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THE DECAY OF ^{140}La TO LEVELS IN ^{140}Ce

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Abstract: The decay of ^{140}La to levels in ^{140}Ce has been studied with Ge(Li) spectrometers and γ-γ coincidence techniques. Precision energy and intensity values for 25 γ-rays are reported. These transitions have been incorporated into a consistent decay scheme which includes an intensity balance for each level. Using the present data and the recent conversion electron data of Karlsson *et al.*, it was possible to determine multipolarities for most of the transitions. The excitation energies (keV), spins and parities proposed for the levels in ^{140}Ce populated via the decay of ^{140}La are 1596.6 (2$^+$), 1903.5 (0$^+$), 2083.6 (4$^+$), 2108.2 (6$^+$), 2348.4 (2$^+$), 2350.2 (5$^-$), 2412.4 (3$^+$), 2464.4 (3$^-$), 2481.3 (4$^+$), 2516.1 (4$^+$), 2521.8 (2$^+$), 2547.5 (1, 2$^+$), 2899.7 (1, 2$^+$), 3118.3 (1, 2$^+$), 3319.7 (1, 2$^+$). The level at 2108.2 keV (6$^+$) was deduced to be isomeric. The proposed level scheme is compared with the excitation spectrum observed in the ^{141}Pr(d, ^{3}He)^{140}Ce reaction and two spectra calculated using the quasi-particle description of pairing correlations.

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RADIOACTIVITY ^{140}La[from ^{139}La(n, γ)]; measured E_γ, I_γ, $\gamma\gamma$-coin. ^{140}Ce deduced levels, J, π, logft, cc. Natural target, Ge(Li) detector.

1. Introduction

The nucleus ^{140}Ce is one of seven stable isotones having the magic neutron number $N = 82$. Its excitation spectrum has been studied through the radioactive decay of $^{140}_{57}$La$_{83}$ [refs. [1, 3–15])] and $^{140}_{59}$Pr$_{81}$ [refs. [16, 17])], charged-particle spectroscopy [2, 18, 19])†† and photonuclear reactions [20, 21]). These investigations have shown that the spectrum of ^{140}Ce has features typical of single-closed-shell nuclei: a large energy gap (1.6 MeV), a low-lying, collective, 3$^-$ state [19]) (2.46 MeV), a relatively small enhancement of the E2 transition [21]) between the first 2$^+$ and ground state (B(E2, $2_1+ \rightarrow 0^+$) = $16B(\text{E2})_{\text{s.p.}}$) and a retarded E2 transition [14]) between the lowest 4$^+$ state and the 2_1+ state (B(E2: $4_1+ \rightarrow 2_1+$) $\rightarrow 0.06B(\text{E2})_{\text{s.p.}}$.

Although there have been numerous experimental investigations of the decay of ^{140}La to levels in ^{140}Ce, uncertainty regarding several features of the decay still prevailed. The existence of most levels was inferred on the basis of energy sum relationships only. A consistent intensity balance for the population and depopulation of each level had not been achieved since several γ-transitions could not be placed, including the intense 868.6 keV transition, and since the intensities of many γ-ray transitions were not known accurately.

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†† Ref. [18]) is based on the theoretical work of Borisoglebzkii [25]).

To clarify these questions, we performed γ-γ coincidence measurements using Ge(Li) detectors and determined γ-ray energy and intensity values using carefully calibrated Ge(Li) spectrometers. This has led to the construction of a decay scheme which includes all observed γ-transitions, β-feeding values for 12 of the 15 excited states in ^{140}Ce populated in this decay, the addition of two new levels to the recent level scheme of Karlsson *et al.* [1]), including an isomeric state at 2108.2 keV and the determination of unique J^{π} values for nearly all the observed states in ^{140}Ce. Several levels which were tentatively proposed by Karlsson *et al.*, are further supported with coincidence data, while the existence of two proposed levels is not supported.

2. Experimental procedure

Energy and intensity measurements were made with a Ge(Li) spectrometer consisting of the following components: an Ortec detector-cryostat with a depleted detector volume 4 $cm^2 \times 0.5$ cm; a Tennelec TC-130 (FET) preamp and TC-200 amplifier, a Victoreen 1600 channel pulse-height analyser. The TC-130 and TC-200 units were modified to include pole-zero cancellation. A detailed description of the calibrations for energy and intensity measurements is given in ref. [22]).

Coincidence spectra were obtained using various NaI-Ge(Li) and Ge(Li)-Ge(Li) detector arrangements. Fast coincidence timing was performed in a fast coincidence unit (CI-1441). The singles counting rates in both the display and gate side were generally in the range $(0.1\text{–}2.0) \times 10^4$ counts/sec. The resolving time 2τ was approximately 50 ns for all prompt coincidence runs. True to accidental ratios were greater than 20 to one for NaI-Ge(Li) spectra and approximately 5 to one for Ge(Li)-Ge(Li) spectra.

The ^{140}La sources consisted of several mg of $La(NO_3)_3$ dissolved in water and irradiated with thermal neutrons for 2–8 h in the UM Reactor ($\approx 2 \times 10^{13}$n/sec $\cdot$ cm^2). The activities were in the range 0.1–1.0 mCi.

3. Experimental results

3.1. GAMMA-RAY ENERGY AND RELATIVE INTENSITY VALUES

The γ-ray spectrum associated with the decay of ^{140}La in the energy range 0.05–3.45 MeV is shown in fig. 1. Gamma-ray energy and relative intensity values are given in table 1. The energies and relative intensities given in columns 1 and 3, respectively, were measured with the UM curved-crystal spectrometer and were reported in ref. [12]). The values in columns 2 and 4 were determined with the Ge(Li) spectrometer. The intensities in columns 3 and 4 are relative to the most intense member within each subgroup. In column 5, the data of both instruments have been combined to give intensity values relative to γ-1596. The intensity values of the various subgroups were renormalized to γ-1596 using the intensities of the strongest lines in each subgroup relative to γ-1596 as measured with the Ge(Li) spectrometer.

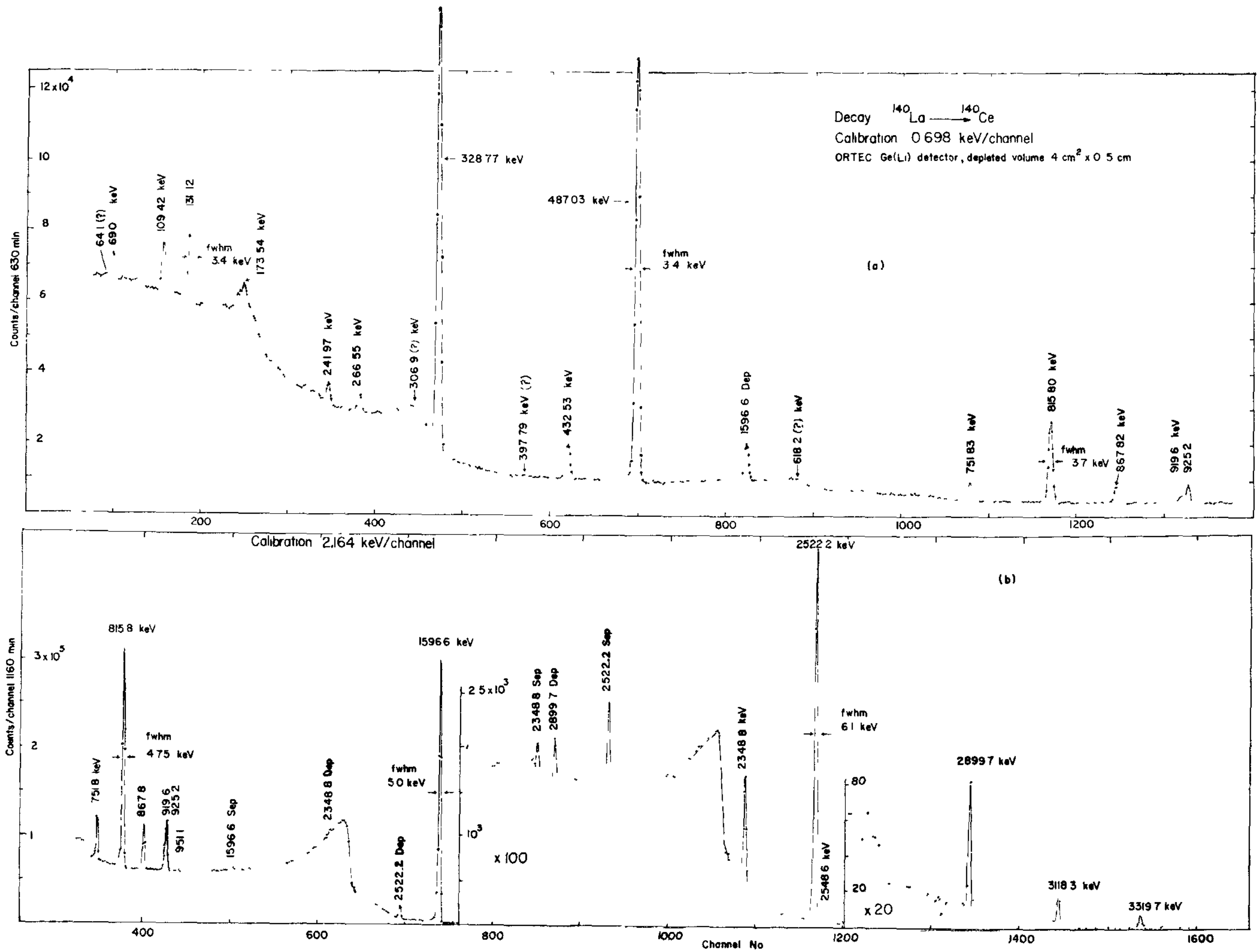

Fig. 1. The γ-ray spectrum following the decay of ^{140}La in the energy range 0.05–3.45 MeV obtained with a 2 cm^3, planar, *Ge*(Li) detector. (a) the spectrum between 0.05–0.97 MeV, (b) the spectrum between 0.75–3.45 MeV.

