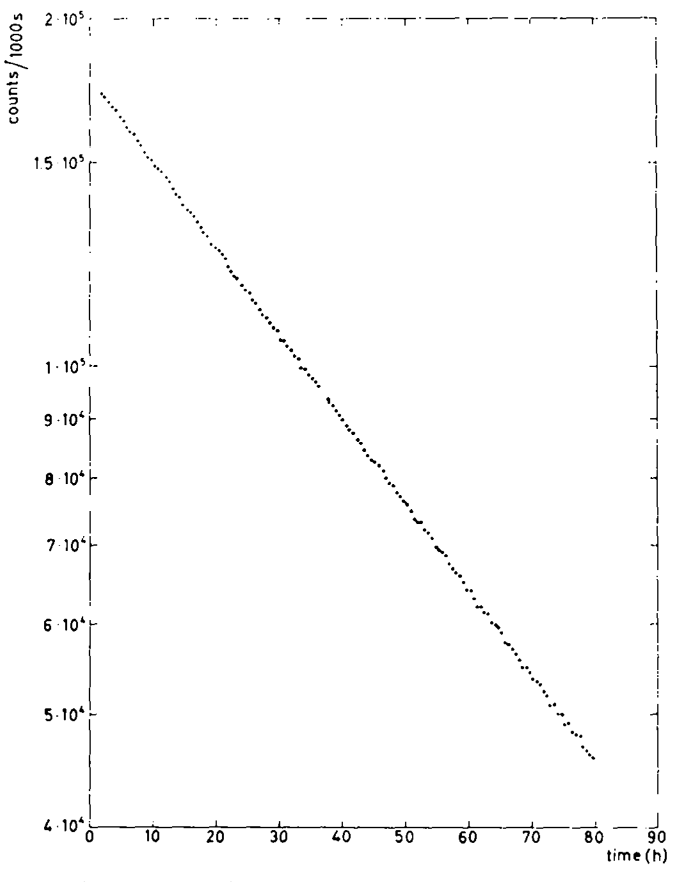

Fig. 1. Half-life determination. The points given are corrected for dead-time and natural background.

focussing, iron-yoke spectrometer with two different sources during about 2 and 4 half-lives, respectively (fig. 1). All points were corrected for the dead-time of the GM tube, and the natural background was subtracted. A computer analysis by the method of least-squares was performed, and a half-life of 40.2±0.2 h was obtained in good agreement with previous investigations [13-15]).

4. Beta transitions

The nucleus ^{140}La is known to decay by negaton emission to excited states in ^{140}Ce. Although many investigations have been performed [2,3,16-19]), conflicting data exist about the end-point energies and the intensities, which is due largely to the complexity of the decay.

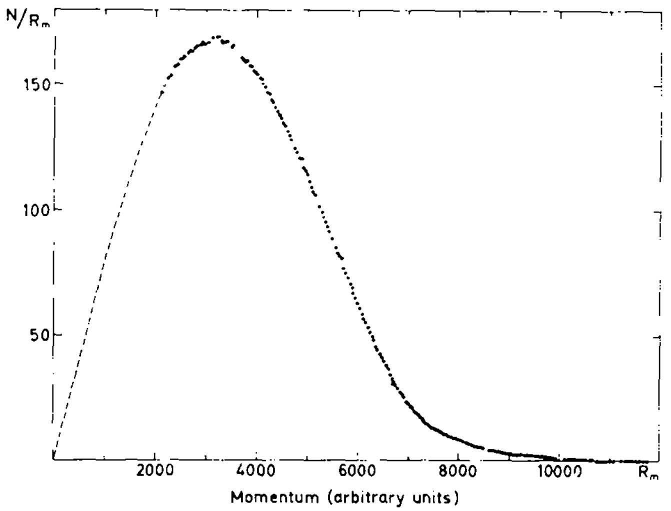

Fig. 2. Negaton spectrum of the decay of ^{140}La.

In the present work, the negaton spectrum from 200 keV to 4.5 MeV was investigated with the iron-yoke, double-focussing spectrometer. The energy region below 200 keV was found not worthwhile to measure as electron scattering due to source thickness and backing material might introduce erroneous results. The source was checked carefully and was found to contain no detectable impurities; also, the 329 keV K-conversion line exhibited no noticeable low-energy tail. Energy calibration was obtained by measuring the internal K-conversion lines of the 329, 1596 and 2522 keV transitions during the beta-spectrum run. Each point was corrected for decay and the spectrum obtained is shown in fig. 2.

The statistics in the most intense part of the spectrum was of the order of 10^{-3}. In the high-energy region, however, the natural background of the spectrometer ($\approx$ 0.1 counts/s) was too high for detecting the 3.85 MeV beta group reported by

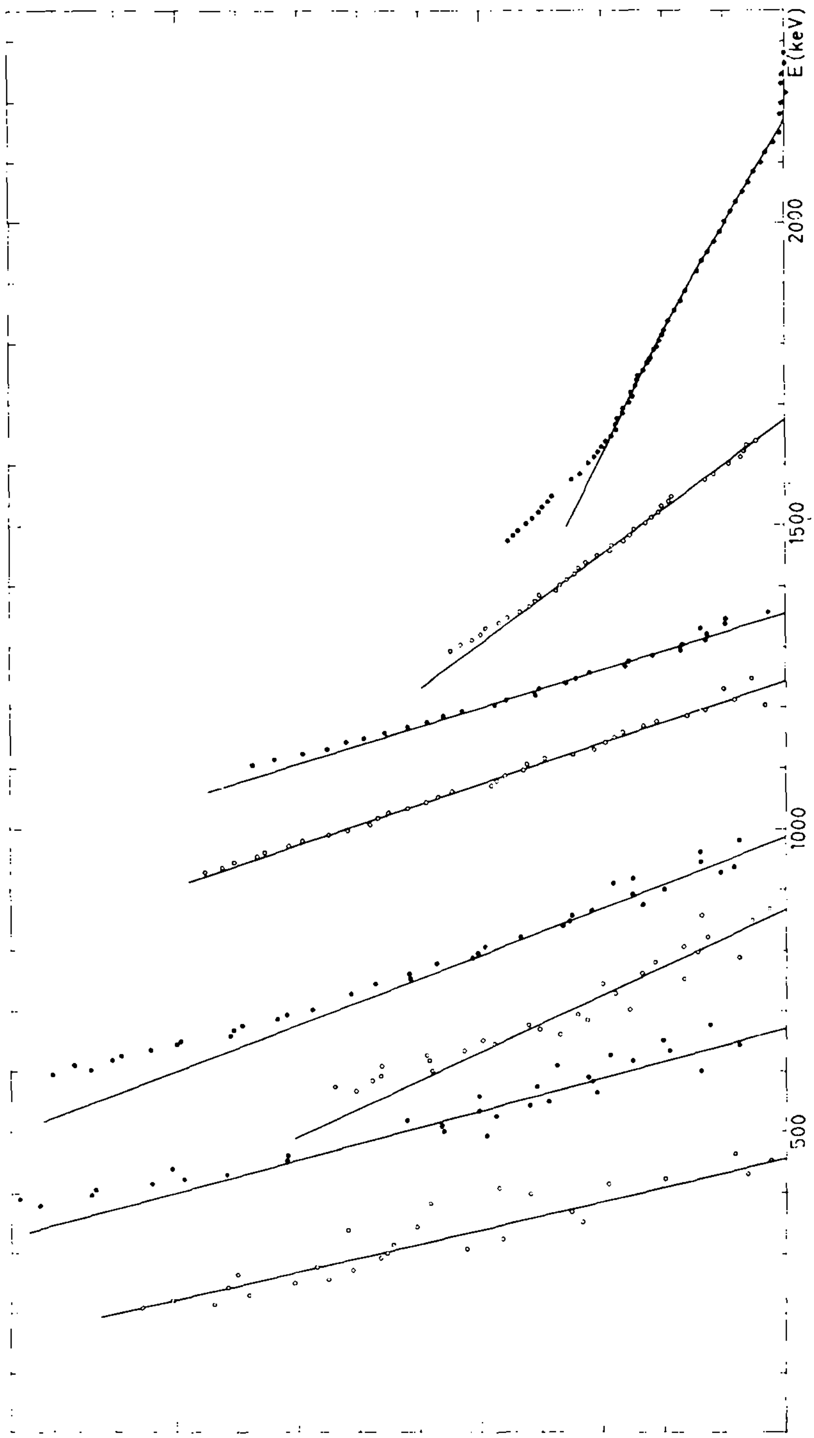

Fig. 3. Fermi-Kurie plots of the eight beta branches obtained in the analysis of the ^{140}La negaton spectrum.

