Further Study on Υ Transitions in ¹⁴⁰Ce

M. S. El-Nesr and M. R. El-Aassar

Nuclear Physics Department, Atomic Energy Establishment, Cairo, U.A.R.

A photoline spectrum from the γ rays of energies greater than 200 keV following the decay of 40-hour ¹⁴⁰La has been studied using a high resolution double focusing β-ray spectrometer. The photoelectrons are produced from an uranium radiator of thickness 2.9 mg/cm². The resulting momentum resolution was $0.3 \rightarrow 0.8\%$ depending on energy. In addition to γ rays previously reported, we have observed 17 new γ transitions in the energy region of about one MeV to 2.53 MeV. The relative γ-ray intensities have been determined from the external conversion spectrum applying the corrections for the angular dependence of the photo-electric process. Gamma energies and intensities higher than 2.53 MeV have been investigated by means of a scintillation spectrometer using a RIDL-transistorized 400 channel analyzer. A complete set of energy sums was computed in order to survey the possibilities of cascade crossover combinations. Thirteen direct ground state transitions of energies 204.87, 241.95, 993.12, 1597.48, 1973.38, 2026.37, 2350.23, 2371.11, 2410.33, 2530.03, 2900, 3100 and 3471 keV were observed. A few modifications on the previously reported level scheme of ¹⁴⁰Ce are proposed after the addition of the 17 new γ rays. Conversion coefficients were obtained by normalizing the ratios of conversion and photon intensities with respect to the 487 keV-E2 transition in ¹⁴⁰Ce. From the known internal conversion coefficient of this transition, the absolute K-internal conversion coefficients of the transitions 200.08, 241.95, 273.69, 337.50, 374.81, 400.53 and 875.30 keV were determined to confirm their multipolarities and support spin and parity assignments of the levels 242, 617, 1260, 1323, 2184, 2515, 2585 and 3390 keV.

The absolute K-internal conversion coefficients of the 542.43, 641.41, 752.62, 927.41, 980.19, 1016.20, 1040.31 and 1054.65 keV transitions were measured for the first time. The multipolarity assignments of these transitions were studied on the basis of the conversion coefficients. These measurements together with the previously known assigned levels establish the spins and parities 3−, 0+, 2+, 4+, 2+, and 2+ for the levels 205, 1889, 1973, 2084, 2350 and 2530 keV, respectively. Spin and parity assignments of 1+ and 4− are proposed for the 2900 and 3100 keV excited levels in ¹⁴⁰Ce.

Lanthanum-140 is an odd-odd nucleus which decays with a halfvalue period of 40 h to the even-even nucleus cerium-140. The decay of ¹⁴⁰La to a number of levels in ¹⁴⁰Ce has been studied previously by several investigators [1−8]. A recent measurement [9] on the electron conversion spectrum associated with the ¹⁴⁰La decay has been studied at this Laboratory for transition energies up to 1054 keV. Since all investigations [3, 4, 6−8] above one MeV have been performed by scintillation techniques and the internal conversion coefficient is low at high energies especially for this intermediate nucleus, it was decided to study carefully the ¹⁴⁰La decay by the external photo-electric conversion method, utilizing

a high accuracy and resolution double focusing β-ray spectrometer. In this investigation precision measurements of γ energies above 200 keV have been performed. In addition to the accurate energy values supposed to be obtained by this method, γ-ray intensities have been determined.

From previous work [9] spin and parity of the excited levels in ¹⁴⁰Ce have been determined from the comparison of the observed internal conversion line intensity ratios $K/\Sigma L$ with the theoretical values calculated by SLIV and BAND [10]. Since the conversion line intensity ratios of some transitions could not give definite multipolarity assignments, we have decided to determine the absolute K-internal conver-

[1] J. M. CORK, A. E. STODDARD, J. M. LEBLANC, C. E. BRANYAN, D. W. MARTIN, and W. J. CHILDS, Phys. Rev. **83**, 856 [1951].
[2] B. L. ROBINSON and L. MADANSKY, Phys. Rev. **84**, 1067 [1951].
[3] H. H. BOLOTIN, C. H. PRUETT, P. L. ROGGENKAMP, and R. G. WILKINSON, Phys. Rev. **99**, 62 [1955].
[4] C. E. COLEMAN, Phil. Mag. **46**, 1132 [1955].
[5] B. S. DZELEPOV, YU. V. KHOLNOV, and V. P. PRIKHODTSEVA, Nucl. Phys. **9**, 665 [1958/59].
[6] V. P. PRIKHODTSEVA and YU. V. KHOLNOV, Izvest. Akad. Nauk, SSSR, Ser. Fiz. **22**, 176 [1958].
[7] P. G. HANSEN and K. WILSKY, Nucl. Phys. **30**, 405 [1962].
[8] L. SIMONS, K.-E. NYSTEN, P. HOLMBERG, H. JUNGNER, A. ANTTILA, S. BERGSTRÖM, and E. HAGEBØ, Acta Polytech. Scand., Phys. Nucl. Ser., No. **22**, 1 [1963].
[9] M. S. EL-NESR, M. R. EL-AASSAR, G. M. EL-SAYAD, and M. MIGAHED, Atomkernenergie (in press).
[10] L. A. SLIV and I. M. BAND, Tables of Internal Conversion Coefficients of γ Rays (Physico-Technical Institute, Academy of Science, Leningrad, 1956). — L. A. SLIV and I. M. BAND, Coefficients of Internal Conversion of γ Radiation (Physico-Technical Institute, Academy of Science, Leningrad, 1958)

sion coefficients of the transitions 200.08, 241.95, 273.69, 337.50, 374.81, 400.53 and 875.30 keV to confirm their multipolarities and consequently to support spin and parity assignments of the levels 242, 617, 1260, 1323, 2184, 2515, 2585 and 3390 keV. By means of the photon intensities determined in this work and the internal conversion electron data [9], we have calculated the absolute conversion coefficients. The K-internal conversion coefficient of the $4 + \rightarrow 2 + 487$ keV transition in ^{140}Ce was used to normalize relative K-electron and γ-ray intensities for these transitions.

Also we decided to determine the multipolarities of the 542.43, 641.41, 752.62, 927.41, 980.19, 1016.20, 1040.31 and 1054.65 keV transitions, which have not been determined previously [9], by measuring the absolute K-internal conversion coefficient. This information, together with the known assigned levels, spin and parity of other excited states of ^{140}Ce could be determined, in particular for the 2900 and 3100 keV levels.