TABLE 1

Energy and relative intensity values for the gamma rays in the $^{140}La \rightarrow {}^{140}Ca$ decay

Photon energy (keV)		Relative gamma ray intensity [b])		
Curved-crystal [a])	Ge(Li)	Curved-crystal [a])	Ge(Li)	Curved-crystal+Ge(Li)
1	2	3	4	5
64.135±0.010			<2	<0.01
	69.0±0.3		10.7 ±1.8	0.065±0.013
109.418±0.007			44.1 ±2.3	0.27 ±0.04
131.121±0.008			100	0.61 ±0.09
173.536±0.012			21.5 ±6.4	0.13 ±0.05
241.966±0.012			73.8 ±5.5	0.45 ±0.06
266.551±0.014			92.1 ±6.6	0.56 ±0.06
306.9 ±0.2		0.044±0.023		0.022±0.011
328.768±0.012		45 ±10	43.2 ±3.0	21.4 ±1.1
397.79 ±0.11		0.11 ±0.050		0.054±0.025
432.530±0.029		6.1 ±1.5	6.29 ±0.31	3.11 ±0.16
487.029±0.019		100	100	49.4 ±2.5
618.2 ±0.7		0.090±0.045		0.044±0.022
751.827±0.080		19 ±3.8	18.3 ±0.6	4.40 ±0.22
815.801±0.086		100	100	24.1 ±1.2
867.82 ±0.14		22.5 ±4.5	23.4 ±0.7	5.64 ±0.28
919.64 ±0.33	919.5±0.2	11.0 ±2.7	11.3 ±0.6	2.73 ±0.16
925.20 ±0.17	925.1±0.2	30.0 ±6.0	30.0 ±1.2	7.24 ±0.43
950.88 ±0.72	951.1±0.4	2.6 ±0.65	2.33 ±0.14	0.56 ±0.05
1596.58 ±0.30	1596.6±0.2			100
	2348.8±0.6		25.5 ±0.8	0.901±0.045
2522.6 ±2.5	2522.2±0.4		100	3.52 ±0.18
	2548.6±0.8		3.46±0.17	0.122±0.009
	2899.7±0.5		2.00 ±0.14	0.070±0.005
	3118.3±0.7		0.775±0.008	0.027±0.003
	3319.7±2.5		0.22 ±0.11	0.008±0.004

[a]) The values in these columns were obtained with a curved-crystal spectrometer and are reported in ref. [12]).

[b]) The γ-ray intensities in columns 3 and 4 are given relative to the most intense member within each subgroup. In column 5, the data of both instruments are combined and the intensities are given relative to the 1596.6 keV γ-ray. When multiplied by 0.955 these numbers correspond to % of total decay.

The uncertainties in the relative intensity values determined with the Ge(Li) spectrometer arise from two independent contributions. First, there is the uncertainty with which the relative area of two peaks in the spectrum can be determined. This uncertainty depends on the shape of the spectral distribution adjacent to each peak and on the number of counts in each peak. The area ratios for each pair of peaks were determined from a minimum of five different spectra, and rms fluctuations in these ratios were used to assign an uncertainty to each ratio. Second, there is the uncertainty in the relative detection efficiency for each pair of γ-rays. The magnitude of this un-

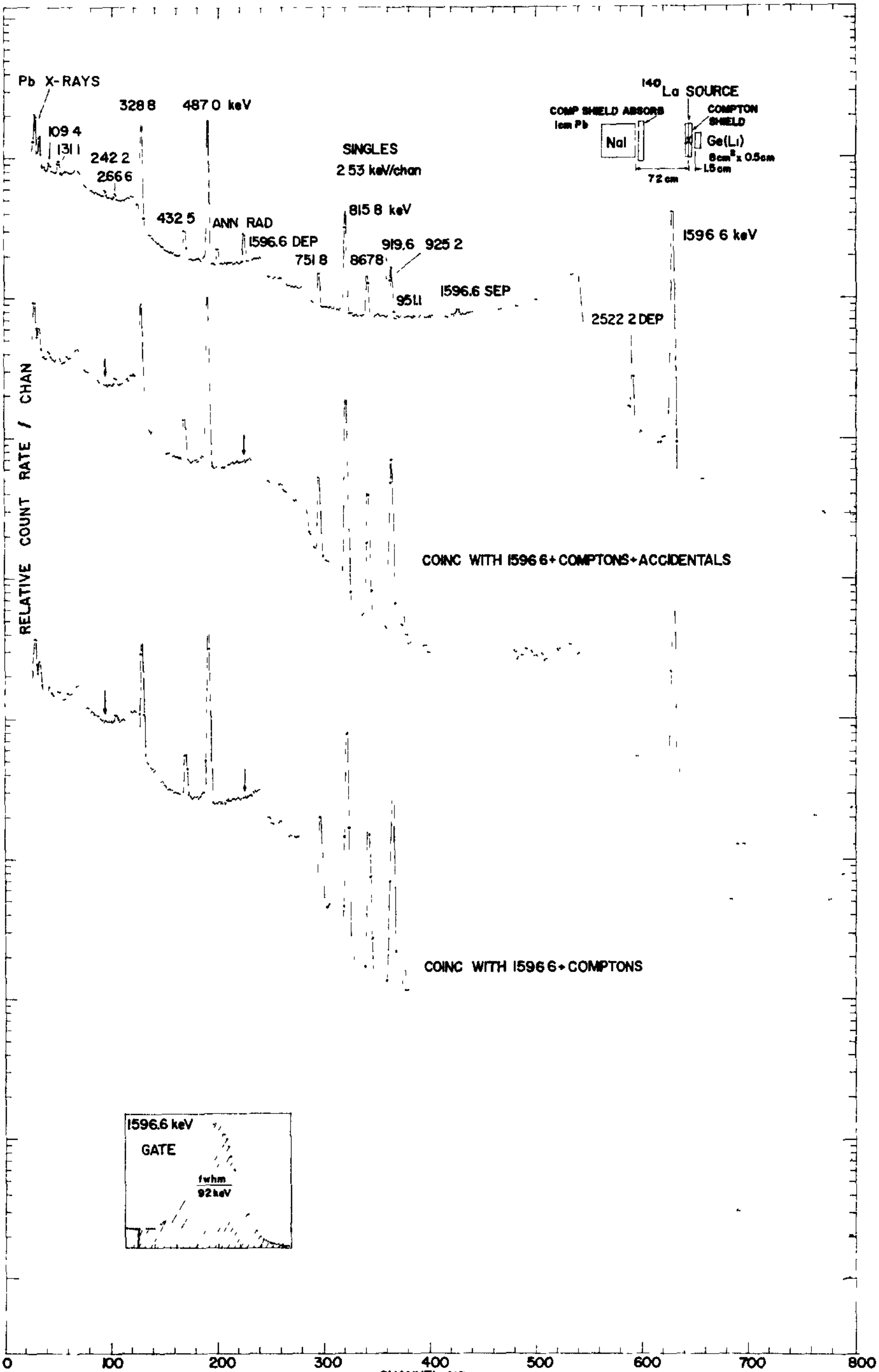

Fig. 2. The γ-ray spectrum in the energy range 0.07–2.02 MeV in coincidence with the 1596.6 keV γ-ray.

certainty depends on the energy separation of the two lines. For this reason, the uncertainties given in column 4 of table 1 are less than those given in column 5.

For the purpose of energy determinations, the centroid of the peak area was taken as the definition of the peak position [discussed in ref. [22])]. Gamma-ray energies between 919.5 and 2548.6 keV were determined using the 487.03 and 815.80 keV γ-ray lines in the spectrum for the calibration. The energies of the 1596.6 and 2522.2 keV γ-rays were determined from the double escape peaks. In the determination of the three γ-ray energies 2899.7, 3118.3 and 3319.7 keV, the calibration energy $E_\gamma = 2753.92 \pm 0.12$ keV [ref. [23])] for the γ-ray following the decay of ^{24}Na was used.

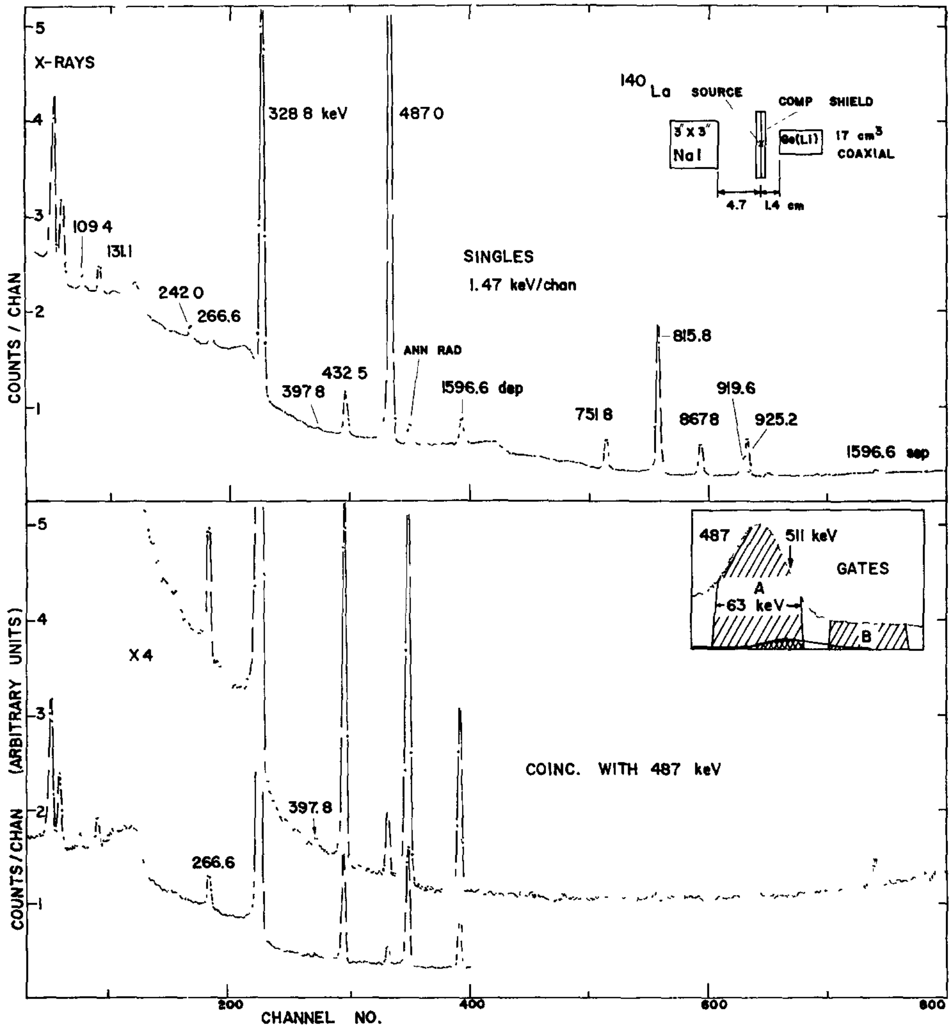

Fig. 3. The γ-ray spectrum in the energy range 0.06–1.18 MeV in coincidence with the 487.0 keV γ-ray.

3.2. GAMMA-GAMMA COINCIDENCE SPECTRA

The spectra in coincidence with most of the stronger γ-rays were obtained, and the results are summarized below.