Dzhelepov *et al.* 3). The Fermi-Kurie plot of the data is shown in fig. 3. The high-energy portion of the spectrum exhibits a curvature in accordance with the result of Langer and Smith 19). The maximum energy of this group was determined to be 2166 ± 7 keV. By successive subtractions from the total spectrum, evidence for a total of 8 different beta groups was obtained. Because of the errors, which are always introduced when making such subtractions, it was not possible to say anything about the shapes of the lower-energy groups, and therefore linearly extrapolated Fermi-Kurie plots were subtracted. It must be pointed out that the reliability of the different branches decreases rather rapidly with decreasing energy caused by the successive subtractions. During the analysis, it was realized that a small deviation from our reported optimized fit of the high-energy branches affected both the end-point energies and the intensities of the low-energy branches markedly.

Table 1

Beta-transition energies (in keV) and intensities (in brackets) from different investigations

Beach *et al.* 16)	Peacock *et al.* 17)	Bashilov *et al.* 18)	Dzhelepov *et al.* 3)	Langer and Smith 19)	Shinners 2)	Present	log *ft*
		420 ± 40			400 ± 20	≈ 460	7.6
		(16)			(4)	(≈ 1)	
					670 ± 20	≈ 670	7.5
					(11)	(≈ 4)	
	830	860 ± 30			930 ± 30	≈ 870	8.0
	(12)	(12)			(9)	(≈ 3)	
	1100	1150 ± 30			1120 ± 30	≈ 985	7.9
	(26)	(20)			(11)	(≈ 7)	
					1270 ± 20	1244 ± 20	7.8
					(18)	(19 ± 4)	
1320	1340	1360 ± 20			1410 ± 40	1354 ± 15	7.6
(70)	(45)	(30)			(26)	(42 ± 6)	
1670	1670	1620 ± 20		1680 ± 20	1730 ± 40	1674 ± 10	8.4
(20)	(10)	(14)			(13)	(17 ± 2)	
2260	2150	2200 ± 20	2200 ± 40	2175 ± 5	2220 ± 50	2166 ± 7	9.2
(10)	(7)	(8)	(10) a)	(≳ 5.7)	(8)	(7 ± 1)	
			3850 ± 100				
			(0.0008)				

a) Used in ref. 3) for normalization.

The end-point energies and intensities of the beta groups are listed in table 1. The intensities are given in per cent of the total decay. The log *ft* values were calculated and are also given in the table. The intensity of the 1596 keV K-conversion line was determined to be 0.063 ± 0.004 % of the total decay. The theoretical 20) K-conversion coefficient for this E2 transition is 6.90×10^{-4}, and thus 91 ± 6 % of the total decay passes through this transition, which is in agreement with previous investigations.

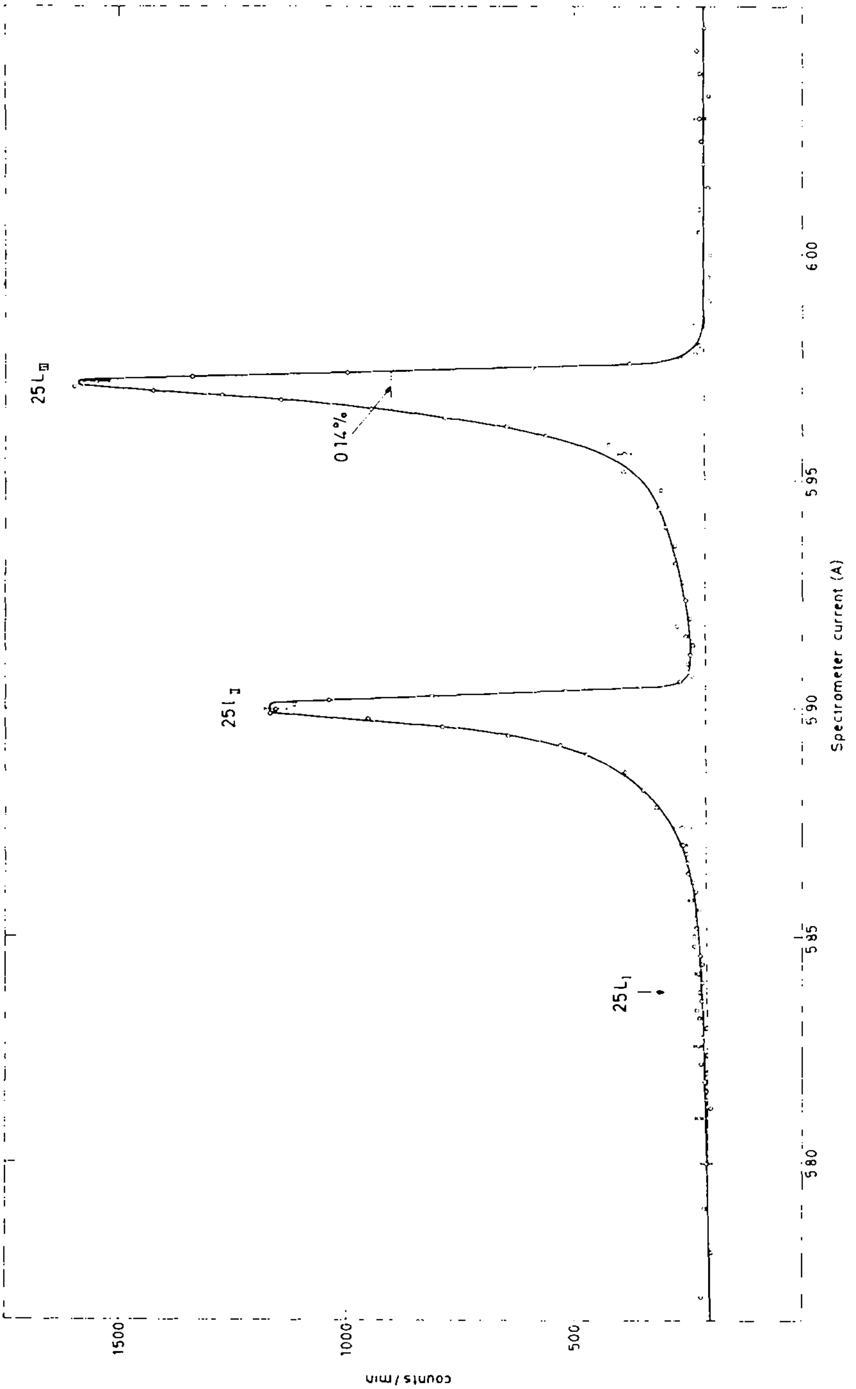

Fig. 4. The L-conversion lines of the 25 keV transition.

5. Internal-conversion measurements

5.1. IRON-FREE INSTRUMENT

The energy region 10-70 keV was scanned. Those parts of the spectrum where lines appeared were carefully remeasured. Each line was measured with at least two sources. All lines were repeated several times for half-life control, which was especially important with those sources where impurities were present. For electron energies above 70 keV, discrete lines were measured. The momentum resolution obtained ranged between 0.08 % and 0.20 %.