1. Experimental Procedures

1.1. Apparatus

The experiments were carried out using an iron-yoke double focusing β-ray spectrometer * ($\varrho_0 = 22.5$ cm). The detector employed was a GEIGER–MÜLLER counter with 1.8 mg/cm² mica end-window. The detector was carefully shielded to avoid the background from direct γ radiation since strong sources were used.

Cylindrical canned thallium-activated NaI crystal 2 in. diam. × 2 in., mounted on Dumont 6292 photomultiplier tube was used to detect the γ radiations above 2.53 MeV. The scintillation spectra were recorded in a transistorized RIDL-400 channel analyzer. The γ-ray spectra were taken with this arrangement where the distance between the source and the crystal was about 50 cm.

1.2. Source preparation

The radioactive lanthanum sources used for our measurements were produced by irradiating spectroscopically pure lanthanum oxide with natural abundance of 99.911 percent ^{139}La in the UAR-reactor at Inchass, over a period of two days in a flux of about 10^{13} n/cm² s. The lanthanum activity was placed in aluminium capsule. The inner dimensions of the capsule were 2 mm diam., 16 mm lenght and 0.5 mm wall thickness. The capsule was enclosed in a copper tube of

0.5 m wall thickness to stop the electrons emitted from the source. The resulting tube was then mounted behind the converter. A rectangular uranium converter of thickness 2.9 mg/cm² (5 × 30 mm²) was used in this investigation. The converter foil was obtained from the same supply [11] that was prepared in Stockholm for similar studies. About 10 sources have been used in this investigation.

1.3. Photo-electron measurements

The main purpose of this investigation was the study of high energy transitions in ^{140}Ce with a high resolution spectrometer as necessary for complex spectra. The photo-electron spectra from about 100 keV to about 2.53 MeV were recorded. This region would include K-photoconversion lines of transitions of energies between about 190 keV to about 2.53 MeV. The resulting momentum resolution was $0.3 \rightarrow 0.8$ percent depending on energy. The spectra were analyzed in such a manner that L and M groups were reconstructed on the basis of position and height of the corresponding K-line, the necessary intensity ratios being taken from empirical data. In the calculation of energies the line position was defined as the line centre at half maximum. The shapes of the partially unresolved lines were constructed on the basis of resolution and line shapes of other close photo-lines in this measurement with the same converter. A large number of sufficiently isolated lines in the photo-conversion spectrum itself yielded, however, the necessary information about the line shapes in the various energy regions. New transitions were actually discovered by this procedure. Examples of the photo-conversion lines measured are shown in Figs. $1 \rightarrow 5$. A number of lines not reported before have been detected. Since the accuracy in general, for energy determination, is lower in the photo-electron experiments it was preferred therefore to utilize the transitions 661.6 keV in ^{137}Ba, and 486.81 and 815.01 keV in ^{140}Ce as energy standards and to adopt for these lines the energy values determined by internal conversion measurements [9, 12]. In the present investigation transition energies were determined mainly with the intention of establishing the identity of transitions relative to those found by other techniques [3, 4, 6−8]. The energies so obtained are given in Table 1, all the γ rays reported in an earlier study [9] are seen to be present. The standard error of the energy measurements was frequently as low as $2 − 5$ parts in 10^3. Seventeen new transitions in ^{140}Ce from the decay of ^{140}La of energies: 993.12, 1207.46, 1254.32, 1272.41, 1381.25, 1529.34, 1620.26, 1842.44, 1879.22, 1973.38, 1997.16, 2026.37, 2057.07, 2108.21, 2129.11, 2220.36, and 2273.22 keV were found. The half-life of all the γ rays was found to be about 40-hr. Thus, these γ rays should all be radiations from the decay of ^{140}La.

* β-ray spectrometer type БПП-2 (Moscow, 1957).
[11] T. NOVAKOV, S. HULTBERG, and G. ANDERSON, Arkiv Fysik 13. 117 [1958].

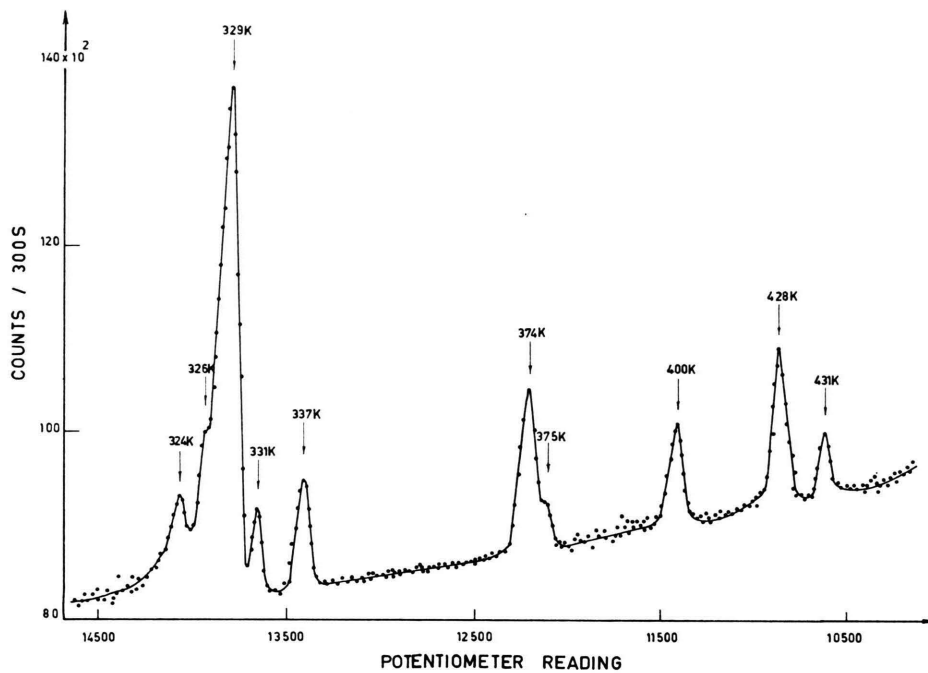[12] K. SIEGBAHN, β- and γ-Ray Spectroscopy, p. 227 [1955].