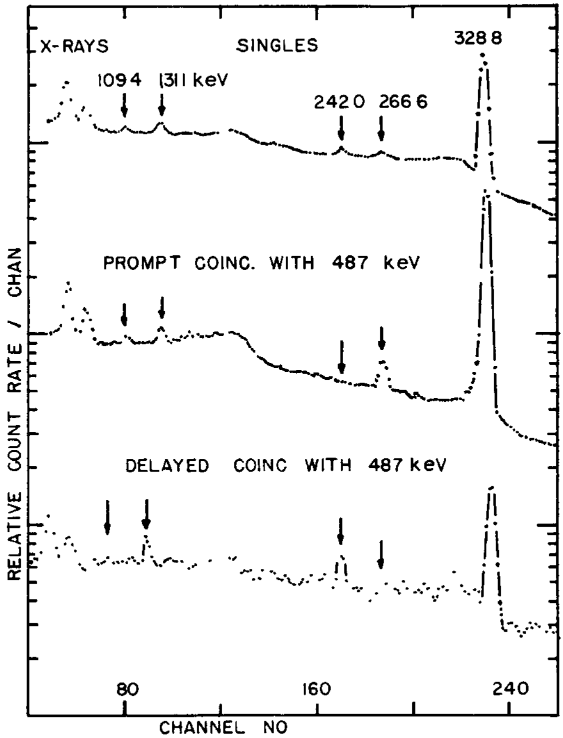

Fig. 4. Low-energy portion of the γ-ray spectrum following the decay of ^{140}La in prompt and delayed (delay is 200 ns, 2τ = 100 ns) coincidence with the 487.0 keV γ-ray. The 131.1 and 242.0 keV γ-rays are seen to be in delayed coincidence.

Gate on 1596.6 keV *gamma ray*. The γ-ray spectrum in the energy range 0.07–2.02 MeV in coincidence with γ-1596 is shown in fig. 2. Gamma rays with the following energies have approximately the same relative peak areas in the coincidence spectrum as in the singles spectrum: 109.4, 266.6, 328.8, 432.5, 487.0, 751.8, 815.8, 867.8, 919.6, 925.2 and 950.9 keV. The 131.1 keV peak is reduced approximately 50 % in the coincidence spectrum (relative to the above lines), and a peak corresponding to the 242.0 keV γ-ray cannot be seen at all.

Gate on 487.0 keV *gamma ray*. The γ-ray spectrum in the energy range 0.06–1.18 MeV in coincidence with γ-487 is shown in fig. 3. The events coincident with the Compton distributions in gate A were subtracted using the spectrum coincident with gate B. The small 487.0 keV peak in the coincidence spectrum is due to the presence of annihilation radiation from γ-1596 in gate A.

Gamma rays with energies 266.6, 328.8, 397.8, 432.5 keV and the 1596.6 double escape peak have approximately the same relative intensity in coincidences with

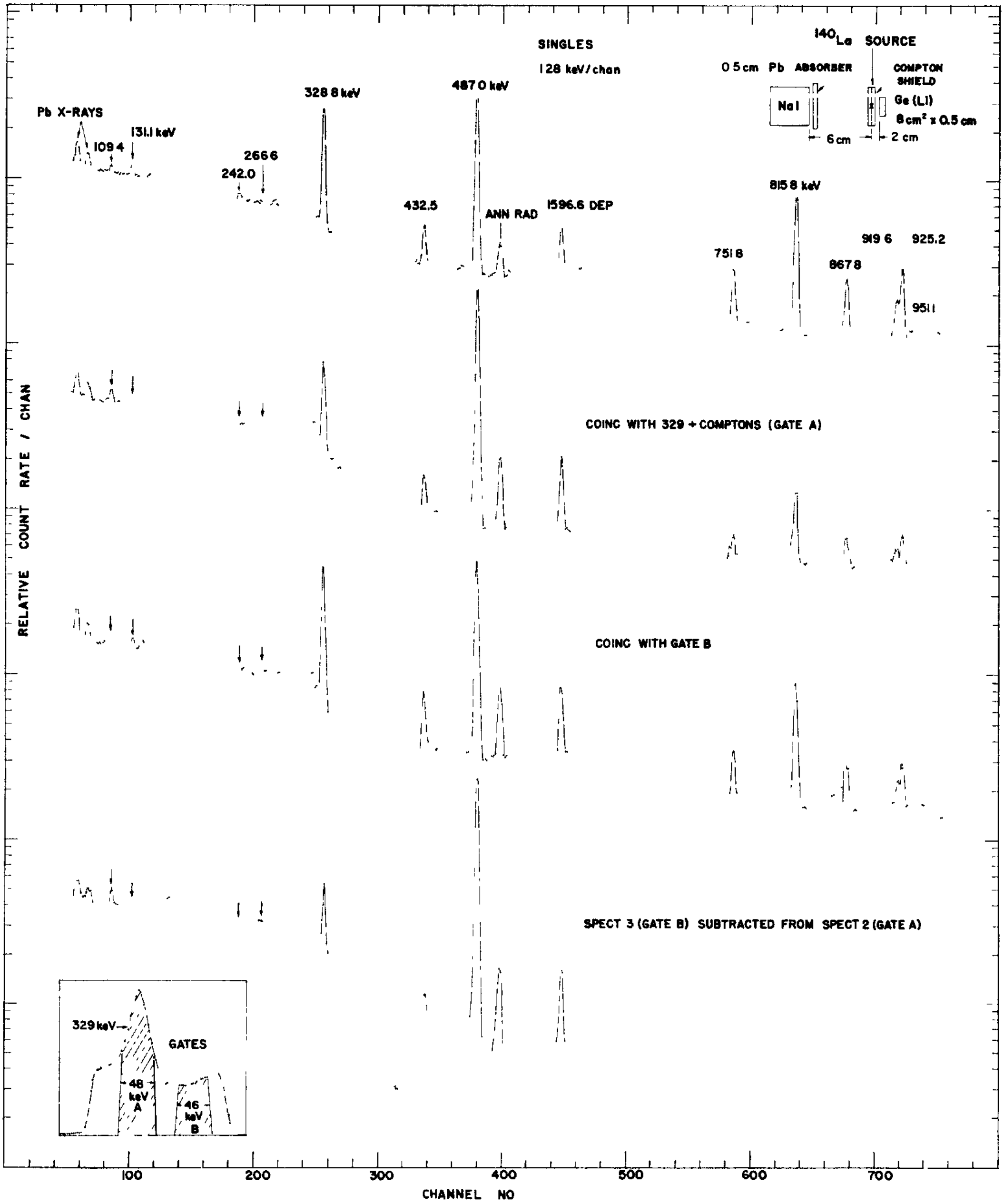

Fig. 5. The γ-ray spectrum in the energy range 0.07–1.02 MeV in coincidence with the 328.8 keV γ-ray.

γ-487 as in singles. The 109.4 and 131.1 keV peaks are reduced approximately 50 % relative to 266.6 keV peak. There is no evidence for the presence of γ-rays in prompt coincidence having the following energies: 242.0, 751.8, 815.8, 867.8, 919.6, 925.2 and 950.9 keV.

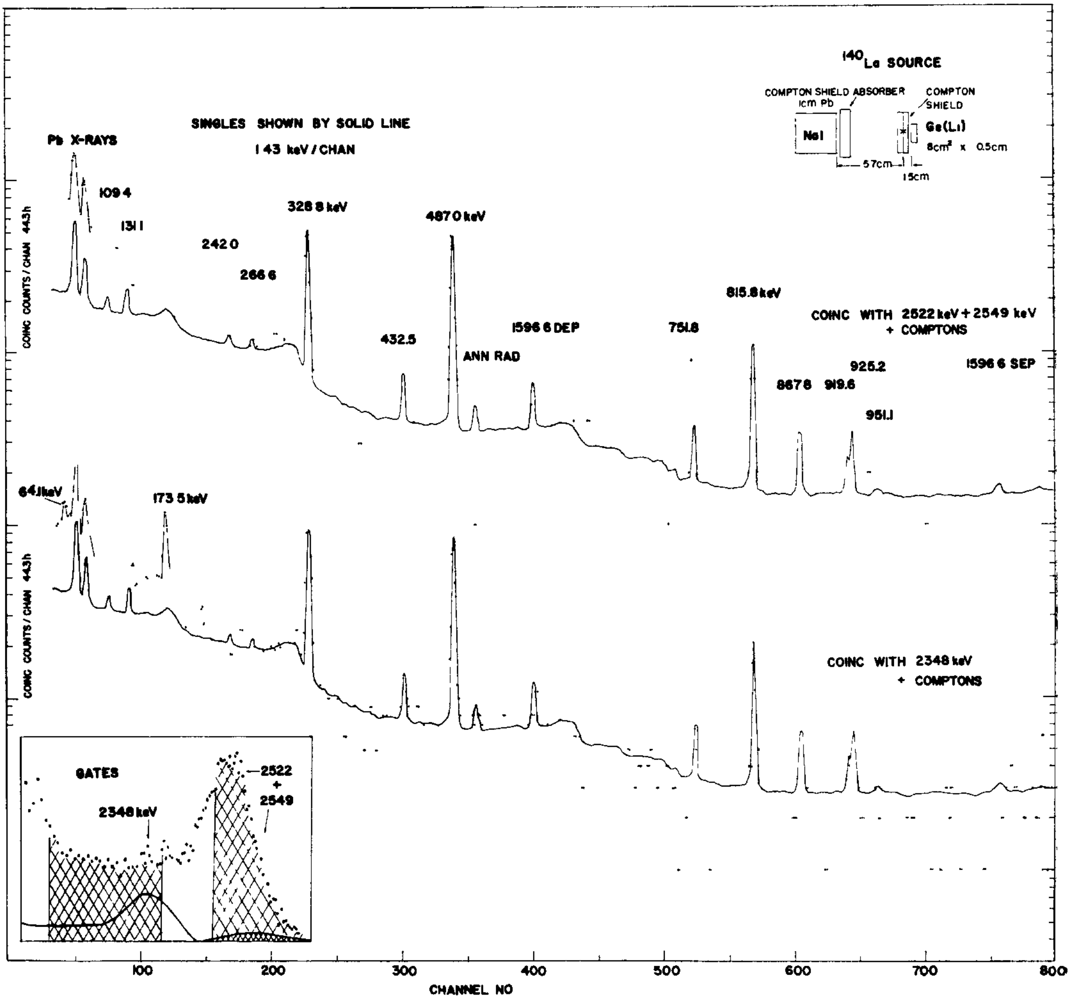

Fig. 6. The γ-ray spectra in the energy range 0.05–1.15 MeV in coincidence with the 2348.8 and 2522.2, 2548.6 keV γ-rays.