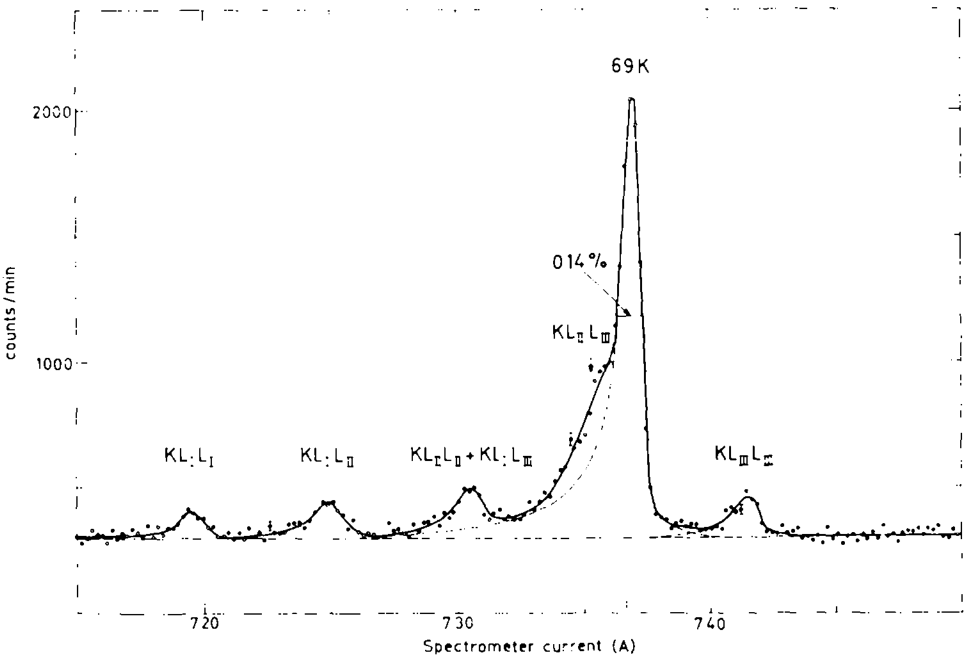

Fig. 5. The KLL Auger spectrum of Ce and the 69 keV K-conversion line.

The spectrometer was operated automatically, and the data were typed and punched out. A FORTRAN program was used to correct for counter dead-time, to subtract constant background and to make decay correction in a CD 3600 computer. Some examples of the corrected spectra obtained are shown in figs. 4-6.

For energy determination, two different definitions of line position were used. With the thin sources, the line position was defined as the intersection between the line contour and a line connecting the midpoints of chords parallel with the background. In analysing spectra from some thicker sources in the beginning of the investigation, where considerable tails on the low-energy lines were obtained, it was found more accurate to define the line position as the high-energy flank intersection with the background [compare ref. [21])].

In order to make an energy calibration of the internal conversion spectrum, the 329 keV K-line was carefully measured in each source. The transition energy was determined to be 328.75±0.05 keV from preliminary energy calibrations of the 329 keV K-line against different standard calibration lines. A more precise value was, however, later reported by Baer *et al.* [8]). Their result of 328.768±0.012 keV was therefore used.

The relative intensities of the lines were determined by measuring the areas, including low-energy tails, and correcting for momentum width and window absorption. The incomplete transmission of the detector window for electrons below 30 keV was corrected for with the aid of an empirically-deduced transmission curve. Though the intensity error of a line in this low-energy region due to this correction is large compared to that of a line of higher energy, one can still obtain a quite accurate ratio between the 25 keV L_{II} and L_{III} line intensities, for instance, as these lines lie near each other and the absorption difference is very small.

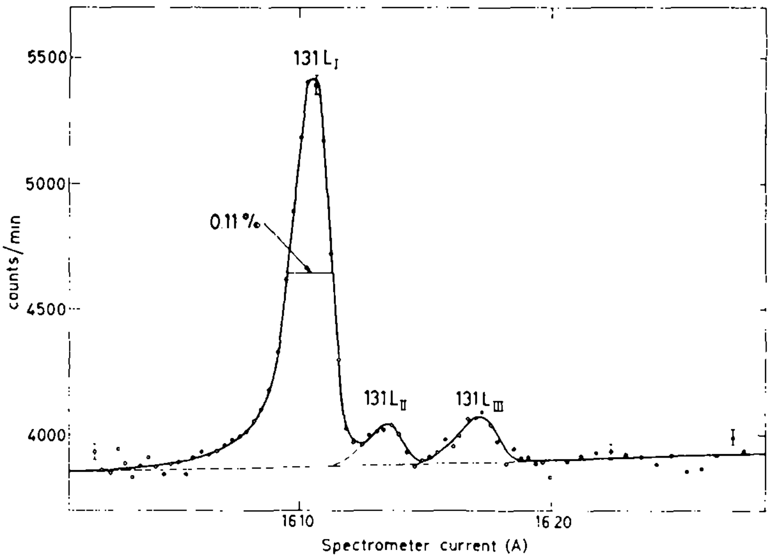

Fig. 6. The L-conversion lines of the 131 keV transition.

Close-lying lines were resolved in plots with a logarithmic intensity scale, taking the line shape from an isolated line in the vicinity. This was done in careful analyses of the L-spectra from the transitions below 300 keV.

The 25 keV transition was not reported prior to this investigation. The existence of two transitions between 60 and 70 keV was established. The K-line from the 69 keV transition was not seriously disturbed by the KLL Auger lines as seen in fig. 5. No evidence was found for the doublet structure of the 109 keV K-line reported by Cork *et al.* [4]) and Bashilov *et al.* [22]).

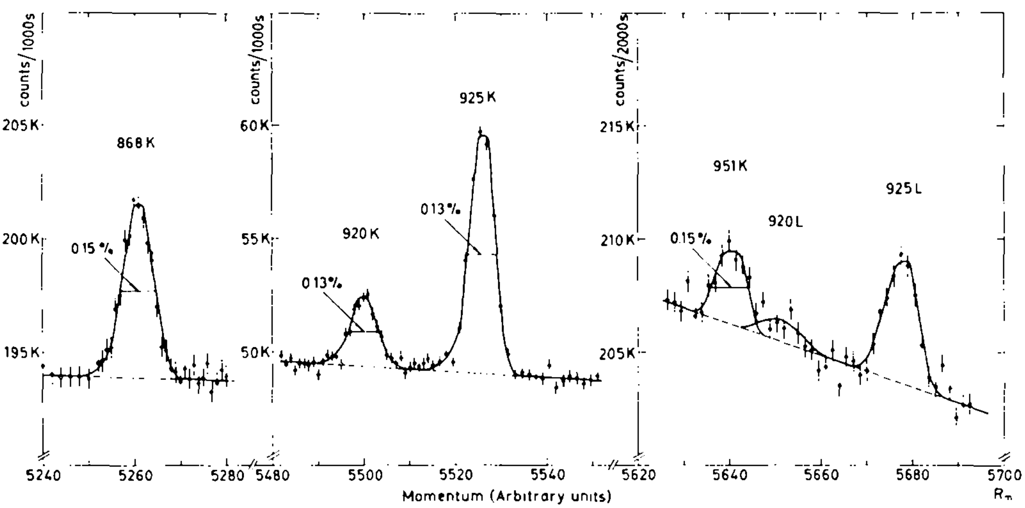

Fig. 7. Parts of the internal conversion spectrum showing the 868, 920, 925 and 951 keV conversion lines.