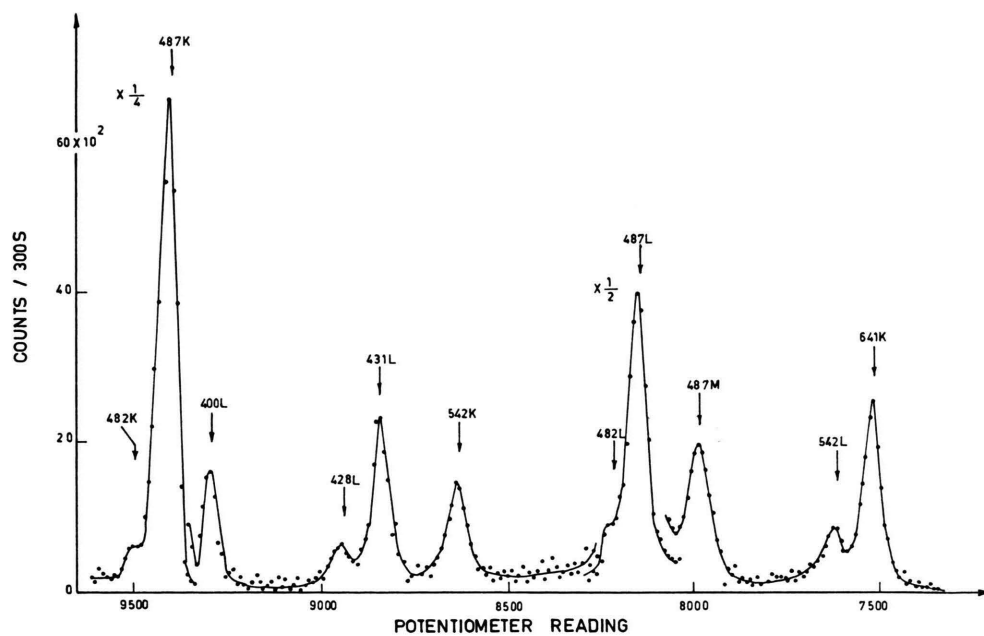Fig. 1. A part of the low energy photo-electron spectrum from 2.9 mg/cm² uranium radiator.

Fig. 2. External conversion lines of the 400, 428, 431, 482, 487, 542 and 641 keV-γ transitions. The COMPTON background is subtracted.
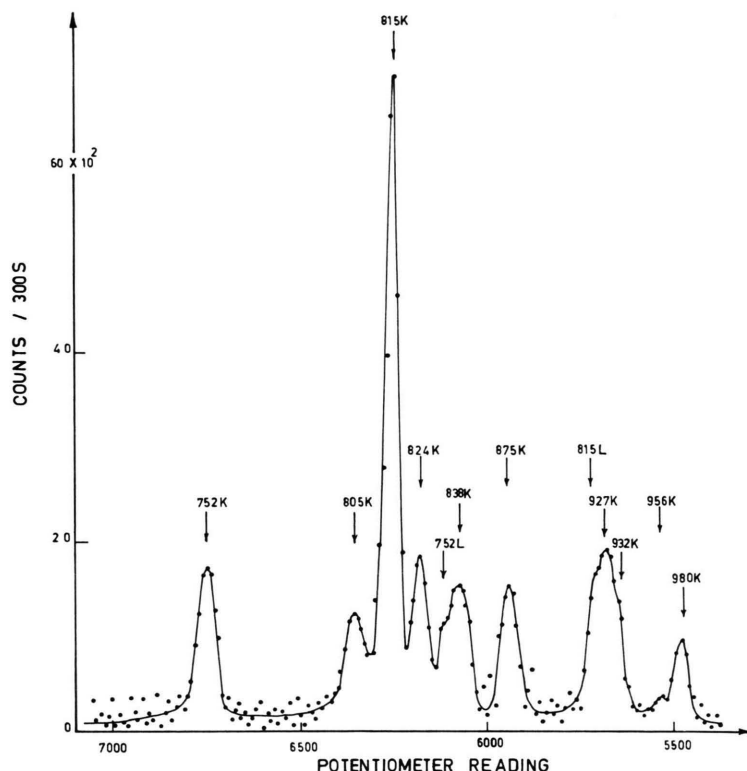
Fig. 3. The external K-conversion lines of the 752, 805, 815, 824, 838, 875, 927, 932, 956 and 980 keV-γ rays. The L-external conversion lines of the 752 and 815 keV transitions are partially resolved. The data were plotted after COMPTON background subtraciton, decay correction is not considered.
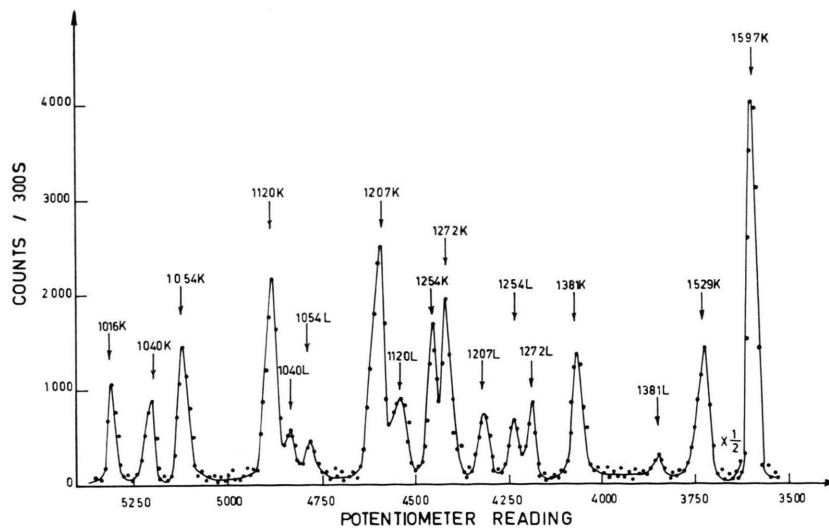

Fig. 4. Part of high energy photo-electron spectrum obtained with 2.9 mg/cm² uranium converter. The external K-conversion lines of the 1016, 1040, 1054, 1120, 1207, 1254, 1272, 1381, 1529 and 1597 keV-γ rays. The L-external conversion lines of the 1040, 1054, 1120, 1207, 1254, 1272, and 1381 keV-γ rays. COMPTON background is subtracted and the data are not decay corrected.