The low-energy portion of the γ-ray spectrum in delayed coincidence (delay is 200 ns, 2τ = 100 ns) with γ-487 is shown in fig. 4. The running time was 42 h. The 131.1 and 242.0 keV γ-rays are seen to be in delayed coincidence. The value of the peak area ratio $A(131.1)/A(242.0)$ in the delayed spectrum is approximately one half the value of this ratio in the singles spectrum.

Gate on 328.8 keV *gamma ray.* The γ-ray spectrum in the energy range 0.07–1.02 MeV in coincidence with γ-329 is shown in fig. 5. For the subtraction of the gate B spectrum from the gate A spectrum, the relative count rates were adjusted so as to remove the 815.8 keV peak. With this normalization, lines in coincidence with γ-487 will appear in the subtracted spectrum since the 328.8 keV peaks sits on the Compton knee of the 487.0 keV γ-ray.

The 109.0 and 1596.6 keV γ-rays are seen to be in coincidence with the 328.8 keV γ-ray. The presence of small peaks in the subtracted spectrum corresponding to γ-rays with energies 131.1, 328.8, 432.5 keV and annihilation radiation may be attributed to the fact that they are in coincidence with γ-487. There is no evidence for the presence of γ-ray lines in the coincidence spectrum with the energies 242.0, 266.6, 751.8, 815.8, 867.8, 919.6, 925.2 and 950.9 keV.

Gate on 2348.8 *and* 2522.2 keV *gamma rays.* The γ-ray spectra in the energy range 0.05–1.15 MeV in coincidence with the 2348.8, 2522.2 and 2548.6 keV γ-rays are shown in fig. 6. The running time was 44 h. It can be seen from the inset that the gate for the 2522.2 keV γ-ray also accepts most of the photopeak of the weak 2548.6 keV γ-ray. There appears to be no γ-ray in coincidence with either γ-2522 or γ-2549. The coincidence spectrum deviates noticeably from the singles spectrum (solid line) below 300 keV. Since there is $\approx$ 11 % β^- feeding to the 2522 keV level, this deviation is probably caused by the bremsstrahlung in coincidence with γ-2522. The two γ-rays with energies 64.1 and 173.5 keV are seen to be in coincidence with γ-2348.

Gate on 751.8 keV *gamma ray.* The γ-ray spectrum in the energy range 0.07–1.00 MeV in coincidence with γ-751.8 was obtained using a Ge(Li)-NaI arrangement. The 173.5 and 1596.6 keV gamma rays appear in coincidence with γ-752.

Gate on 867.8, 919.6 *and* 925.2 keV *gamma rays.* By using a Ge(Li)-Ge(Li) arrangement with a biased amplifier on the gate side, it was possible to gate on each of these peaks separately. The coincidence spectra in the range 0.07–1.65 MeV were obtained with running times of 35 h. Only γ-1596.6 could definitely be seen in coincidence with each of these three γ-rays.

4. Construction of the $^{140}La \rightarrow {}^{140}Ce$ decay scheme

4.1. TRANSITION ENERGIES, INTENSITIES AND K-SHELL CONVERSION COEFFICIENTS

Energy and total transition intensities for 28 transitions in ^{140}Ce following the β^- decay of ^{140}La are shown in table 2. The γ-ray intensities in percent of total decays were obtained by multiplying the relative γ-ray intensities of column 5, table 1 by 0.955. The theoretical value [24]) α_K (1596.6, E2) $= 0.69 \times 10^{-3}$ and the fact that the ground state β^- feeding [7]) is $\approx 4 \times 10^{-4}$ % were used in determining this factor. The K-shell conversion transition intensities (column 3) were obtained from the relative intensities of Karlsson *et al.* [1]). In determining the total transition intensities (column 4), the K/L ratios measured by Karlsson *et al.* were used. For the 1903.5 keV transition, the theoretical branching ratio [18,25]) $\lambda_\pi/\lambda_{K_e} = 0.21$ was used to estimate the internal pair transition intensity. The experimental K-shell conversion coefficients obtained from the values in columns 2 and 3 are given in column 5.

TABLE 2

Energy, intensity and K-shell conversion coefficient values for transitions in ^{140}Ce following β^--decay of ^{140}La

Transition energy [a]) (keV)	I_γ [d]) (% decays)	I_e (K) [e]) (% decays)	I_{total} [d, e]) (% decays)	$\alpha_K \times 10^3$
24.595 [b])			0.32 ±0.04	
64.135	<0.01	$(2.4 \pm 0.4) \cdot 10^{-2}$	0.04 ±0.02	
68.916 [b])	0.062±0.012	$(1.5 \pm 0.3) \cdot 10^{-1}$	0.24 ±0.06	2420 ±674
109.418	0.26 ±0.04	$(1.48 \pm 0.05) \cdot 10^{-1}$	0.43 ±0.04	569 ±90
131.121	0.58 ±0.09	$(2.10 \pm 0.08) \cdot 10^{-1}$	0.83 ±0.09	362 ±58
173.536	0.12 ±0.05	$(2.2 \pm 0.3) \cdot 10^{-2}$	0.15 ±0.05	183 ±80
241.966	0.43 ±0.06	$(3.19 \pm 0.22) \cdot 10^{-2}$	0.47 ±0.06	74.2 ±11.5
266.551	0.53 ±0.06	$(3.0 \pm 0.3) \cdot 10^{-2}$	0.56 ±0.06	56.6 ±8.5
306.9	0.021±0.011		0.022±0.011	
328.768	20.4 ±1.1	$(7.24 \pm 0.10) \cdot 10^{-1}$	21.2 ±1.1	35.5 ±2
397.79	0.052±0.024	$(2.2 \pm 1.4) \cdot 10^{-3}$	0.055±0.024	42 ±33
432.530	2.97 ±0.15	$(5.5 \pm 0.3) \cdot 10^{-2}$	3.03 ±0.15	18.5 ±1.4
487.029	47.2 ±2.4	$(4.20 \pm 0.22) \cdot 10^{-1}$	47.7 ±2.4	8.90 ±0.65
618.2	0.042±0.021	$<2.1 \times 10^{-3}$	0.042±0.021	
751.827	4.20 ±0.21	$(1.88 \pm 0.22) \cdot 10^{-2}$	4.22 ±0.21	4.48 ±0.57
815.801	23.0 ±1.1	$(9.1 \pm 0.6) \cdot 10^{-2}$	23.1 ±1.1	3.96 ±0.32
867.82	5.39 ±0.27	$(5.8 \pm 1.4) \cdot 10^{-3}$	5.40 ±0.27	1.08 ±0.27
919.64	2.61 ±0.15	$(5.8 \pm 1.4) \cdot 10^{-3}$	2.62 ±0.15	2.22 ±0.55
925.20	6.91 ±0.41	$(2.17 \pm 0.22) \cdot 10^{-2}$	6.93 ±0.41	3.14 ±0.37
950.88	0.53 ±0.05	$(1.3 \pm 0.4) \cdot 10^{-3}$	0.53 ±0.05	2.45 ±0.79
1596.6	95.5 ±0.2	6.59×10^{-2}	95.6 ±0.2	0.69
1903.5 [c])		$(1.45 \pm 0.14) \cdot 10^{-2}$	$(1.93 \pm 0.16) \cdot 10^{-2}$ [f])	
2348.4 [c])	0.860±0.043	$(3.2 \pm 0.5) \cdot 10^{-4}$	0.860±0.043	0.37 ±0.06
2521.8 [c])	3.36 ±0.17	$(1.16 \pm 0.14) \cdot 10^{-3}$	3.36 ±0.17	0.345±0.045
2547.5 [c])	0.117±0.009	$(3.3 \pm 0.8)\ 10^{-5}$	0.117±0.009	0.28 ±0.07
2899.7	0.067±0.005	$(1.7 \pm 0.3) \cdot 10^{-5}$	0.067±0.005	0.25 ±0.05
3118.3	0.026±0.003	$(6.5 \pm 2.2) \cdot 10^{-6}$	0.026±0.003	0.25 ±0.09
3319.7	0.008±0.004	$(9 \pm 5) \cdot 10^{-7}$	0.008±0.004	0.11 ±0.08

[a]) Values taken from table 1 of present work except where indicated otherwise.

[b]) Value taken from ref. [1]).

[c]) Value adopted on basis of energy sums of lower energy transitions.

[d]) Values based on the relative γ-ray intensities given in table 1 and on the assumption that the 1596.6 keV transition is pure E2 with α_K (1596.6) $= 0.69 \times 10^{-3}$.

[e]) Values based on the relative conversion electron intensities of ref. [1]).

[f]) The theoretical branching ratio $\lambda_\pi/\lambda_e = 0.21$ has been used to estimate the internal pair transition intensity.

4.2. TRANSITION MULTIPOLARITIES

A comparison of theoretical and experimental K-shell conversion coefficients is given in table 3. The possible transition multipolarities based on this comparison are shown in column 2, table 4. Also shown in this table are the possible multipolarities consistent with the data on L-subshell ratios [1]), K/L ratios [1]) and the γ-$\gamma(\theta)$ correlation data [9-11]). For several transitions where an appreciable admixture of a component with $L \geqq 3$ was not excluded by the conversion coefficient data, the fact that the corresponding γ-ray was seen in a coincidence spectrum was used to exclude these higher multipolarities. In column 5 of table 4, the possible multipolarities consistent with all the data are indicated. The transition multipolarities consistent with the data and with the presently proposed level scheme are shown in column 6.