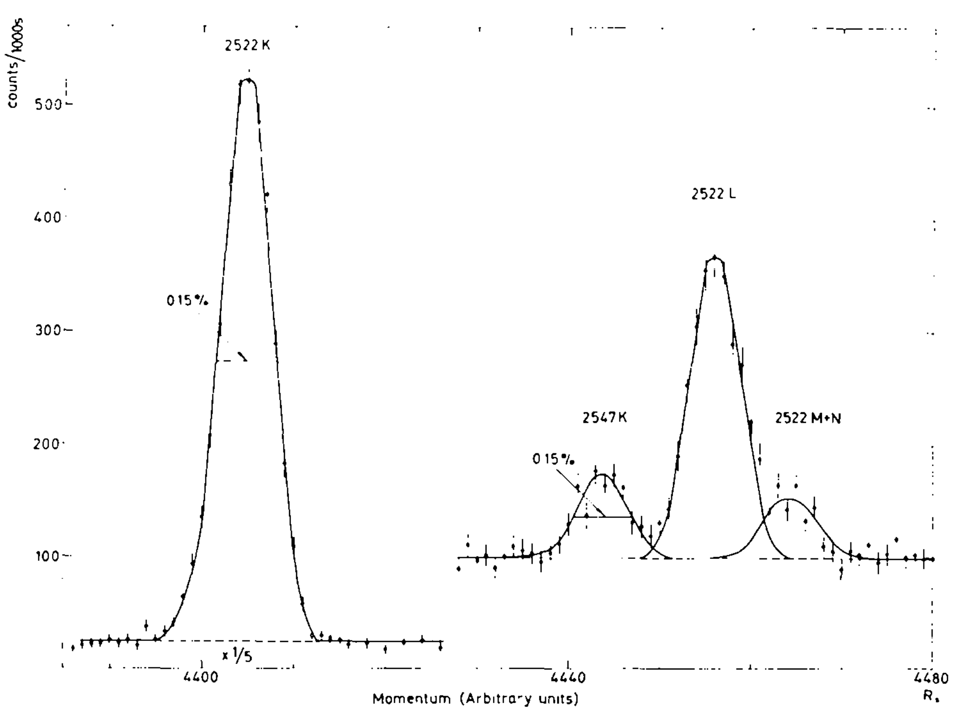

Fig. 8. Conversion lines of the 2522 and 2547 keV transitions.

5.2. IRON-YOKE INSTRUMENT

The spectrum was scanned from 60 keV up to 3.5 MeV with a momentum resolution of 0.13-0.25 %. The very intense negaton spectrum made it difficult to observe weak lines. However, all lines with an intensity exceeding 0.6 % of the 329 keV K-line were detected. In the high-energy region, the two GM tubes were always operated in coincidence, which reduced the natural background by a factor of five to about 0.1 counts/s, which was very useful in detecting the very weak transitions at 2900, 3119 and 3322 keV, the latter only reported once previously [23]). All K-conversion lines, except the weak transitions at 398, 868, 951, 2547, 2900, 3119 and 3322 keV, were measured at least three times with the same source and with a time interval of about 40 h between each run. All lines were measured with at least two different sources in order to check their relative intensities.

The transitions at 398, 868, 951 and 2547 keV and the doublet structure of the 923 keV transition earlier observed only in gamma measurements were confirmed by detecting their corresponding K-conversion lines (figs. 7 and 8).

Those regions of the spectrum where other investigators have reported transitions that were not observed in the scanning were remeasured with greater accuracy. The 618.2±0.7 keV transition, observed in the gamma spectrum and by Baer *et al.* [8]) has a K-conversion line intensity of less than 0.2 % of the 329 keV K-line. Bashilov *et al.* [22]) reported a 730 keV transition with a K-line intensity of 1.7 % of the 329 keV K-line. According to the present measurements, however, the K-line intensity of such a transition must be less than 0.2 % of the 329 keV K-line. Except for that transition the results of Bashilov *et al.* [22]) and those of the present investigation are in good agreement. The following gamma transitions (with our maximum K-conversion intensities in per cent of the 329 keV K-line within parentheses) have also been reported: 307 keV [refs. [8,24])] (< 0.3), 643 keV [ref. [25])] (< 0.1), 1088 keV [ref. [24])] (< 0.05), 1120 keV [ref. [5])] (< 0.02), 1415 keV [ref. [24])] (< 0.01) and 1680 keV [ref. [5])] (< 0.02), but none of these was observed.

In the energy region below 1600 keV, energy calibration was obtained with the strong transitions at 329 and 816 keV, the energies of which were taken from ref. [8]) and the iron-free spectrometer measurements, respectively. In the high-energy region, sources of ^{60}Co and ThB (X-line) were utilized for energy calibrations. Each line was measured twice with the source-ring turned 180° between each run in order to eliminate errors due to a slight deviation in the source position. The calibration energies were from refs. [26,27]). The line position was determined as the intersection of the low- and high-energy slopes of the line. The relative intensities were determined by the same method as described for the iron-free instrument, except that corrections for window thickness were not needed.

5.3. SUMMARY

The properties of the two spectrometers turned out to supplement each other in a nice way. Both energy and intensity values agree very well. In table 2, the transition energies are given as calculated from both instruments separately. The binding energies of Ce used in this investigation were taken from the tables of Bearden and Burr [28], and to their values a spectrometer work function of 4 ± 1 eV was added. The intensities of the K-conversion lines and the K/∑L ratios are given in table 3. Where both spectrometers were used for measuring a line, only the mean intensity value is given. The errors are estimated standard deviations.

TABLE 2

Energies of transitions in ^{140}Ce

Baer *et al.* [8]	Present investigation		
transition energies (keV)	transition energies (keV)		observed lines
	iron-free spectrometer	iron-yoke spectrometer	
	24.595 ±0.004		L_{II}, L_{III}, M_{II}, M_{III}, N
64.135 ±0.010	64.130 ±0.007		K, L_{I}, L_{II}
	68.916 ±0.006		K, L_{I}, L_{II}, M_{I}, N_{I}
109.418 ±0.007	109.417 ±0.006		γ, K, L_{I}, L_{II}, L_{III}, M_{I}, N_{I}
131.121 ±0.008	131.122 ±0.008		γ, K, L_{I}, L_{II}, L_{III}, M
173.536 ±0.012	173.550 ±0.011		γ, K, L_{I}
241.966 ±0.012	241.961 ±0.022		γ, K, L_{I}
266.551 ±0.014	266.547 ±0.022		γ, K, L_{I}
306.9 ±0.2			
328.768 ±0.012	328.768 ±0.012 [a]	328.768 ±0.012 [a]	γ, K, L_{I}, M
397.79 ±0.11		397.8 ±0.3	K
432.530 ±0.029	432.62 ±0.06	432.60 ±0.12	γ, K, L
487.029 ±0.019	487.042 ±0.029	487.06 ±0.11	γ, K, L, M
618.2 ±0.7			γ
751.827 ±0.080	751.75 ±0.08	751.71 ±0.12	γ, K, L
815.801 ±0.086	815.85 ±0.07	815.85 ±0.07 [b]	γ, K, L, M
867.82 ±0.14	867.87 ±0.15	867.92 ±0.20	γ, K
919.64 ±0.33	919.63 ±0.15	919.6 ±0.3	γ, K, L
925.20 ±0.17	925.24 ±0.09	925.33 ±0.20	γ, K, L
950.88 ±0.72		950.9 ±0.3	γ, K
1596.58 ±0.30	1596.49 ±0.24	1596.40 ±0.30	γ, K, L, M
	1903.57 ±0.50	1903.15 ±0.30	K, L, M
2348 ±2		2348.1 ±0.7	γ, K, L
2522 ±2		2521.7 ±0.5	γ, K, L, M
2547.5 ±2.5		2547.1 ±0.8	γ, K
2900 ±3		2900 ±2	γ, K
3123 ±5		3119 ±2	γ, K
		3322 ±4	K

[a] Calibration energy from ref. [8].

[b] Normalized to the measurements on the iron-free spectrometer.