The γ-ray intensities were measured by the method of external conversion which was explained in detail by HULTBERG [13]. Accordingly, the intensity of a γ ray can be expressed as:

$$I_\gamma = C\,\frac{A_\gamma}{f\,\tau}$$

[13] S. HULTBERG, Arkiv Fysik 15, 307 [1959].

where C is a constant depending on the converter thickness, source strength and the instrumental transmission factor. A_γ is the measured intensity of a photoline and was taken as the area under the photoconversion peak after normalization to unit momentum interval, by dividing each point by the corresponding $B\varrho$-value. τ is the photo-electric cross section for the shell in which the conversion takes place. The basic quantity
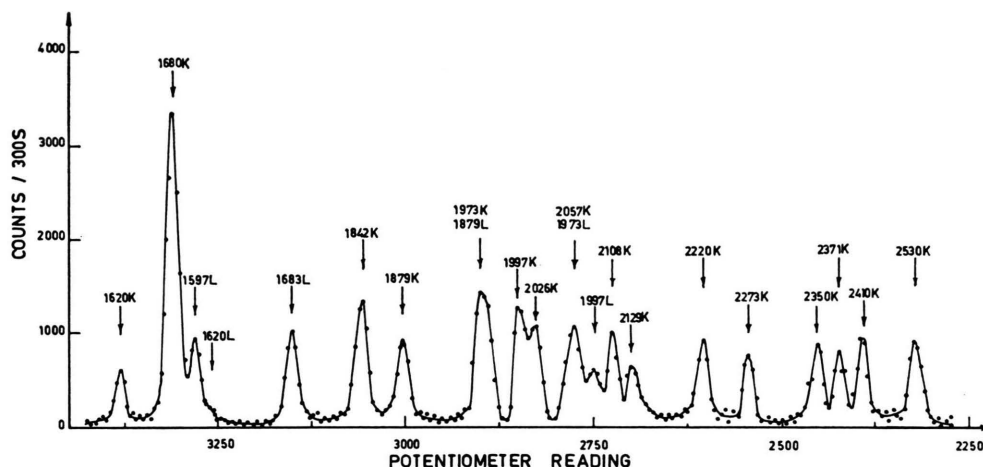
Fig. 5. Photo-electron spectrum from 2.9 mg/cm² uranium converter. The data with the COMPTON background subtracted are plotted, and not corrected for decay. The external K-conversion lines of the 1620, 1680, 1842, 1879, 1973, 1997, 2026, 2057, 2108, 2129, 2220, 2273, 2350, 2371, 2410, and 2530 keV-γ rays are shown. L-photolines of the 1597, 1620, 1683, 1879, 1973 and 1997 keV-γ- rays are indicated.

for the determination of the intensity of a photon (by the photo-conversion method) or its internal conversion coefficient is the integrated photo-electric cross section τ. It is therefore essential to have access to accurate tables of τ. The calculations of τ have been performed by WHITE-GRODSTEIN [14] and by HULTBERG et al. [15]. They are corrected to any order in α_Z but neglect the effect of screening. The correction for the latter effect is rather small for the K shell.

The f-factor depends on the character of the appropriate photo-electric angular distribution and on the details of the experimental arrangement of the γ-ray source and the photo-electric converter inside the spectrometer. The factor f may be calculated for different γ-ray energies for extended plane sources and for K-shell photo-conversion in any element. HULTBERG [13] had developed the procedure of calculating the f factors from the measured angular distributions for various source converter geometries. For a rectangular source and converter, which is the most useful geometry for measurements with a magnetic spectrometer of a double focusing type, correction factors f including all the above mentioned effects are computed [16] by means of the electronic computer BESK at Stockholm for 13 γ energies from 159 to 5000 keV for the specific geometry used in the present experiment. The accuracy in the determination of the relative intensities of the γ rays depends on the energy and on the shell in which the conversion takes place. The most accurate determinations are obtained from the K conversion of γ rays with an energy about 200 keV. The present investigation is devoted to transitions above 200 keV. The ac-

curacy of the γ-ray intensities determined from the K-photo electrons at lower energies is impaired by the errors in the f factors, mainly as a result of the electron scattering in the converter material. These errors were taken into account in the theoretical calculation of the f factors. There is also an additional uncertainty in the γ-ray intensities for the low energy region which comes from the self-absorption of the γ rays in the source material. The corrections for this effect are very sensitive to the error in the absorption coefficient used in the calculation.

In our measurements, it was always attempted to cover as large an energy region as possible with the same source, since this gives more accurate information on the variation of the COMPTON background. The data were corrected for the 40-hour decay of ^{140}La. The areas under the peaks were determined after normalization to unit momentum interval by dividing each point by the corresponding $B\varrho$-value before plotting. The results were corrected for the dead time of the GEIGER–MÜLLER counting circuit and the absorption in the mica counter window. The relative intensities of the γ rays were measured with respect to the 1597 keV radiation whose K-shell photo electron peak stands out clearly in the spectrum, see Fig. 4. The photo lines superimposed on the background come from the COMPTON-scattering electrons due to the high energy γ rays. This background contributes appreciably to the uncertainty in the determination of the areas under the lines especially for those of low intensities. For weaker lines the intensity was simply assumed to be proportional to the height compared with that of a neighbouring line

[14] G. WHITE-GRODSTEIN, National Bureau of Standards Circular, p. 583 [1957].

[15] S. HULTBERG, B. NAGEL, and P. OLSSON, Arkiv Fysik 20, 555 [1962].

[16] E. BASHANDY, M. MIGAHED, G. M. EL-SAYAD, and M. R. EL-AASSAR, Nuovo Cim. 39, 1017 [1965].