There appears to be a discrepancy in the multipolarity assignment for the 109.4 keV transition. The L-subshell ratios are consistent with an M1+E2 admixture and exclude an E1+M2 admixture. The K-shell conversion coefficient, on the other

TABLE 3

Comparison of experimental and theoretical K-shell conversion coefficients

Transition energy (keV)	Theoretical values [a]) of $\alpha_K \times 10^3$ E1	E2	E3	M1	M2	M3	Experimental value of $\alpha_K \times 10^3$
68.9	570	3350		2970	36000		2420 ±674
109.4	165	930		790	6700		569 ± 90
131.1	100	530		470	3450		362 ± 58
173.5	45.3	220		215	1275		183 ± 80
242.0	18.7	76	275	86	420	1700	74.2 ±11.5
266.6	14.5	56.5	195	67	305	1150	56.6 ± 8.5
306.9		36					
328.8	8.5	29.3	92	38.0	155	520	35.5 ±2.0
397.8	5.3	16.8	49	23.5	84	260	42 ±33
432.5	4.32	13.4	38.2	18.5	65	195	18.5 ±1.4
487.0	3.28	9.7	24.3	13.3	43	120	8.90 ±0.65
618.2		5.3					
751.8	1.30	3.30	7.60	5.00	13.5	30.5	4.48 ±0.57
815.8	1.08	2.67	6.02	4.05	10.6	23.0	3.96 ±0.32
867.8	0.96	2.35	5.15	3.52	9.0	19.2	1.08 ±0.27
919.6	0.86	2.05	4.45	3.08	7.70	16.4	2.22 ±0.55
925.2	0.855	2.03	4.40	3.05	7.65	16.0	3.14 ±0.37
950.9	0.810	1.93	4.10	2.86	7.15	14.8	2.45 ±0.79
1596.6		0.690					
2348.4	0.175	0.325	0.570	0.380	0.780	1.28	0.37 ±0.06
2521.8	0.155	0.290	0.485	0.320	0.650	1.05	0.345±0.045
2547.5	0.153	0.288	0.481	0.317	0.643	1.04	0.28 ±0.07
2899.7	0.127	0.232	0.382	0.242	0.480	0.77	0.25 ±0.05
3118.3	0.114	0.205	0.33	0.210	0.41	0.65	0.25 ±0.09
3319.7	0.105	0.185	0.29	0.185	0.35	0.55	0.11 ±0.08

[a]) Theoretical values taken from Sliv and Band [24]).

hand, is consistent with an E1+M2 admixture and appears to exclude an M1+E2 admixture. Since the measurements involved in determining α_K are subject to systematic errors, the L-subshell ratios were considered to be more reliable. Also, since the parities of the 2521.8 and 2412.4 keV levels can be established independently to have a positive value, the 109.4 keV transition between these levels cannot have an E1+M2 character.

TABLE 4

Multipolarity determinations for transitions in ^{140}Ce

Transition energy (keV)	Possible multipolarities: K-shell conversion coefficients [a]	Possible multipolarities: L-subshell ratios [c] K/ΣL ratios	Possible multipolarities: γ-$\gamma(\theta)$ [d]	Multipolarity assignment: Data	Multipolarity assignment: Data + internal consistency [e] with level scheme
24.6		M1+E2, E2		M1+E2, E2	E2(< 42 % M1)
64.1		M1+E2, M1		M1+E2, M1	M1(< 3.7 % E2)
68.9	E1+M2, M1, E2, M1+E2	M1+E2, M1		M1+E2, M1	M1(< 0.7 % E2)
109.4	E1+M2	M1+E2		M1+E2	M1+E2
131.1	E1+M2, M1	E1+M2		E1+M2	E1+(2–19 %)M2
173.5	E1+M2, M1, E2, M1+E2	E1+M2, E1, M1, M1+E2		E1+M2, M1, M1+E2	M1+E2, M1
242.0	E1+M2, M1, E2, M1+E2	E1+M2, E1, M1, M1+E2		E1+M2, M1, M1+E2	E1+(11–17 %)M2
266.6	E1+M2, M1, E2, M1+E2	E1+M2, M1, M1+E2, M2		E1+M2, M1, M1+E2	E1+(12–17 %)M2
328.8	E1+M2, M1, M1+E2	E1+M2, E1, M1, M1+E2	$L = 1; L = 2 \leqq 0.005$	M1	M1
397.8	E1+M2, M1, E2, M1+E2			E1+M2, M1, E2, M1+E2	M1+E2, M1
432.5	E1+M2, M1, M1+E2	E1+M2, M1, M1+E2, E2, M2		E1+M2, M1, M1+E2	E1+M2, M1, M1+E2
487.0	E1+M2, E2	M1+E2, E2	$L = 2, L = 3 \leqq 0.005$	E2	E2
751.8	E1+M2, M1, M1+E2			E1+M2, M1, M1+E2	M1+(0–64 %)E2
815.8	E1+M2, M1, M1+E2	E1+M2, E1, M1, M1+E2, E2, M2	$L = 1; L = 2 \leqq 0.002$	M1	M1
867.8	E1+M2, E1			E1+M2, E1	E1+(0–5 %)M2
919.6	E1+M2, E2, M1+E2			E1+M2, E2, M1+E2	E1+M2, E2, M1+E2
925.2	E1+M2, M1, M1+E2	E1+M2, E1, M1, M1+E2, E2, M2		E1+M2, M1, M1+E2	M1+(0–27 %)E2
950.9	E1+M2, M1, E2, M1+E2			E1+M2, M1, E2, M1+E2	M1+E2, M1
1596.6	E2 [b]		$L = 2$	E2	E2
1903.5	E0	E0		E0	E0
2348.4	M1, E2			M1, E2	E2
2521.8	M1, E2			M1, E2	E2
2547.5	M1, E2			M1, E2	M1, E2
2899.7	M1, E2			M1, E2	M1, E2
3118.3	M1, E2			M1, E2	M1, E2
3319.7	E1, M1, E2			E1, M1, E2	M1, E2

[a]) Based on values given in table 3.

[b]) Adopted transition multipolarity.

[c]) Based on work of ref. [1]).

[d]) Values of L consistent with the γ-$\gamma(\theta)$ measurements of refs. [9–11]).

[e]) Admixtures for transitions in the energy range 24.6–131.1 keV correspond to those reported in ref. [1]). Admixtures for all other transitions are based on the K-shell conversion coefficients of the present work.

4.3. THE DECAY $^{140}_{57}La_{83} \rightarrow ^{140}_{58}Ce_{82}$

In fig. 7 is presented a scheme for the decay of ^{140}La to levels of ^{140}Ce which incorporates in a consistent manner all the data of the present work as well as those of earlier investigators. To the most recent level scheme of Karlsson *et al.* [1]), two new levels at 2108.2 and 2464.4 keV have been added, and further evidence for the proposed levels at 2350.2 and 2481.3 keV is presented. The existence of the two proposed levels at 2325.5 and 3216.1 keV is not supported.

The β-feeding percentages are based on the γ-transition intensity balance for each level. The value $(4 \pm 1) \times 10^{-4}$ % of the ground state β-feeding is reduced by a factor of two from that reported by Dzhelepov *et al.* [5]), since they assumed that the β-feeding to the 1596.6 keV level is 10 %. From the present work it is seen that this feeding is approximately 5 %. The indicated $\log ft$ values are obtained by making the allowed approximation and using partial β-transition probabilities and end-point energies [26]) †.

The mean lifetime values of several of the low-lying states in ^{140}Ce are from refs. [14,15,20,21]). On the basis of the present coincidence studies, an upper limit of 30 ns can be placed on the mean lifetime of each level in the range 2348.4–2547.5 keV with the exception of the upper limit on the 2464.4 keV level; this value is discussed later. The value of the magnetic moment of the 2083.6 keV level is from ref. [27]).

The spin and parity assignments shown in fig. 7 for the 15 excited states of ^{140}Ce are based on the interpretation of all the data presently available. Values of J and/or π enclosed by parentheses are regarded as tentative. A discussion of how spin and parity assignments were made and of other data pertinent to the level structure follows.

Level at 2108.2 keV. An isomeric state at this energy is here proposed for the following reasons. The energy 266.551 ± 0.014 keV of the cross-over transition compares well with the sum $24.595 + 241.966 = 266.561 \pm 0.013$ keV of the proposed cascade transitions. The 50 % reduction in intensity of the 131.1 keV γ-ray peak relative to the 266.6, 432.5 and 328.8 keV γ-ray peaks in the prompt coincidence spectrum gated by γ-487 indicates that the 2350.2 keV level is being depopulated by a γ-ray with an intensity nearly equal to that of the 266.6 keV γ-ray. The 242.0 and 266.6 keV γ-rays have nearly the same intensity. The decay sequence of the 242.0–24.6 keV cascade is most clearly established by the photonuclear reaction data of Krehbiel and Meyer-Berkhout [20]). They found two γ-rays with energies 480 ± 10 keV and 1600 ± 40 keV having nearly equal intensity in delayed coincidence with the primary excitation pulse in the reactions $^{140}Ce(\gamma, \gamma')^{140m}Ce$ and $^{142}Ce(\gamma, 2n)^{140m}Ce$. If the sequence of decay were 24.6–242.0 keV as suggested by Karlsson *et al.*, the 242.0 keV γ-ray would also have been observed in delayed coincidence with the excitation pulse. Since this γ-ray seems not to have been observed, the decay sequence must be as shown in fig. 7. The highly L-converted 24.6 keV transiton (theoretical α_L (24.6, E2) $\approx$ 465) would have escaped detection in the work of Krehbiel and

† Ref. [29]) is based on the work of Verrall *et al.* [26]).

Meyer-Berkhout. These investigators determined the decay half-life of the 480 and 1600 γ-rays relative to the excitation pulse to the 6.5 ± 1.5 μs. This lifetime must now be attributed to the 2108.2 keV level. All the coincidence data of the present investiga-

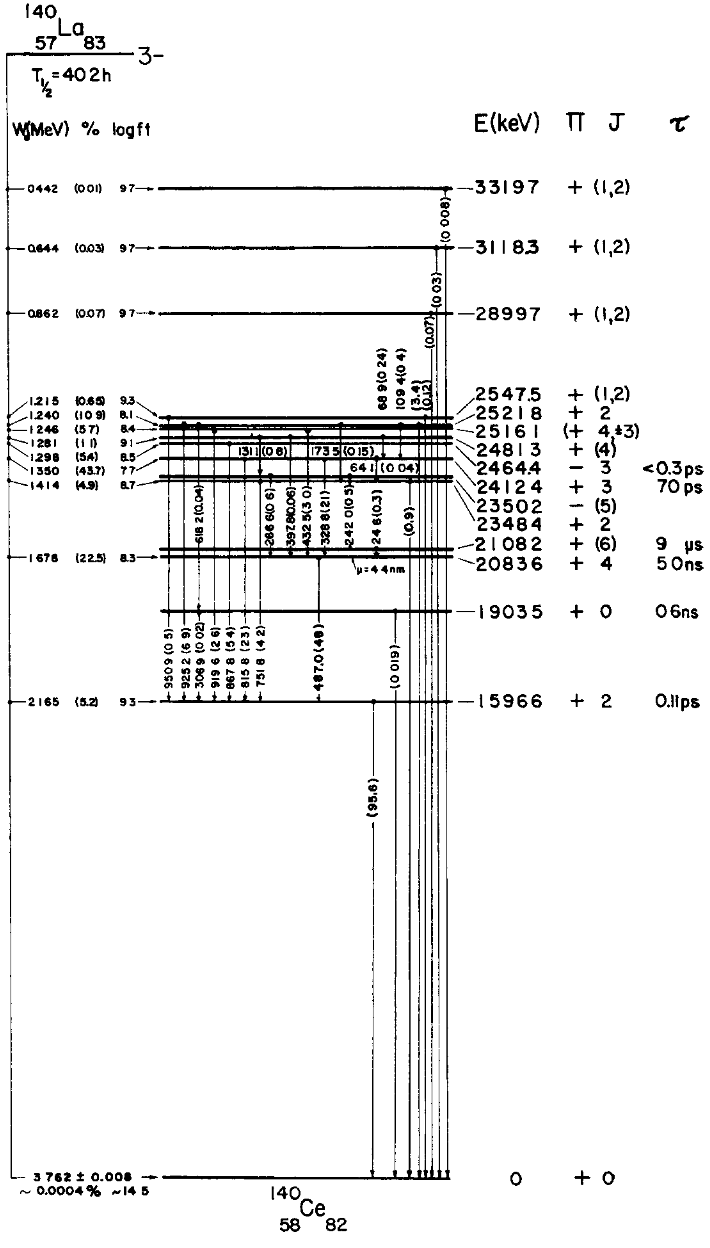

Fig. 7. The decay scheme ^{140}La → ^{140}Ce proposed on the basis of the present work.

tion including the delayed coincidence spectrum shown in fig. 4 support this interpretation.