TABLE 3

Gamma-ray, K-conversion and total intensities, conversion coefficients, K/ΣL ratios and deduced multipolarities for transitions found in the decay of ^{140}La

Transition energy (keV)	I_γ	$I_e(K)$	I_{tot} (% of total decay)	α_K	K/ΣL	Multipolarity
25			0.32 ±0.04			E2 (< 42 % M1)
64		$(2.5 \pm 0.4) \cdot 10^{-2}$	0.04 ±0.02		5.5 ± 2.5	M1 (< 3.7 % E2)
69		$(1.6 \pm 0.3) \cdot 10^{-1}$	0.24 ±0.06		6.0 ± 2.3	M1 (< 0.7 % E2)
109	0.5 ±0.2	$(1.55 \pm 0.05) \cdot 10^{-1}$	0.7 ±0.3	$(3.1 \pm 1.2) \cdot 10^{-1}$	5.6 ± 0.4	M1 + E2
131	1.05 ±0.15	$(2.20 \pm 0.08) \cdot 10^{-1}$	1.3 ±0.2	$(2.1 \pm 0.3) \cdot 10^{-1}$	5.6 ± 0.6	E1 + M2 (2–19 % M2)
174	< 0.8	$(2.3 \pm 0.3) \cdot 10^{-2}$	< 0.8	$> 2.5 \cdot 10^{-2}$	8.1 ± 1.3	M1(+E2)[a], E1(+M2)
242	0.83 ±0.10	$(3.34 \pm 0.23) \cdot 10^{-2}$	0.83 ±0.10	$(4.0 \pm 0.6) \cdot 10^{-2}$	7.4 ± 1.0	E1 + M2 (3–7 % M2)
267	0.83 ±0.10	$(3.1 \pm 0.3) \cdot 10^{-2}$	0.83 ±0.10	$(3.7 \pm 0.6) \cdot 10^{-2}$	6.5 ± 1.0	E1 + M2 (6–10 % M2)
329	25.4 ±2.0	$(7.58 \pm 0.10) \cdot 10^{-1}$	25.1 ±1.9	$(2.98 \pm 0.24) \cdot 10^{-2}$	7.4 ± 0.3	M1 + E2[a]), E1 + M2
398	0.06 ±0.03[b])	$(2.3 \pm 1.5) \cdot 10^{-3}$	0.06 ±0.03	$(4 \pm 2) \cdot 10^{-2}$		
433	3.5 ±0.3	$(5.8 \pm 0.3) \cdot 10^{-2}$	3.4 ±0.3	$(1.66 \pm 0.17) \cdot 10^{-2}$	6.7 ± 0.9	M1 + E2[a]), E1 + M2
487	49.6 ±3.2	$(4.40 \pm 0.23) \cdot 10^{-1}$	47.9 ±3.2	$(8.9 \pm 0.7) \cdot 10^{-3}$	6.0 ± 0.4	E2
618	0.4 ±0.3	$< 2.2 \cdot 10^{-3}$	0.4 ±0.3			
752	4.5 ±0.4	$(1.97 \pm 0.23) \cdot 10^{-2}$	4.3 ±0.4	$(4.4 \pm 0.6) \cdot 10^{-3}$	> 4.6	M1 + E2[a]), E1 + M2
816	23.5 ±2.0	$(9.5 \pm 0.6) \cdot 10^{-2}$	22.5 ±1.9	$(4.0 \pm 0.4) \cdot 10^{-3}$	7.0 ± 1.2	M1(+E2)[a]), E1 + M2
868	5.6 ±0.5	$(6.1 \pm 1.5) \cdot 10^{-3}$	5.3 ±0.5	$(1.1 \pm 0.3) \cdot 10^{-3}$		E1 (+M2)
920	2.5 ±0.6	$(6.1 \pm 1.5) \cdot 10^{-3}$	2.4 ±0.6	$(2.4 \pm 0.8) \cdot 10^{-3}$		E2(+M1)[a]), E1 + M2
925	6.8 ±0.6	$(2.27 \pm 0.23) \cdot 10^{-2}$	6.5 ±0.6	$(3.3 \pm 0.4) \cdot 10^{-3}$	9.0 ± 3.0	M1 (+E2)[a]), E1 + M2
951	0.8 ±0.3	$(1.4 \pm 0.4) \cdot 10^{-3}$	0.8 ±0.3	$(1.8 \pm 0.8) \cdot 10^{-3}$		E2(+M1)[a]), E1 + M2
1596	100 ±5	$(6.9 \pm 0.4) \cdot 10^{-2}$	95.5 ±4.8	$(6.9 \pm 0.5) \cdot 10^{-4}$	8.2 ± 1.0	E2
1903	< 0.2	$(1.52 \pm 0.15) \cdot 10^{-2}$	0.019 ±0.003	$> 7 \cdot 10^{-2}$	8.4 ± 1.4	E0
2348	1.0 ±0.2	$(3.3 \pm 0.5) \cdot 10^{-4}$	1.0 ±0.2	$(3.3 \pm 0.8) \cdot 10^{-4}$	6.5 ± 1.5	E2 or M1
2522	3.5 ±0.2	$(1.21 \pm 0.15) \cdot 10^{-3}$	3.3 ±0.2	$(3.5 \pm 0.5) \cdot 10^{-4}$	7.7 ± 1.4	M1 or E2
2547	0.11 ±0.02	$(3.5 \pm 0.8) \cdot 10^{-5}$	0.11 ±0.02	$(3.2 \pm 1.0) \cdot 10^{-4}$		M1 or E2
2900	0.06 ±0.01	$(1.8 \pm 0.3) \cdot 10^{-5}$	0.06 ±0.01	$(3.0 \pm 0.7) \cdot 10^{-4}$		M1 or E2
3119	0.03 ±0.01	$(6.8 \pm 2.3) \cdot 10^{-6}$	0.03 ±0.01	$(2.3 \pm 1.0) \cdot 10^{-4}$		M1 or E2
3322		$(9 \pm 5) \cdot 10^{-7}$				

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a) Favoured from decay scheme. b) Intensity from ref. [8]).

6. Gamma-ray measurements

The gamma-ray spectrum was studied using the Ge(Li) detector. The source was placed 6 cm from the detector. The efficiency of the system was measured with standard reference sources. An error of 5 % was attributed to the calibration curve obtained. Several spectra were taken at various times after the end of the irradiation.

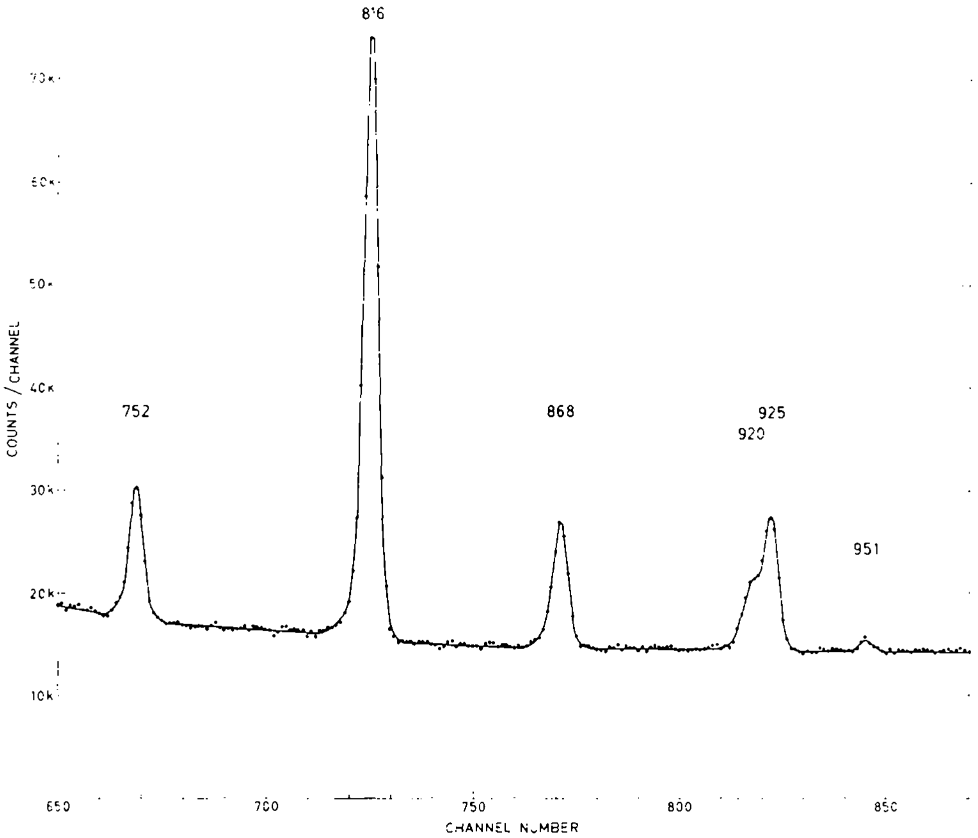

Fig. 9. Part of the gamma spectrum recorded with the Ge(Li) detector.

All the transitions appeared to have the same relative intensities in all the runs. A part of the spectrum is shown in fig. 9.