Present Work			Bolotin et al.[3]		Prikhodtseva et al.[6]		Hansen et al.[7]		Simons et al.[8]	
Transition Energy (keV)	Int.%	Initial and final level (keV)	Energy (keV)	Int.%	Energy (keV)	Int.%	Energy (keV)	Int.%	Energy (keV)	Int.%
190.93 ± 0.03[a]	0.22 ± 0.04	3471 → 3280								
200.08 ± 0.20	0.53 ± 0.11	3100 → 2900								
204.87 ± 0.10	0.36 ± 0.07	205 → 0								
241.95 ± 0.24	2.54 ± 0.41	242 → 0								
244.51 ± 0.02	1.02 ± 0.15	2654 → 2410								
266.19 ± 0.05	0.95 ± 0.10	508 → 242								
267.88 ± 0.03	0.76 ± 0.15	2922 → 2654								
273.69 ± 0.04	5.67 ± 0.68	1597 → 1323								
324.51 ± 0.09	2.03 ± 0.35	2350 → 2026			323	2.1				
326.18 ± 0.09	1.22 ± 0.18	2410 → 2084								
329.75 ± 0.35	20.0 ± 0.20	1323 → 993	328	40					328	19
331.02 ± 0.50	2.81 ± 0.35	2515 → 2184								
337.50 ± 0.67	4.43 ± 0.70	1597 → 1260								
374.81 ± 0.18	5.62 ± 0.63	617 → 242								
375.65 ± 0.75	1.27 ± 0.21	1973 → 1597								
400.53 ± 0.20	4.01 ± 0.63	2585 → 2184			400	3				
428.62 ± 0.43	5.83 ± 0.53	2026 → 1597								
431.06 ± 0.21	2.93 ± 0.44	2515 → 2084	438	6	434	2.5			435	0.4
482.00 ± 0.49	2.48 ± 0.37	2371 → 1889								
486.81 ± 0.05	43.21 ± 3.01	2084 → 1597	490	50	491	42			490	44.0
542.43 ± 0.08	1.98 ± 0.30	2515 → 1973								
641.41 ± 0.50	4.13 ± 0.67	2530 → 1889			643	1			635	<1
752.62 ± 0.60	4.57 ± 0.73	2350 → 1597			748	3.4			753	5
805.74 ± 0.61	1.83 ± 0.28	3390 → 2585								
815.01 ± 0.08	21.06 ± 1.47	2410 → 1597	815	46	815	20			818	22
824.51 ± 0.25	3.65 ± 0.55	2084 → 1260								
838.38 ± 0.42	3.34 ± 0.54	2922 → 2084								
875.30 ± 0.13	4.07 ± 0.61	3390 → 2515			868	5			874	5
927.41 ± 0.46	1.82 ± 0.27	2900 → 1973			903	0.8				
932.98 ± 0.46	1.21 ± 0.18	2530 → 1597			923	10			927	9.5
956.02 ± 0.90	0.43 ± 0.08	3471 → 2515								
980.19 ± 0.48	2.25 ± 0.34	1597 → 617								
993.12 ± 0.53	0.67 ± 0.13	993 → 0								
1016.20 ± 0.20	13.13 ± 1.32	3100 → 2084								
1040.31 ± 0.31	11.07 ± 1.11	3390 → 2350								
1054.65 ± 0.23	17.05 ± 1.71	1260 → 205								
1120.2 ± 1.9[b]	26.51 ± 1.9	3471 → 2350							1120	1
1207.5 ± 2.1	30.07 ± 2.12	2530 → 1323								
1254.3 ± 5.0	14.36 ± 1.01	3280 → 2026								
1272.4 ± 5.1	16.26 ± 1.12	1889 → 617								
1381.2 ± 4.1	16.25 ± 1.11	1889 → 508								
1529.3 ± 4.6	17.51 ± 1.72	1597 → 68								
1597.5 ± 3.2	100 ± 5	1597 → 0	1600	100	1597	100	1598	100	1597	100
1620.3 ± 8.1	3.47 ± 0.45	1973 → 353								
1683.4 ± 5.0	18.52 ± 1.83	3280 → 1597							1680	1
1842.4 ± 9.2	6.95 ± 0.71	2350 → 508								
1879.2 ± 9.4	4.62 ± 0.51	2084 → 205					1900	0.15		
1973 ± 11	3.69 ± 0.49	1973 → 0								
1997 ± 12	4.52 ± 0.43	2350 → 353								
2026 ± 12	3.69 ± 0.51	2026 → 0								
2057 ± 12	2.89 ± 0.43	2410 → 353								
2108 ± 12	3.81 ± 0.57	2350 → 242								
2129 ± 12	2.77 ± 0.42	2371 → 242								
2220 ± 11	4.97 ± 0.51	2350 → 130								
2273 ± 11	4.05 ± 0.61	2515 → 242								
2350 ± 12	4.74 ± 0.71	2350 → 0			2343	0.78			2355	0.6
2371 ± 12	3.54 ± 0.53	2371 → 0					2378	0.86		
2410 ± 12	4.39 ± 0.66	2410 → 0								
2530 ± 13	4.85 ± 0.72	2530 → 0	2500	1	2515	4.0	2535	3	2530	4
2900 ± 15[c]	0.23 ± 0.04	2900 → 0	3000	0.04	2890	0.1	2890	0.082	2900	0.15
3100 ± 20	0.08 ± 0.04	3100 → 0					3100	0.035	3100	1
3470 ± 30	0.01 ± 0.008	3471 → 0					3250	0.005		

[a] The γ-ray energies from 190.93 to 1054.65 keV are quoted from the internal conversion measurements [9].

[b] The γ-ray energies from 1120.2 to 2530 keV are quoted from the present external conversion measurements.

[c] The γ-ray energies from 2900 to 3471 keV are quoted from the present scintillation measurements.

Table 1. Energies and relative intensities of γ rays following the decay of ^{140}La obtained in this investigation compared to those measured by different methods.

of measured area. Due to that the standard error of these intensities is believed to be about 5 percent for the intense lines and more than 10 percent for the weaker lines.

The results of the relative intensities of the γ rays following the decay of ^{140}La obtained in this investigation are given in Table 1, and compared with those obtained by different methods [3, 6-8].