Only the 242.0 and 24.6 keV transitions have been observed to feed and depopulate the 2108.2 keV level; their respective intensity values are 0.47 ± 0.06 and 0.32 ± 0.04 % decay. The upper limits on the intensities of γ-ray transitions to the ground state, 1596.6 and 1903.5 keV levels as determined from the Ge(Li) singles spectrum are $I_\gamma(2108.2) < 0.05$ %, $I_\gamma(512) < 0.2$ %, $I_\gamma(200.7) < 0.1$ % decay. The intensity value $I_\gamma(24.6) = 0.0007$ % decay is obtained using the theoretical [24]) value $\alpha_L(24.6, \text{E2}) = 465$ and the experimental value $I_{L_e}(24.6) = 0.32$ % decay.

TABLE 5
Hindrance factors

Assumed J^π for 2108.2 keV level	Single-proton transition estimate $\lambda_{s.p.}$ (sec^{-1})	Maximum γ-ray transition probability from data	Hindrance factor $\lambda_{s.p.}/\lambda_\gamma$
2^+	$\lambda(2108, \text{E2}) = 2.2 \times 10^{12}$	$\lambda_\gamma < 0.1\ \lambda_t$	$> 10^8$
3^+	$\lambda(511.6, \text{M1}) = 3.9 \times 10^{12}$	$\lambda_\gamma < \lambda_t$	$> 10^7$
4^+	$\lambda(511.6, \text{E2}) = 1.9 \times 10^9$	$\lambda_\gamma < \lambda_t$	$> 10^4$
5^+	$\lambda(24.6, \text{M1}) = 4.3 \times 10^8$	$\lambda_\gamma < 0.2\ \lambda_t$	$> 10^4$
6^+	$\lambda(24.6, \text{E2}) = 4.8 \times 10^2$	$\lambda_\gamma \approx 2.4 \times 10^2\ sec^{-1}$	≈ 2

The possible J^π values of this state consistent with the E2(+M1) character of the 24.6 keV transition and the fact that the 2083.6 keV level is 4^+ are 2^+, 3^+, 4^+, 5^+ and 6^+. The mean lifetime of this state is $9.4 \pm 2.2\ \mu s$, which corresponds to a total decay probability $\lambda_t = 1.1 \times 10^5\ sec^{-1}$. A comparison of this transition probability with single-proton transition estimates [32]) for various unobserved, depopulating, γ-ray transitions favors a 6^+ assignment. The hindrance factors for the unobserved 2108.2 and 511.6 keV transitions between the 2108.2 keV level and the ground and first-excited states which would exist if the 2108.2 keV level had the various J^π values in the above mentioned range are given in table 5. Also given is the hindrance factor for the 24.6 keV, M1 transition if the 2108.2 keV level were assumed to be 5^+.

The maximum γ-ray transition probabilities for the 2^+, 3^+ and 4^+ cases derive from the intensity limits stated above for the unobserved γ-ray transitions and the fact that the 24.6 keV transition has an intensity 0.32 % decay. For the 5^+ case, λ_γ is obtained using the theoretical conversion coefficient [24]) $\alpha_L(24.6, \text{M1}) \approx 7$. For the 6^+ case, it has been assumed that $\lambda_{L_e} \approx \lambda_t$, so that the γ-ray transition probability is given by $\lambda_\gamma \approx \lambda_t/\alpha_L(24.5, \text{E2})$. When the above lower limits on hindrance factors are compared to the range of factors generally observed in nuclear transitions with the same multipolarity [31]), it is seen that they fall above this range. At present one does not expect M1 and E2 γ-ray transition rates between low-lying states in doubly even nuclei to be hindered by more than four orders of magnitude from single-proton estimates. Thus, since any value of J^π other than 6^+ would require the existence of an extremely large hindrance factor, the assignment 6^+ to the 2108.2 keV level is favored.

Furthermore, a J^π value of 2^+, 3^+, 4^+ or 5^+ would permit a first-forbidden β-transition to populate this state, whereas a 6^+ value requires a third-forbidden transition. In this decay, β-transitions proceed to all the observed levels which can be populated via first-forbidden transition. The absence of β-feeding to the 2108.2 keV level therefore adds weak support to the 6^+ assignment.

Level at 2412.4 keV. The spin and parity of this level have generally been adopted to be 3^+ without regard to conflicting evidence. The γ-$\gamma(\theta)$ correlation measurements[9, 11]) on the 328.8–487.0 keV cascade are consistent with a pure E2, 487.0 keV transition and an M1, 328.8 keV transition with 0.1–0.5 % quadrupole admixture. The K-shell conversion coefficient data have not been consistent with this. Experimental determinations [1, 3]) of the K-shell conversion coefficient of the 487.0 keV transition have given a value very nearly equal to the theoretical value $\alpha_K(487.0, E2) = 9.7 \times 10^{-3}$. The experimental K-shell conversion coefficient for the 328.8 keV transition determined by Bashilov *et al.* [3]) is 29×10^{-3} and that determined by Karlsson *et al.* [1]) is $(29.8 \pm 2.4) \times 10^{-3}$. Comparison with theoretical values, $\alpha_K(328.8, M1) = 38.0 \times 10^{-3}$ and $\alpha_K(328.8, E2) = 29.3 \times 10^{-3}$, would suggest a nearly pure E2 character for the 328.8 keV transition (in contradiction to the γ-$\gamma(\theta)$ data).

Since the 487.0 keV transition is very nearly pure E2, the theoretical value α_K $(487.0, E2) = 9.7 \times 10^{-3}$ should be used to determine the K-shell conversion coefficient of the 328.8 keV transition so as to reduce the effect of systematic errors in the relative γ-ray and K-shell conversion electron intensities. By doing this and by using the relative K-shell conversion electron intensities [1]) $I_e(328.8)/I_e(487.0) = 1.72 \pm 0.09$ and the relative γ-ray intensities (column 4, table 1) $I_\gamma(487.0)/I_\gamma(328.8) = 2.31 \pm 0.16$, the value $\alpha_K(328.8) = (38.5 \pm 3.3) \times 10^{-3}$ is obtained. This is in good agreement with the theoretical value for an M1 transition and thereby resolves the ambiguity.

The M1 multipolarities determinations of the 328.8 and 815.8 keV transitions and the fact that the 1596.6 and 2083.6 keV levels are 2^+ and 4^+, respectively, uniquely affix the value $J^\pi = 3^+$ to the 2412.4 keV level.

Levels at 2350.2 *and* 2481.3 keV. Levels at these energies were suggested by Karlsson *et al.* on the basis of energy sum relationships. The coincidence data of the present work give strong support to the existence of these levels. In the coincidence spectrum gated by γ-487.0, the 266.6, 328.8, 397.8 and 432.5 keV lines have approximately the same relative intensity as in the singles spectrum. Within the framework of the present level scheme, this indicates that the 266.6 and 397.8 keV transitions must feed the 2083.6 keV level, thereby establishing levels at 2350.2 and 2481.3 keV. Spin and parity assignments can be made as follows.

The positive parity of the 2481.3 keV level is established by the fact that the 68.9 keV transition between the 2481.3 keV level and the 2412.4 keV, 3^+ level is of character M1+E2 or pure M1. The negative parity of the 2350.2 keV level is then established since the 131.1 keV transition between the 2481.3 and 2350.2 keV levels is of character E1+M2. The 266.6 and 242.0 keV transitions depopulating the 2350.2 keV, +, level to positive-parity states therefore must have E1+M2 character. The multipolarities of these two transitions determine the J of the 2350.2 keV level to be 5 if the 2083.6 and 2108.2 keV levels are assumed to have $J = 4$ and $J = 6$, respectively. For the 2481.3 keV level, only the value $J = 4$ is now consistent with the E1+M2 character of the 131.1 keV transition and the M1+E2 character of the 68.9 keV transition. The multipolarity of the 397.8 keV transition between the 2481.3 (4^+) and 2083.6, 4^+ keV levels must therefore be M1(+E2), which is consistent with the data. For these reasons the assignments $J^\pi = 5^-$ and $J^\pi = 4^+$ for the 2350.2 and 2481.3 keV levels, respectively, are favored.

The total intensity of the 242.0 and 266.6 keV transitions depopulating the 2350.2 keV level is 1.03 ± 0.08 % decay, whereas the intensity of the populating 131.1 keV transition is 0.83 ± 0.09 % decay. To within uncertainties, an intensity balance is therefore achieved with negligibly small β-feeding. The absence of β-feeding is consistent with the fact that second forbidden transition is required to feed this 5^- level. For the 2481.3 keV level, the total depopulating intensity of the 68.9, 131.1 and 397.8 keV γ-decays is 1.12 ± 0.11 % decay. Since no populating γ-transitions have been observed, β-feeding of approximately 1.1 % must be assumed. The corresponding log ft value 9.1 falls on the high side of the range of values generally observed [30]) for first-forbidden β-transitions in this mass region.

Gamma rays corresponding to possible E2 transitions depopulating the 2481.3 keV (6^+), 1596.6 keV, 2^+ levels were not observed. The upper limits I_γ(373 keV) < 0.1% and I_γ(885 keV) < 0.1 % decay were determined.