The intensities were determined relative to the gamma intensity of the 1596 keV transition and are listed in table 3. The quoted errors include those due to statistics, evaluation method and efficiency uncertainty. Most of the transitions observed in the internal conversion measurements were found (compare table 2.) The 618 keV transition reported by Baer *et al.* [8]) and Salling [29]) was observed. It was, however, not possible to detect the weak 307 transition also reported by Bear *et al.* A

307 keV photopeak would be located on the Compton edge of the strong 487 keV transition and thus difficult to detect.

Indications of photopeaks at 147 and 270 keV were observed. Nothing definitely can, however, be stated about the existence of the corresponding transitions, since the observed peaks are located at the backscattering peak of the 329 keV gamma ray and the Compton edge of the 433 keV transition, respectively. The 174 keV photopeak is located on the backscattering peak of the 487 keV transition, and it was for that reason not possible to determine its gamma-ray intensity. All the relative intensities are in good agreement with those reported by Baer *et al.* ^{8}) and Prikhodtseva and Khol'nov ^{25}).

7. Multipolarities

The theoretical ^{20}) K-conversion coefficient for the 1596 keV E2 transition is 6.90×10^{-4}; this value was used for normalizing the conversion line intensities of table 3. The K-conversion coefficients were obtained as the ratios of the normalized K-conversion intensities and the gamma-ray intensities of this work. In fig. 10, these experimentally determined coefficients are compared to the theoretical ones of Sliv and Band ^{20}).

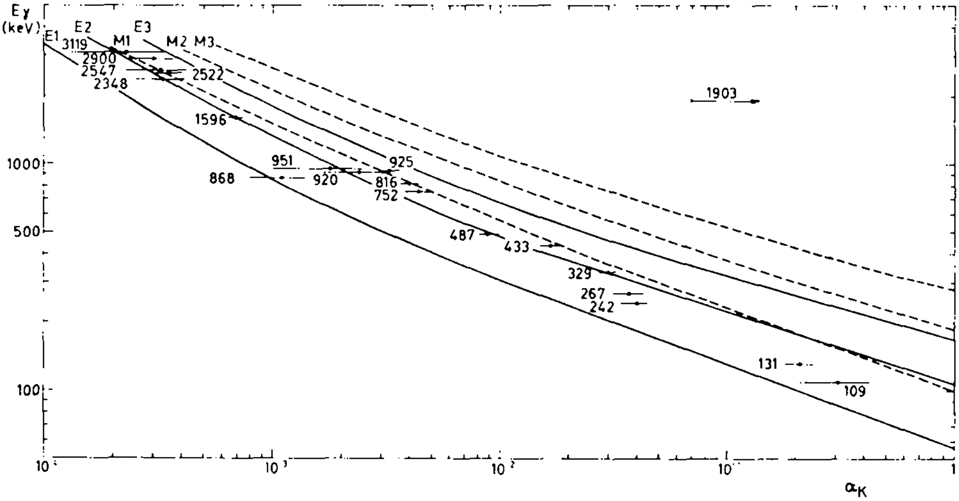

Fig. 10. Experimental K-conversion coefficients compared to the theoretical coefficients for $Z = 58$ given by Sliv and Band ^{20}). The 1596 keV pure E2 transition was used for normalization.

In the low-energy region, where the gamma-ray intensities were difficult to determine accurately, the $K/\sum L$ or L-subshell ratios generally provide better information of multipolarity assignments. In fig. 11 curves of $K/\sum L$ ratios are drawn using the conversion coefficients of Sliv and Band ^{20}) compared to the experimental ratios listed in table 3. However, from that figure it is obvious that in most cases the errors of the K/$\sum$L ratios of this work are too large and thus prevent definite assignments. The L-subshell ratios were determined for the low-energy transitions. In table 4 these ratios and the K/$\sum$L ratios are listed and compared with the theoretical ones [20].

Transitions proceeding to or from 0^+ states must be of pure multipolarity. This means that the high-energy ground state transitions at 2348, 2522, 2547, 2900 and 3119 keV must, according to fig. 10, be of M1 or E2 multipolarity. It is, however, not possible to distinguish between these two alternatives. The E0 assignment of the 1903 keV transition is confirmed.

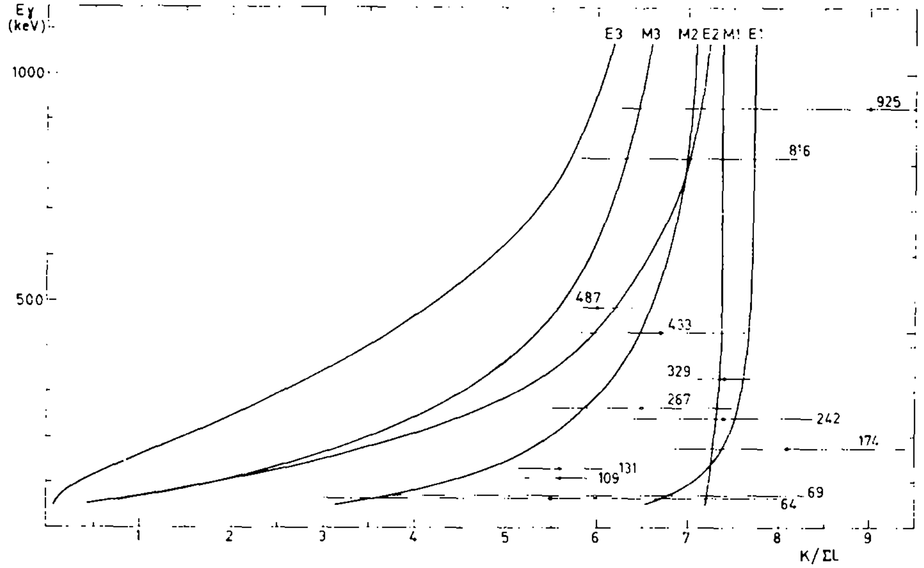

Fig. 11. Experimental K/ΣL ratios compared to the theoretical values of Sliv and Band [20].

All transitions ranging in energy from 752 to 951 keV are compatible with mixtures of M1+E2 or E1+M2 except the 868 keV transition, which seems to be of pure E1 multipolarity. However, the 920 and 951 keV lines may be pure E2 transitions and the 816 and 925 keV lines are probably M1 transitions.

The experimental values of α_K and K/$\sum$L for the 487 keV transition are both compatible with a pure E2 assignment, which is in agreement with previous determinations.

The K-conversion coefficient of the 433 keV transition is consistent with the theoretical values for M1+E2 and E1+M2 mixtures. The M3 multipolarity as proposed by El-Nesr and El-Sayad [30] is excluded from the present data.

Concerning the 329 keV transition, the K-conversion coefficient from this work, which is in excellent agreement with the value $\alpha_K = 2.9 \times 10^{-2}$ reported by Bashilov *et al.* [22], indicates a pure E2 multipolarity. An E2 assignment is, however, in disagreement with the K/$\sum$L ratio (fig. 11) and also with our determinations of the lower

TABLE 4

Experimental and theoretical K/ΣL and L-subshell ratios for the lowest energy transitions