1.4. Scintillation spectrum of high energy γ rays

The single γ-ray spectrum of ^{140}La has been measured with a crystal-photomultiplier assembly consisting of a 2 in. × 2 in. NaI crystal and a Dumont 6292 photomultiplier tube. With this assembly the resolution was better than 8 percent for the 661 keV-γ transition in ^{137}Ba. The pulse spectrum was observed with a RIDL 400-channel pulse analyzer. The β rays of ^{140}La were absorbed by 1.08 g·cm^{-2} of aluminium, placed between the source and the crystal. In order to obtain better statistics for the higher energy part of the spectrum, the time of measurement for that part was 2 hours. The spectrum is given in Fig. 6. The γ ener-
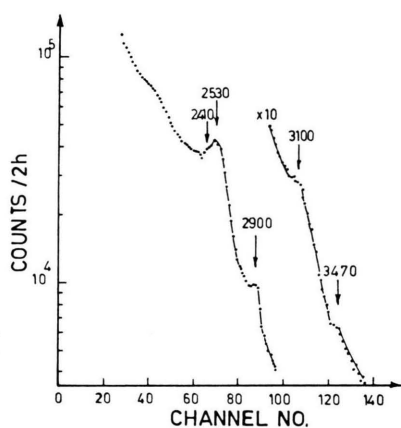

Fig. 6. The high energy part of the γ-ray spectrum of ^{140}La.

gies obtained from mixed source calibrations are given in this figure. During these measurements gain stabilization was applied with a strong ^{137}Cs source. The shapes for COMPTON and pair peaks are obtained from the pulse distribution of various single γ-ray sources, taken under condition similar to this experiment. Interpolations between the shapes of the spectra of the calibration sources provided information for a careful analysis of the single spectrum of ^{140}La. The use of a $\log(N/\sqrt{E})$ diagram, where N is the number of counts per channel and E is the energy in keV, appreciably reduces the amount of work in the analysis, since in these diagrams the shape of the photopeak is constant over a fairly large energy region [17]. The analysis of the high energy γ spectrum above about 2.53 MeV reveals

the existence of three γ rays with energies (2900 ± 15), (3100 ± 20) and (3471 ± 30) keV. The intensity of these γ rays has been determined relative to the 1597 keV-γ ray. These results are also included in Table 1.

2. Results and Conclusion

The external conversion spectrum of the transitions in ^{140}Ce of energies greater than 200 keV was measured. The scintillation technique was used to investigate the transitions of energy greater than 2.53 MeV. All the γ rays of energies between about 0.2 MeV and about 1 MeV which were observed [9] in the internal conversion spectrum are found to be present in the photo-conversion spectra. γ energies lower than 200 keV have carefully been investigated [9] from the internal conversion spectrum measurements. The transition energies determined in the present investigation are summarized in Table 1, together with the transition energies measured by BOLOTIN et al. [3], PRIKHODTSEVA et al. [6], HANSEN et al. [7] and SIMONS et al. [8]. Seventeen new γ transitions with energies 993.12, 1207.46, 1254.32, 1272.41, 1381.25, 1529.34, 1620.26, 1842.44, 1879.22, 1973.38, 1997.16, 2026.37, 2057.07, 2108.21, 2129.11, 2220.36, and 2273.22 keV were found, Figs. 4 and 5. All these γ rays could be identified as transitions from the decay of 40-hour ^{140}La. The high resolution double focusing β-ray spectrometer as well as the strong sources used in this work facilitated the discovery of these γ rays which have not been reported before. A complete set of energy sums was computed in order to survey the possibility of cascade-crossover combinations. The levels were derived from certain energy combinations which must be considered to be of high statistical significance. An energy level diagram based on the results of our studies is given in Fig. 7. All these new energies could be fitted in this decay scheme which includes all levels known before and it is an extension to that proposed previously [9]. Some of the energies given in Fig. 7 differ slightly from those reported by previous investigations [3, 4, 6-8]. Evidence has been found for a total of 29 excited states. We could not observe the γ rays of energies 353.37, 969.77 and 1889 keV in the photo-conversion spectrum, which result confirms the 0 + assignment for the 353, 1323 and 1889 keV excited states in ^{140}Ce. In a previous work [9], the K-internal conversion electrons of the 353.37 keV transition as well as the K- and L-internal conversion electrons

[17] J. B. VAN DER KOOI, Thesis Utrecht 1964. — J. B. VAN DER KOOI and H. J. VAN DEN BOLD, Nucl. Phys. 70, 449 [1965].
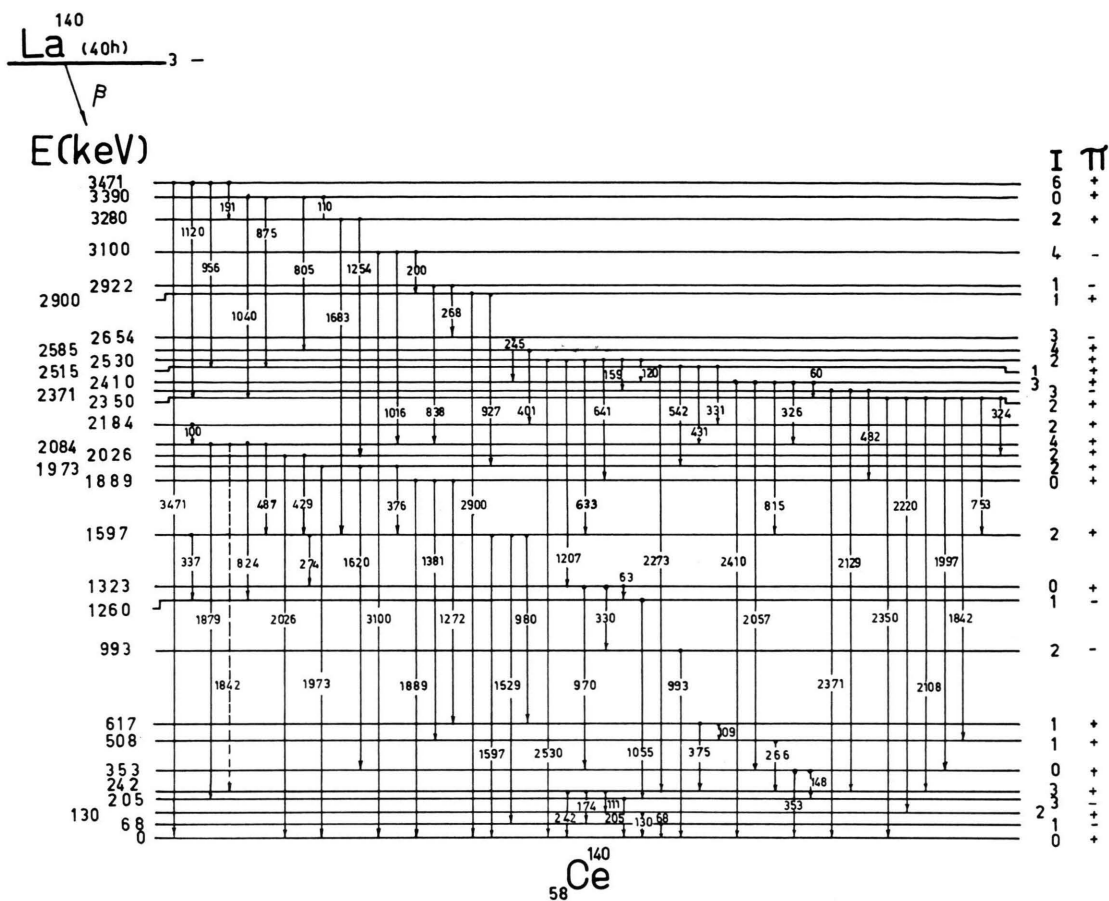
Fig. 7. Proposed decay scheme of 40-hour ^{140}La.