Level at 2464.4 keV. Although a level at this energy has not appeared previously in any proposed decay scheme of ^{140}La, a level at this excitation energy in ^{140}Ce was suggested by Hansen and Nathan [19]) on the basis of inelastic α-particle scattering experiments. In the reaction ^{140}Ce(α, $\alpha'\gamma$)^{140}Ce, they detected an 0.87 MeV γ-ray which they attributed to the transition between levels at 2.47 and 1.60 MeV. The coincidence data of the present investigation are in good agreement with this interpretation if the 0.87 MeV γ-ray is identified with the 868.8 keV γ-ray and the 2.47 and 1.60 MeV levels with the 2464.4 and 1596.6 keV levels. The E1 character of the 867.8 keV transition (table 4) is consistent with the proposed [19]) 3^- assignment.

An upper limit of 0.3 ps on the mean lifetime of the 2464.4 keV level is obtained using the measured value [19]) $B(\mathrm{E3}, 0^+ \rightarrow 3^-) = 76\ e^2\ 10^{-74}\ \mathrm{cm}^6$ and the intensity limit I_γ(2464.4 keV) < 100 I_γ(867.8 keV) determined from the Ge(Li) singles spectrum.

The intensity of the 867.8 keV transition depopulating the 2464.4 keV level is 5.40 ± 0.27 % decay. Since no γ-transitions has been observed to feed this level, it must be assumed that this level is primarily populated through β-decay. The corresponding log ft value 8.5 falls on the high side of the observed range [31]) for allowed β-transitions.

Gamma rays corresponding to the possible E1 transitions between the 2464.4 keV 3^- and 2348.4, 2^+, 2083.6, 4^+ keV levels were not observed. The upper limits, I_γ(116 keV) < 0.08 % and I_γ(381 keV) < 0.1 % decay were determined.

Level at 2516.1 keV. A level at this energy has been suggested [1,12]) primarily on the basis of energy sum relationships. The coincidence data of the present work add strong support to the existence of this level. The 432.5 and 328.8 keV γ-rays have approximately the same relative intensity in the spectrum coincident with γ-487 as in the singles spectrum. One must therefore assume that the 432.5 keV transition is in cascade with the 487.0 keV transition, thereby establishing a level at 2516.1 keV. Also, the fact that the 919.6 keV γ-ray appears only in coincidence with the 1596.6 keV γ-ray is evidence supporting the existence of the 2516.1 keV level.

The possible multipolarities of the 919.6 and 432.5 keV transitions (table 4) and the fact that the 1596.6 and 2083.6 keV levels have J^π values of 2^+ and 4^+, respectively, limit the J^π values of the 2516.1 keV level to 3^-, 3^+ or 4^+. The experimental values of the K-shell conversion coefficients of the 919.6 and 432.5 keV transitions have nearly the same values as the theoretical conversion coefficients for pure E2 and M1 transitions, respectively. This tends to favor a 4^+ assignment. Other weak arguments based on the absence of γ-ray transitions also favor the 4^+ assignment.

The total intensity of the depopulating 919.6 and 432.5 keV transitions is 5.65 ± 0.21 % decay. Since no populating γ-transitions have been observed this level must be fed primarily through β-decay. The corresponding value $\log ft = 8.7$ falls within the observed range [30,31]) of allowed and first-forbidden β-transitions.

Several upper limits on γ-ray intensities for unobserved, depopulating γ-ray transitions are reported in ref. [12]). Upper limits for transitions between the 2516.1 and 2350.2 (5^-), 2108.2 (6^+) keV levels are I_γ(166 keV) < 0.1 % and I_γ(408 keV) < 0.1 % decay.

Level at 2521.8 keV. The parity of this level has generally been considered to be positive and the spin has variously been considered [1,5,6]) to be 1 or 2. The uncertainty in the spin value can be attributed to the fact that the theoretical values $\alpha_K(2521.8, \text{M1}) = 0.320 \times 10^{-3}$ and $\alpha_K(2521.8, \text{E2}) = 0.290 \times 10^{-3}$ differ by only 10 %. The experimental value $\alpha_K(2521.8) = (0.345 \pm 0.045) \times 10^{-3}$ given in table 2 is consistent with (and only with) an M1 or E2 multipolarity assignment. It is again reasonable to redetermine the experimental conversion coefficient so as to reduce the effect of systematic errors in the relative γ-ray and K-shell conversion electron intensities. Using the relative K-shell conversion electron intensity [1]) $I_e(2521.8)/I_e(2348.4) = 3.67 \pm 0.72$, the relative γ-ray intensity (table 1) $I_\gamma(2348.4)/I_\gamma(2521.8) = 0.255 \pm 0.008$, and the theoretical value [24]) $\alpha_K(2348.4, \text{E2}) = 0.325 \times 10^{-3}$, the conversion coefficient $\alpha_K(2521.8) = (0.30 \pm 0.06) \times 10^{-3}$ is determined. This agrees very well with the theoretical value for an E2 transition although M1 cannot be excluded. However, the multipolarity of the 109.4 keV transition between the 2521.8 and 2412.4 keV, 3^+ level has M1+E2 character (but not pure E2). Hence, only a 2^+ assignment to the 2521.8 keV level is compatible with both data. The 925.2 keV transition between the 2521.8, 2^+ and 1596.6, 2^+ keV levels must be M1 (+E2), which is in good agreement with the data.

The total intensity of the five γ-transitions depopulating the 2521.8 keV level is 10.91 ± 0.45 % decay. No populating γ-transitions have been observed. The log *ft* value 8.1 based on the intensity balance falls within the observed range [30, 31]) of first-forbidden non-unique transitions.

A γ-ray corresponding to the possible E1 transition between the 2521.8, 2^+ and 2464.4, 3^- keV levels was not observed. The intensity limit I_γ(57 keV) < 0.05 % decay was determined.

Level at 2547.5 keV. The possible J^π values of this level can be restricted to 1^+ or 2^+ by the multipolarity determination of the ground state transition. The relative K-shell conversion electron intensity [1]) $I_e(2547.5)/I_e(2348.4) = 0.106 \pm 0.029$, the relative γ-ray intensity (table 1) $I_\gamma(2348.4)/I_\gamma(2547.5) = 7.34 \pm 0.43$ and the theoretical conversion coefficient $\alpha_K(2348.4, \text{E2}) = 0.325 \times 10^{-3}$ combine to give $\alpha_K(2547.5) = (0.25 \pm 0.07) \times 10^{-3}$. This agrees only with the theoretical values for an M1 or E2 transition, thereby establishing the spin and parity to be either 1^+ or 2^+. The 950.9 keV transition between the 2547.5 and 1596.6 keV, 2^+ level must therefore have M1(+E2) character. This is consistent with the data.

The total intensity of the 950.9 and 2547.5 keV transitions depopulating this level is 0.65 ± 0.05 % decay. No populating γ-transitions have been observed. If a β-feeding of 0.65 % is assumed, the corresponding log *ft* value is 9.3. This falls on the high side of the range generally observed [30, 31]) for first-forbidden transitions.

Levels at 2899.7, 3118.3 *and* 3319.7 keV. The presence of these levels is established by the fact that the γ-rays and K-shell conversion electrons [1, 7]) corresponding to the ground state transitions have been observed. On the basis of the measured K-shell conversion coefficients, the multipolarities of the 2899.7 and 3118.3 keV transitions are restricted to M1 or E2. For the 3319.7 keV transition, the possible multipolarities are E1, M1 or E2. However, the E1 multipolarity seems unlikely. If a $J^\pi = 1^-$ value is adopted for the 3319.7 keV level, the β-transition feeding this level would be second forbidden. The log *ft* value 9.7 based on the intensity balance is smaller than the values generally observed [30]) for second forbidden transitions. Thus the spin and parity of all three levels is either 1^+ or 2^+, and the β-transitions feeding these levels are first-forbidden.

5. Discussion and comparison with theory

A comparison of level schemes of ^{140}Ce as observed through the decay of ^{140}La, the reaction ^{141}Pr(d, ^{3}He)^{140}Ce [2]) and as calculated [33, 34]) using a quasi-particle (qp) description of pairing correlations is shown in fig. 8. Experimental and theoretical E2 transition rates in terms of single proton units are shown in level schemes (1) and (3), respectively. Orbital angular momentum transfer values *l* determined from ^{3}He angular distributions are shown in spectrum (2).

Rho's calculation indicated that the lowest two 2^+ and 4^+ states are mostly admixtures of $(g_{\frac{7}{2}})^2$ and $(d_{\frac{5}{2}})^2$ quasi-proton configurations, and that the relatively pure

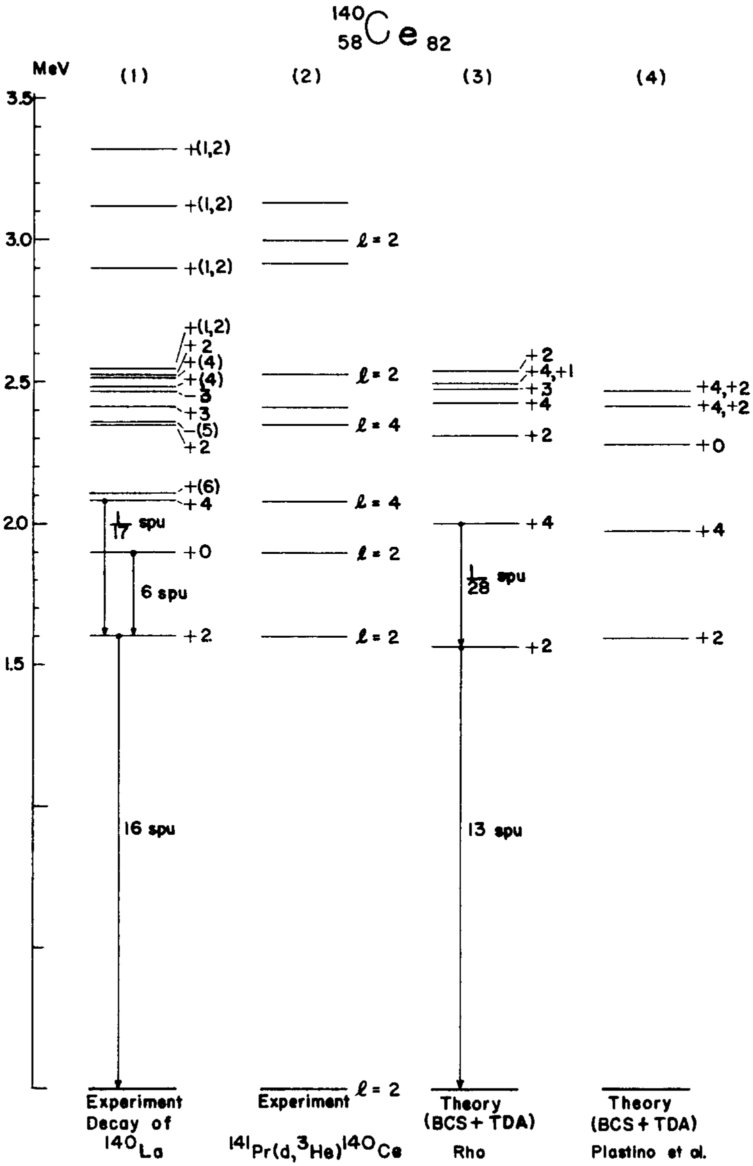

Fig. 8. A comparison of excitation spectra of ^{140}Ce as observed through the decay of ^{140}La, the reaction ^{141}Pr(d, ^{3}He)^{140}Ce and as calculated using a quasi-particle description of pairing correlations.