		Intensity ratio							
		Exp.	Theoretical [a]						Multipolarity
			E1	M1	E2	M2	E3	M3	
25	L_I/L_{II}	< 0.03	1.9	11.2	0.005	13.2	0.013	11.2	E2 (< 42 % M1)
	L_I/L_{III}	< 0.02	1.3	52	0.004	2.0	0.010	0.25	
	L_{II}/L_{III}	0.68 ± 0.03	0.63	4.6	0.69	0.16	0.73	0.022	
64	K/ΣL	5.5 ± 2.5	6.7	7.2	0.80	3.35	0.10	0.95	M1 (< 3.7 % E2)
	L_I/L_{II}	> 3	4.3	12.4	0.16	9.2	0.011	6.4	
	L_I/L_{III}	> 4.5	3.0	58	0.13	3.8	0.010	0.75	
69	K/ΣL	6.0 ± 2.3	6.8	7.2	0.95	3.75	0.12	1.1	M1 (< 0.7 % E2)
	L_I/L_{II}	> 6.7	4.6	12.5	0.19	9.0	0.015	6.2	
	L_I/L_{III}	> 20	3.3	59	0.16	4.1	0.014	0.82	
109	K/ΣL	5.6 ± 0.4	7.15	7.25	2.07	4.5	0.42	2.05	M1 + E2
	L_I/L_{II}	8.5 ± 1.5	6.6	13.1	0.49	8.6	0.073	5.9	
	L_I/L_{III}	13 ± 3	4.8	64	0.45	6.2	0.074	1.4	
	L_{II}/L_{III}	1.5 ± 0.5	0.75	4.8	0.94	0.72	1.05	0.25	
131	K/ΣL	5.6 ± 0.6	7.23	7.26	2.60	4.82	0.65	2.44	E1 + M2 (2–19 % M2)
	L_I/L_{II}	9.2 ± 3.0	7.5	13.4	0.67	8.7	0.12	5.8	
	L_I/L_{III}	8.9 ± 2.5	5.6	65	0.65	7.5	0.13	1.8	
	L_{II}/L_{III}	0.9 ± 0.2	0.76	4.8	0.98	0.88	1.13	0.31	

[a] Ref. [20].

limits of the L_I/L_{II} (> 6) and L_I/L_{III} (> 15) ratios. The remaining alternatives are E1 + M2 and M1 + E2 mixtures. From the data of this investigation it is not possible to distinguish between these alternatives, but according to angular correlation experiments [6, 31]) the 329 keV transition is an M1 + E2 mixture.

From fig. 10 it is obvious that the 242 and 267 keV transitions are E1 + M2 mixtures, which is also consistent with the $K/\sum L$ ratios. The M2 contents of these lines are, according to the K-conversion coefficients 3-7 % and 6-10 %, respectively.

Since the intensity of the 174 keV gamma ray may be influenced by backscattering, only its upper limit is given. Therefore, only a lower limit of α_K was obtained, from which no conclusion can be drawn. However, a low multipolarity assignment is supported by the $K/\sum L$ ratio.

From the $K/\sum L$ and L-subshell ratios, the 131 keV transition was found to be a mixed E1 + M2 transition which is also consistent with the determined K-conversion coefficient. Concerning the 109 keV transition, the $K/\sum L$ and L-subshell ratios give a multipolarity assignment of M1 + E2 with a small E2 content. However, the α_K for this transition points to E1 + M2 mixture. The M1 + E2 assignment was chosen since the possibility of an improper determination of the gamma intensity at such a low energy cannot be excluded.

The 64 and 69 keV transitions were both found to have magnetic dipole character with less than 3.7 % and 0.7 % E2 content, respectively. As the 69 K-line intensity is about six times stronger than that of the 64 K-line, it is astonishing that Baer *et al.* [8]) did not observe the 69 keV gamma ray in their investigation.

From the L-subshell ratios for the 25 keV transition, a pure E2 assignment is possible, but an M1 admixture of as much as 42 % cannot be excluded.

8. Decay scheme and discussion

A tentative scheme for the decay of ^{140}La consistent with the results obtained in this investigation and with most previous measurements is given in fig. 12. All levels in ^{140}Ce suggested in ref. [1]) except those at 2650 and 3380 keV are included. The levels at 2516 and 2547 keV suggested by Baer *et al.* [8]) from their gamma-ray measurements are confirmed, and new levels at 2325, 2350, 2481, 3216 and 3322 keV are proposed.

The 2522, 2547, 2900 and 3119 keV transitions are of pure M1 or E2 character and, since the ground state of ^{140}Ce is 0^+, the parities of the corresponding levels are even and their spins 1 or 2. As for the 2900 and 3119 keV levels the ground state transitions are the only de-exciting transitions found, no additional assignment information can be obtained for those levels. The multipolarity E2(+M1) of the 951 keV transition, which also de-excites the 2547 keV level, is compatible with both assignments given for that level. The 2522 keV level is de-excited by four transitions besides the ground state transition but only the 109 keV transition favours one of the two possibilities. This mixed M1 + E2 transition, which is not compatible with a pure

E2 assignment from L subshell ratios, proceeds to the 2412 keV 3^+ level. The J^π assignment of the 2522 keV level must therefore be 2^+. This result is in disagreement with that of Dzhelepov *et al.* [33]) and Antonova *et al.* [34]), who reported an M1 multipolarity for the 2522 keV transition.

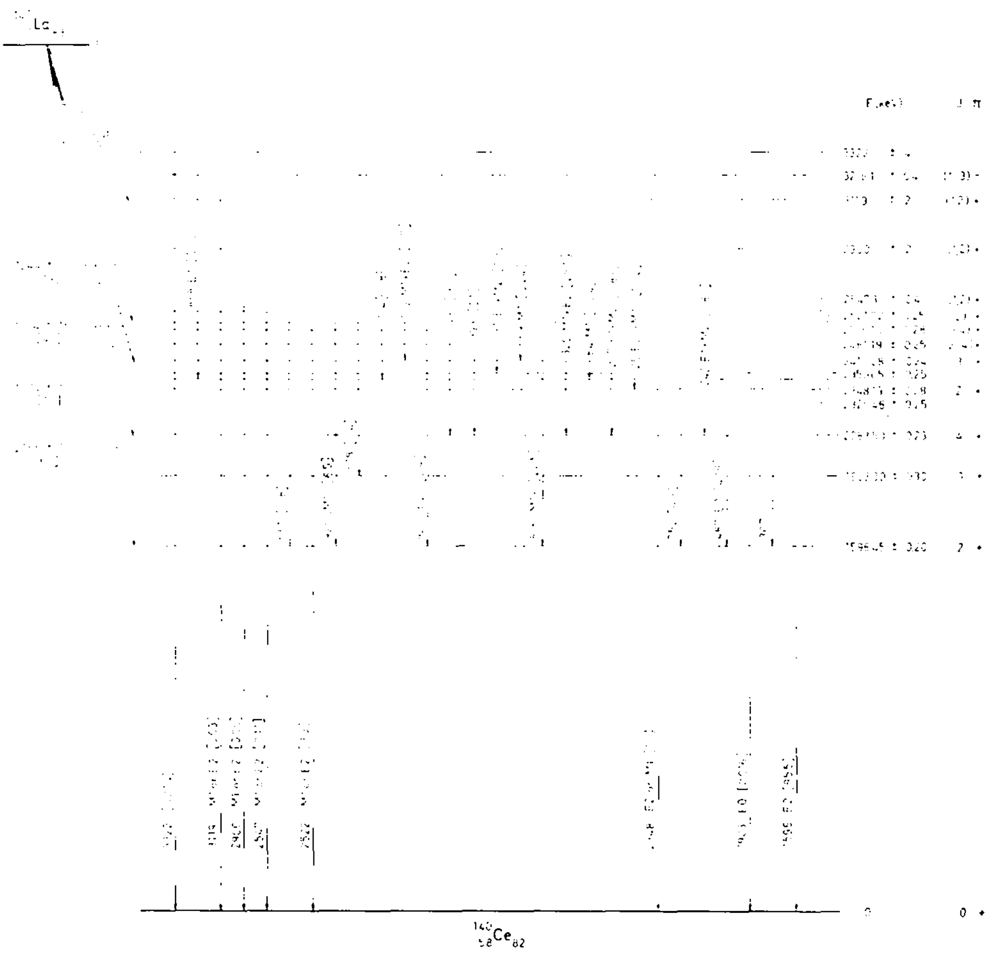

Fig. 12. Decay scheme proposed from this investigation. The levels drawn with dashed lines are based on weak arguments. The 307 keV transition according to Baer *et al.* [8]) is also dashed in the scheme. The total intensities of the transitions, in per cent of the number of disintegrations, are given between brackets. The level spacings in the energy region 2325-2547 keV are not drawn to scale.