of the 969.77 keV transition were observed. It was shown [9] that the 0 + level at 1902 keV proposed by DZELEPOW et al. [5] is compatible with the 1889 keV level and the ratio α_K/α_L is 6.33 for the transition de-exciting this level to the ground state. The lifetime of this 0 + level has also been measured by PER SALLING [18] to be ≤ 0.6 μsec. The 980.19 keV-γ ray is shown very clearly in Fig. 3. The 1842.44 keV-γ transition could be fitted either between the $2350 \rightarrow 508$ keV levels (solid line) or between the $2084 \rightarrow 242$ keV levels (dashed line).

It is concluded that the γ rays of energy 204.87, 241.95, 993.12, 1597.48, 1973.38, 2026.37, 2350.23, 2371.11, 2410.33 and 2530.03 keV which appeared in the photo-conversion spectrum are ground state transitions from the 205, 242, 993, 1597, 1973, 2026, 2350, 2371, 2410 and 2530 keV levels, respectively.

[18] PER SALLING, Nucl. Phys. 65, 520 [1965].

γ energies of 2900 ± 15, 3100 ± 20, and 3471 ± 30 keV have been observed in the scintillation spectrum, see Figs. 6 and 7; and Table 1, and they are supposed to be ground state transitions from the 2900, 3100 and 3471 keV levels respectively.

The relative intensities of γ rays obtained are presented in Table 1. The results are compared with those of other workers [3, 6-8] who used different methods. All the data have been normalized to the intensity of the 1597 keV-γ ray which is taken to be 100. The results obtained for γ-ray intensities in the case of strong transitions show satisfactory agreement, see Table 1. A value of relative intensity down to 0.01 relative to 100 quoted for the 1597 keV-γ ray could be obtained. The γ intensities for energy below about 300 keV were not reported before, these are obviously difficult to obtain from scintillation measurements. The largest uncertainty in these measurements is in the determination of the area

of the K-external conversion lines. From possible limiting curves drawn through the data an uncertainty of about 20 percent was found for the weak lines and less than that for strong lines.

2.1. Internal conversion coefficients and transition multipolarities

The spins and parities of the excited states in ^{140}Ce have been assigned in a previous work [9]. However, the assignments of the levels 242, 617, 1260, 1323, 2184, 2515, 2585 and 3390 keV were not certain, since the $K/\Sigma L$ conversion electron ratio of the 200.08, 241.95, 273.69, 337.50, 374.81, 400.53 and 875.30 keV-γ transitions could not give definite multipolarity assignment. The determination of absolute internal conversion coefficients of these transitions is necessary to assign exact multipolarities and consequently spin and parity of the above excited states. The photon intensities determined [9] in this work and the internal conversion electron data determined [9] previously have been used in the calculation.

The internal-external conversion method was applied [13, 19]. This method is very suitable for complex decays such as that of ^{140}Ce, see Fig. 7. If we let A_{in} and A_{ex} denote the intensities of conversion electrons and photo-electrons respectively, it can easily be shown that the internal conversion coefficient α_i is given by:

$$\alpha_i = \frac{(A_{in})_i}{(A_{ex})_j} \tau_j f_j K \, d \, b \, q .$$

The internal conversion takes place in the i-th shell or subshell and the external conversion in the j-th shell or subshell. The quantity K is the relative source strength if different radioactive sources are employed for internal conversion and external conversion, d is the thickness of the converter (usually expressed in mg/cm^2), b is a dimensional factor and q is the relative instrumental transmission if the latter is not the same for internal conversion and external conversion.

In the present work the method was employed without any numerical calculation of K, d, b, and q by comparing the equation above for a transition in the same source with known α_K with the transition of unknown α_K to be measured. The K-internal conversion coefficient of the 487 keV transition in

^{140}Ce was used for comparison in this work, it was well determined by BOLOTIN et al. [3], $\alpha_K = 0.0073$ and agrees with the theoretical value $\alpha_K = 0.0098$ for pure quadrupole radiation. Also the internal conversion ratio of this transition, previously measured [9] $K/\Sigma L = 6.47 \pm 0.65$ was in good agreement with the 6.617 theoretical E2-conversion ratio. The 487 keV transition de-exciting the 4+ 2084 keV level was proved to be in coincidence with the 1597 keV transition de-exciting the 2+ 1597 keV level. Hence, its location in the decay scheme confirms the E2 multipolarity for the 487 keV-γ ray. In our calculations we have adopted the theoretical value α_K for the 487 keV transition.

The K-conversion coefficient $\alpha_K(x)$ of any transition was thus determined as:

$$\alpha_K(x) = \alpha_K(487) \, \frac{(A_{in})^x}{(A_{in})^{487}} \, \frac{(A_{ex})^{487}}{(A_{ex})^x} \, \frac{\tau_K(x)}{\tau_K(487)} \, \frac{f(x)}{f(487)} .$$

The comparative method of determining the internal conversion coefficient is straight-forward. It does not depend upon any knowledge of the decay scheme and it shows great advantages over other methods in cases where the decay is complicated.

The K-internal conversion coefficients of the transitions 200.08, 241.95, 273.69, 337.50, 374.81, 400.53 and 875.30 keV are calculated by using the theoretical value 0.0098 for the 487 keV-E2 transition to normalize relative K electron and γ-ray intensities for these transitions. The results obtained for α_K of these transitions are given in Table 2 together with the theoretical values calculated by SLIV and BAND [10]. Because of the different line intensities and possible interference of other lines, the error in A_{in}/A_{ex} varies strongly from one transition to another. The largest uncertainty in these measurements is in the determination of the area of the K-external conversion line. From possible limiting curves drawn through the data an uncertainty of $10 \to 20$ percent was found. The uncertainties in τ_K and f_K are taken to be 6 percent and 5 percent, respectively, in accordance with refs. [19, 20].