2 qp states $(g_{\frac{7}{2}}, d_{\frac{5}{2}})$ with $J = 1, 2, 3, 4$ have an excitation energy of approximately 2.5 MeV. The calculated wave functions reproduced qualitatively the enhanced E2 rate

for the $2^+ \to 0^+$ transition and the retarded E2 rate for the $4_1^+ \to 2_1^+$ transition when an effective proton charge $2e$ was used.

The 6^+ level at 2.108 MeV is separated by less than 25 keV from the 4_1^+ level; from present data it is not possible to determine whether one or both levels were excited in the (d, ^{3}He) reaction on ^{141}Pr. However, since the ^{141}Pr ground state has $J^\pi = \frac{5}{2}^+$, any level in ^{140}Ce strongly populated by an $l = 4$ transition must have a large $(g_{\frac{7}{2}}\, d_{\frac{5}{2}})$ component. The presence of a state with a relatively pure $(g_{\frac{7}{2}}\, d_{\frac{5}{2}})$ configuration at $\approx$ 2.1 MeV excitation would middly disagree with the results of Rho's calculations.

The 3^- state (2.464 MeV) in ^{140}Ce has a measured electric-octupole excitation probability relative to the single-proton transition rate [19]) $B(\text{E3})/B(\text{E3})_{\text{s.p.}} = 93$. The log *ft* value for the allowed β-transition between the 3^- ground state of ^{140}La and the 3^- state in ^{140}Ce is 8.5. (The average log *ft* value observed for allowed β-transitions is [31]) 5.7 ± 1.1.) These two data support [35]) the interpretation that the 3^- state may be characterized as an octupole vibration. As further evidence for the collective nature of the 3^- state, we note that the 867.8 keV, E1 transition between the 2.464 and 1.597 MeV levels is the only observed depopulating transition. Since E1 transition are forbidden between states having only proton configuration involving the shell model levels between the $Z = 50$ and $Z = 82$ major shell, the 3^- state must have components involving excitations from the core. If the 1.597 MeV state is mostly an admixture of $(d_{\frac{5}{2}})^2$ and $(g_{\frac{7}{2}})^2$ configurations, it is likely that the 3^- state has components involving the $1f_{\frac{7}{2}}$ proton orbital. This would result in a non-vanishing E1 transition matrix element between the 3^- and 2^+ levels.

All the transitions either populating or depopulating the 5^- level at 2.350 MeV have E1+M2 character. Again, this suggests that core excitations are involved in the 5^- state.

Several levels at $\approx$ 2.5 MeV excitation are depopulated by a number of different γ-ray transitions. It is interesting to compare relative γ-ray intensities with corresponding relative single-proton transition estimates. Since the transitions proceed predominantly by the lowest multipole order (table 4), the theoretical estimates for pure multipole transitions are used in the following discussion. Furthermore, since no reliable configuration assignments can yet be made for the various states, the Moszkowski transition probabilities [32]) with $S = 1$ are used.

The 2481.3 keV, (4^+) *level.* We may compare the intensity ratios $I_\gamma(397.8)/I_\gamma(131.1)/I_\gamma(68.9) = 9/100/11$ of the depopulating γ-ray transitions to the corresponding single-particle transition ratios $\lambda(397.8, \text{M1})/\lambda(131.1, \text{E1})/\lambda(68.9, \text{M1}) = 30/100/0.16$. The 68.9 keV transition between the 2481.3 keV, (4^+) and 2412.4 keV, 3^+ levels appears to be preferred to the other transitions.

On the basis of single-particle transition estimates, one expects that the possible 884.7 keV, E2 transition between the 2481.3 keV, (4^+) and 1596.6 keV, 2^+ levels should compete favorably with the 68.9 keV transition. However, this transition has not been observed.

The 2516.1 keV, (4^+) *level.* If this level has $J^\pi = 4^+$, its character must be quite different from the 2481.3 keV, 4^+ level, since the two levels depopulate differently. For example, the 2516.1 keV level depopulates to the 1596.6 keV, 2^+ level via an E2 transition while the corresponding transition is not observed for the 2481.3 keV level.

The 2521.8 keV, 2^+ *level.* This level has an interesting property in that only those transitions expected on the basis of relative single-particle transition rates are observed. We compare the intensity ratios of the five depopulating γ-ray transitions, $I_\gamma(2521.8)/I_\gamma(925.2)/I_\gamma(618.2)/I_\gamma(173.5)/I_\gamma(109.4) = 100/206/1.3/3.7/7.7$ with the corresponding single-particle transition ratios $\lambda(2521.8, \text{E2})/\lambda(925.2, \text{M1})/\lambda(618.2, \text{E2})/\lambda(173.5, \text{M1})/\lambda(109.4, \text{M1}) = 100/420/0.09/2.8/0.69$. The 109.4 and 618.2 keV transitions are enhanced by a factor of ≈ 10 relative to the other three transitions. It would be interesting to know the lifetime of this 2^+ state since this would lead to a more complete interpretation of the above branching ratios and the nature of some of the levels.

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References

1) S. E. Karlsson, B. Svahn, H. Pettersson and G. Malmsten, Nucl. Phys. **A100** (1967) 113
2) W. Jones, L. Borgman, W. C. Parkinson and J. Bardwick, Division of Nuclear Physics, 1967 Meeting, Am. Phys. Soc. Madison, Wisc., Abstract CC8 and private communication
3) A. A. Bashilov, B. S. Dzhelepov, N. D. Novosil'tseva and L. S. Chervinskaia, Bull. Acad. Sci. USSR (phys. ser.) **22** (1958) 176
4) B. S. Dzhelepov, Yu V. Kholnov and V. P. Prikhodtseva, Nucl. Phys. **9** (1959) 665
5) B. S. Dzhelepov, B. A. Emel'yanov, K. P. Kupriyanova and Yu N. Podkopaev, Bull. Acad. Sci. USSR (phys. ser.) **24** (1960) 275
6) S. F. Antonova, S. S. Vasilenko, M. G. Kaganskii and D. L. Kaminskii, JETP (Sov. Phys.) **11** (1960) 554
7) V. A. Balalaev, B. S. Dzhelepov, A. I. Medvedev, A. Meshter, V. P. Prikhodtseva and I. F. Uchevatkin, Bull. Acad. Sci. USSR (phys. ser.) **29** (1966) 2089
8) R B. Begzhanov and S. L. Rakovitskii, Sov. J. Nucl. Phys. **5** (1967) 6
9) W. W. Black and A. C. G. Mitchell, Phys. Rev. **132** (1963) 1193
10) L. Dorikens-Vanpraet, O. Segaert, M. Dorikens and J. Demuynck, Proc. Phys. Soc. **82** (1963) 488
11) M. Schmorak, H. Wilson, P. Gatti and L. Grodzins, Phys. Rev. **134** (1964) B718
12) H. W. Baer, J. J. Reidy and M. L. Wiedenbeck, Nucl. Phys. **86** (1966) 332
13) H. W. Baer, thesis, The University of Michigan (1967)
14) W. M. Currie, Nucl Phys. **32** (1962) 574, **48** (1963) 561
15) G. Chandra, Nuovo Cim. **31** (1964) 297
16) K. Hisatake, Y. Yoshida, K. Etoh and T. Murata, Nucl. Phys. **56** (1964) 625
17) R. L. Graham and J. S. Geiger, Bull. Am. Phys. Soc. **11** (1966) 11
18) P. R. Christensen and Fu-Ckia Yang, Nucl. Phys. **72** (1965) 657
19) O. Hansen and O. Nathan, Nucl. Phys. **42** (1963) 197
20) H. Krehbiel and U. Meyer-Berkhout, Z. Phys. **165** (1961) 99;
H. Krehbiel, Phys. Lett. **13** (1964) 65

21) S. Ofer and A. Schwarzschild, Phys. Rev. **116** (1959) 725
22) D. P. Donnelly, H. W. Baer, J. J. Reidy and M. L. Wiedenbeck, Nucl. Instr., **57** (1967) 219
23) G. Murray, R. L. Graham and J. S. Geiger, Nucl. Phys. **63** (1965) 353
24) L. A. Sliv and I. M. Band, in Alpha-, beta-, and gamma-ray spectroscopy, Vol. 2, ed. by K. Siegbahn (North-Holland Publ. Co., Amsterdam, 1965) appendix 5, pp. 1639–1672
25) L. A. Borisoglebzkii, Sov. Phys. Uspek. **6** (1964) 715
26) R. I. Verrall, J. C. Hardy and R. E. Bell, Nucl. Instr. **42** (1966) 258
27) H. J. Körner, E. Gerdau, C. Günther, K. Auerbach, G. Mielken, G. Strube and E. Bodenstedt, Z. Phys. **173** (1963) 203
28) F. R. Petersen and H. A. Shugart, Bull. Am. Phys. Soc. **5** (1960) 343
29) C. M. Lederer, J. M. Hollander and I. Perlman, Table of isotopes, 6th ed. (Wiley, New York, 1967) appendix 4, pp. 573–574
30) C. E. Gleit, C. W. Tang and C. D. Coryell, Nuclear Data Sheets 5–5–138 (1963)
31) N. B. Gove, in Nuclear spin-parity assignments, ed. by N. B. Gove and R. L. Robinson (Academic Press, New York, 1966) p. 83
32) S. A. Moszkowski, in Alpha-, beta and gamma-ray spectroscopy, Vol. 2, ed. by K. Siegbahn (North-Holland Publ., Co. Amsterdam, 1965) chapt. 15
33) M. Rho, Nucl. Phys. **65** (1965) 497 and private communication
34) A. Plastino, R. Arvieu and S. A. Moszkowski, Phys. Rev. **145** (1966) 837
35) C. F. Perdrisat, Revs. Mod. Phys. **38** (1966) 41