The existence of a level at 2516 keV, as proposed by Baer *et al.* [8]), is supported by the results of this investigation since the agreement between the transition energy 919.63±0.15 keV and the sum 432.61+487.05 = 919.66±0.07 keV is very good. The multipolarity of the 920 keV transition is most probably E2 but a mixture of

E2+M1 or E1+M2 cannot be excluded from the K-conversion coefficients obtained. The 433 keV transition is a mixed M1+E2 or E1+M2 transition. Combining these multipolarity assignments with the spins and parities of the levels fed by the two transitions agreement with the assignments $3^{\pm}$ or $4^{\pm}$ for the 2516 keV level is obtained. From the relative beta feeding to the levels (see below), however, the negative-parity states are excluded and the 4^{+} assignment is favoured.

The new levels introduced at 2325, 2350 and 2481 keV are based mainly on energy-sum relationships. The energy sum $24.595+241.961 = 266.556\pm0.023$ agrees very well with the energy of the 266.547 ± 0.022 keV transition. Two other energy sums agree also very well; $68.916+328.768 = 397.684\pm0.014$ keV and $131.122+266.547 = 397.669\pm0.024$ keV. The K-conversion line of a possible cross-over transition with an energy of 397.8 ± 0.3 keV was also observed. The probability that the good agreement between the energy sums is only accidental is vanishingly small since the number of transitions observed is rather limited and since the errors in the transition energies are very small. The 398 keV transition must therefore be a cross-over transition to the 69-329 keV and the 131-267 keV cascades, the 267 keV transition being the cross-over transition to the 242-25 keV cascade.

The location of the 329 keV transition in the level scheme is well known [1]. The condition that the 69 and 329 keV transitions shall form a cascade means that the 69 keV transition either feeds the 2412 keV level or de-excites the level at 2084 keV. The latter possibility is excluded since no transition has been found which can de-excite a level at 2015 keV. A level at 2481 keV is therefore most probable. The order between the transitions in the 131-25-242 keV cascade can only be determined from intensity considerations since no transition from the possible levels to previous levels is observed except for the 2084 keV level. The summed total intensity of the 242 and 267 keV transitions is somewhat larger than the intensity of the 131 keV transition, and the intensity of the 25 keV transition is less than that of the 242 keV transition. The summed intensity of the 25 and 267 keV transitions, however, agrees very well with the intensity of the 131 keV transition. To maintain intensity balance between the feeding and de-exciting transitions to the new levels the weaker transitions ought to precede the stronger ones. The deficient feeding to the 2325 keV level may be explained by a weak, non-observed beta branch to that level. This intensity consideration favours the location of the levels at 2325 and 2350 keV as given in the decay scheme. However, the intensity differences are small and intensity balance may also be maintained by weak, non-observed transitions to lower levels. Alternative locations of these levels can therefore not be excluded. The possible alternative levels are

$$2083.50+\ 24.60 = 2108.10\pm0.23\ \text{keV},$$

$$2083.50+131.12 = 2214.62\pm0.23\ \text{keV}$$

$$2481.19-\ 24.60 = 2456.59\pm0.25\ \text{keV}.$$

A transition of energy 618.2 ± 0.7 keV has been observed by Baer *et al.* [8]) and in the gamma-ray measurements in this work. This energy value agrees very well with the difference in energy between the possible level at 2215 keV and the 1596 keV level, but it also agrees with the difference between the 2522 and 1903 keV levels. From coincidence measurements Salling [29]) also found that a transition of this energy feeds the 1903 keV level. Since the intensity reported by Baer *et al.* [8]) for the 307 keV transition de-exciting the 1903 keV level is about half the intensity of the 618 keV transition and the total intensity of the 1903 keV transition is about the same as that for the 307 keV transition [29]), the intensity of the 618 keV transition is well accounted for by the feeding of the 1903 keV level.

In table 3 the multipolarity assignments for the 131, 242 and 267 keV transitions are E1 + M2 and for the 25 keV transition E2(+ M1). These multipolarities all indicate negative parities for the 2325 and 2350 keV levels. The values of J^π for the 2325 keV level may be 3^-, 4^- or 5^- and those for the 2350 keV level may be 2^-, 3^-, 4^- or 5^-. The absence of observed beta feeding indicates 5^- for both levels.

Only the 868 keV transition remains to be placed into the decay scheme but since no energy relationship is obtained between this transition and other transitions in ^{140}Ce, its location must be based on intensity considerations. Preliminary to these considerations a discussion of the beta feeding of the levels is required.

From previous measurements [1]) the beta branch with an end-point energy of about 2166 keV is known to feed the 1596 keV level. The Q-value obtained for the decay of ^{140}La to ^{140}Ce is therefore 3762 ± 8 keV. This value is in good agreement with that tabulated by Mattauch *et al.* [32]) (3769 ± 5 keV) and with the end-point energy of the very weak beta branch feeding the ground state of ^{140}Ce, 3850 ± 100 keV, reported by Dzhelepov *et al.* [3]).

Other beta branches feed the 1596, 2084 and 2412 keV levels. The 1244 ± 20 keV branch feeds one, two or all three of the levels at 2516, 2522 and 2547 keV. A level at about 2777 keV is possible, based on the 985 keV beta transition, but no transition de-exciting such a level was found. Due to the large errors introduced by the subtraction of the strong, high-energy branches, the results for the comparatively weak, low-energy beta branches must be considered as very uncertain. Although the beta transitions are forbidden, no shape factors were applied in the Fermi-Kurie analysis except for the branch of the highest energy. This fact may cause additional errors in end point energies for the low-energy transitions. Another fact which must be taken into account is that beta transitions of a non-negligible intensity may proceed to those levels to which no beta feeding was observed. This may especially be the case to levels in the region 2325-2547 keV, where the levels are located very near each other and a small deviation from linearity near the end-point energy of a stronger transition would not be observed. Agreement between the end-point energies and the intensities reported by different investigators (see table 1) is also poor. Therefore, the conclusion must be drawn that the feeding to the high-energy levels remains uncertain, and coincidence studies are needed in order to solve the problem.

The high log *ft* values obtained for the beta transitions to the 1596, 2084 and 2412 keV levels and the group around 2520 keV are in agreement with first-forbidden transitions which ought to occur from the 3^- ground state [1, 35]) of ^{140}La to even-parity levels with spins 2, 3 or 4 in ^{140}Ce. The high log *ft* value obtained for the 1244 keV beta transition excludes the possibility of odd parity for the 2516 keV level. Because of the low beta feeding to that level in comparison with that to the 2412 keV 3^+ level, the 4^+ assignment for the 2516 keV level is weakly favoured relative to the 3^+ possibility.

Intensity balance well within the error limits was obtained for all the levels below 2550 keV except for the 2325, 2348 and 2481 keV levels. For the 2325 and 2481 keV levels balance is obtained by assuming weak ($\approx$ 1 % of the total number of decays) beta transitions feeding these levels. Such weak branches are difficult to observe, since their end-point energies are so near to the strong 1354 and 1244 keV branches. A beta feeding of as much as 4.8 ± 0.7 % is required to obtain intensity balance for the 2348 keV level. Such a beta branch would have been observed and the deficient feeding of this level must be accounted for in some other way. There is a considerable excess of feeding to the high-energy levels of 15 ± 8 % of the total number of decays. The intensity of the 868 keV transition is 5.3 ± 0.5 % and a feeding by this transition should accordingly completely eliminate the deficient feeding to the 2348 keV level and also reduce the excess of feeding to the upper levels in the scheme. Due to these weak arguments the 868 keV transition is placed between the 2348 keV level and a new level at 3216 keV. Since this transition most probably is an E1 transition and the 2348 keV level has the J^π assignment 2^+, the possible J^π values for the 3216 keV level are 1^-, 2^- and 3^-. The log *ft* value for a transition to this level with an intensity of 5.3 % of the total decay rate is 7.1, a value that does not definitely favour any of the possible assignments.

The decay scheme of ^{140}La shown in fig. 12 is consistent both in regard to the energies and to the intensities except for the excess of beta feeding to the high-energy levels in ^{140}Ce. To eliminate the uncertainty about feeding to these levels, coincidence measurements are needed. The levels represented by dashed lines are tentative and must be confirmed by further investigations.

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