The possible multipolarities given in the last column of Table 2 could support spin and parity assignments of the levels 242, 617, 1260, 1323, 2184, 2515, 2585, and 3390 keV to be 3+, 1+, 1−, 0+, 2+, 1+, 4+, and 0+, respectively.

[19] S. HULTBERG and R. STOCKENDAL, Arkiv Fysik 14, 565 [1959]; 15, 355 [1959].

[20] R. STOCKENDAL and S. HULTBERG, Arkiv Fysik 15, 33 [1959].

Transition energy (keV)	Experimental K-internal conversion coefficient α_K		Theoretical K-internal conversion coefficients as computed by SLIV and BAND [10]								Multi-polarity
			E1	E2	E3	E4	M1	M2	M3	M4	
200.08 ± 0.20	0.54	± 0.11	0.03	0.14	0.53	1.98	0.14	0.79	3.58	15.79	E3
241.95 ± 0.24	1.72	± 0.29	0.02	0.07	0.27	0.95	0.09	0.42	1.71	6.82	M3
273.69 ± 0.04	0.056	± 0.008	0.014	0.055	0.189	0.632	0.066	0.298	1.145	4.315	E2
337.50 ± 0.67	0.998	± 0.149	0.990	0.546	0.051	0.546	0.651	0.264	0.811	0.352	E1
374.81 ± 0.18	0.029	± 0.004	0.008	0.028	0.086	0.262	0.037	0.144	0.487	1.623	E2
400.53 ± 0.20	0.031	± 0.006	0.007	0.030	0.073	0.218	0.032	0.124	0.407	1.320	E2
875.30 ± 0.13	0.0035 ± 0.0007		0.0010	0.0023	0.0050	0.0104	0.0034	0.0088	0.0189	0.0390	M1

Table 2. Deduction of multipolarities of the 200, 242, 274, 337, 375, 401 and 875 keV transitions in ^{140}Ce.

Also another trial to determine the multipolarities of the 542.43, 641.41, 752.62, 927.41, 980.19, 1016.20, 1040.31 and 1054.65 keV transitions has been undertaken. These transitions were not assigned before [9], due to the fact that in the internal conversion spectra only the K lines have been observed. The absolute K-internal conversion coefficient are determined by applying the same method. The results are shown in Table 3 as well as the proposed multipolarities. On the basis of these multipolarities together with the previously known assigned levels, spin and parity of the levels 205, 1889, 1973, 2084, 2350 and 2530 keV have been determined to be 3−, 0+, 2+, 4+, 2+ and 2+, respectively.

2.2. Spin and parity assignments for the 2900 and 3100 keV excited states of ^{140}Ce

The 927.41 keV transition de-excites the 2900 keV level to the 1973 keV level. The multipolarity of this transition is determined from $\alpha_K = 0.0031 \pm 0.0005$ to be M1, see Table 3. Spin and parity 2+ was previously asigned [9] to the 1973 keV level. From this informations the spin and parity 1+ are proposed for the 2900 keV excited state in ^{140}Ce.

The measured [9] K/Σ L-internal conversion ratio of the 200.8 keV transition, lying between the 3100 and 2900 keV levels, agree with E3 or E4 assignment. The measured K-internal conversion line intensity and γ-ray intensity of this transition gave the conversion coefficient $\alpha_K = 0.5421 \pm 0.1084$, see Table 2. This value agree with the theoretical coefficient for E3. Since the 2900 keV level has 1+ assignment, the spin and parity 4− are proposed for the 3100 keV level.

2.3. Mixing ratio of the 752.62 keV transition

The K-conversion coefficient of the 752.62 keV transition in ^{140}Ce is determined, $\alpha_K = 0.0054 \pm 0.0008$. This value is compatible with M1+E2 multipolarity for this transition. The mixing ratio is obtained by using the following relation:

$$\delta^2 = \frac{E2}{M1} = \frac{\beta_1^K - \alpha_{exp}^K}{\alpha_{exp}^K - \alpha_2^K},$$

where β_1^K is the theoretical K-conversion coefficient for pure M1, and α_2^K is the theoretical K-conversion coefficient for pure E2. Using the theoretical values for β_1^K and α_2^K given in Table 3, we have

$$\delta^2(752.62) = 0.381 \pm 0.041 .$$

Transition energy (keV)	Experimental K-internal conversion coefficient α_K		Theoretical K-internal conversion coefficients as computed by SLIV and BAND [10]								Multi-polarity
			E1	E2	E3	E4	M1	M2	M3	M4	
542.43 ± 1.08	0.011	± 0.002	0.003	0.007	0.019	0.046	0.011	0.034	0.089	0.228	M1
641.41 ± 0.50	0.005	± 0.001	0.0018	0.0048	0.01166	0.0271	0.0074	0.0209	0.0511	0.1209	E2
752.62 ± 0.60	0.0054	± 0.0008	0.0013	0.0033	0.0074	0.0161	0.0062	0.0133	0.0302	0.0662	M1+E2
927.41 ± 0.46	0.0031	± 0.0005	0.00085	0.0020	0.0043	0.0088	0.0030	0.0076	0.0159	0.0320	M1
980.19 ± 0.48	0.0027	± 0.0004	0.00076	0.0018	0.0038	0.0075	0.0026	0.0065	0.0134	0.0264	M1
1016.20 ± 0.20	0.00076 ± 0.00008		0.00071	0.00167	0.00346	0.00680	0.00242	0.00594	0.01202	0.02337	E1
1040.31 ± 0.31	0.0017	± 0.0002	0.007	0.0016	0.0034	0.0066	0.0024	0.0058	0.0117	0.0228	E2
1054.65 ± 0.23	0.0018	± 0.0002	0.0007	0.0016	0.0034	0.0066	0.0024	0.0058	0.0117	0.0226	E2

Table 3. Multipolarities of the 542, 641, 753, 927, 980, 1016, 1040 and 1054 keV transitions in ^{140}Ce.