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# THE LEVEL STRUCTURE OF THE NUCLEUS $^{140}$Ce

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**Abstract:** Precision energy measurements on 24 gamma-ray lines in the $^{140}$La → $^{140}$Ce decay were performed with a 2 m curved-crystal spectrometer and a lithium-drifted germanium spectrometer. The relative intensities of 15 gamma rays were determined. A level scheme for $^{140}$Ce is proposed with the inclusion of two new levels at 2516.14 and 2547.5 keV. The new level scheme is compared with recent calculations using the quasi-particle description.

E | RADIOACTIVITY $^{140}$La[from $^{139}$La(n, γ)]: measured $E_\gamma$, $I_\gamma$. $^{140}$Ce deduced levels. Natural target.

## 1. Introduction

The nucleus $^{140}$Ce is one of seven stable isotones having a closed neutron shell with $N = 82$. It has eight protons outside the $Z = 50$ major closed proton shell. In recent years such nuclei have been considered within the framework of the quasi-particle description for spherical nuclei. Some calculations on $^{140}$Ce have been performed [1,2]). It is thus of interest to determine the energy level structure of $^{140}$Ce.

Precision measurements of nuclear gamma-ray energies afford a simple check on proposed nuclear energy level structures through the use of the sum rule $E = E_1 + E_2$, where $E_1$ and $E_2$ are the energies of two cascade transitions and $E$ the corresponding cross-over transition. Since the curved-crystal spectrometer (ccs) and lithium-drifted germanium (Ge(Li)) spectrometer extend considerably the accuracy of many earlier measurements of gamma-ray energies in the $^{140}$La → $^{140}$Ce decay, the use of this sum rule provides a basis for eliminating some aspects of the previously proposed level schemes, as well as suggesting new possibilities.

A total of 24 gamma-ray energies were measured in the $^{140}$La decay: 20 were measured with the ccs ranging in energy from 64.135 to 2522.6 keV; four additional gamma-ray energies ranging in energy from 2348 to 3123 keV were measured with a Ge(Li) spectrometer. Using the data from both instruments, the relative intensities of 15 transitions were determined.

The excited levels of $^{140}$Ce have been studied by many investigators through the $^{140}$La → $^{140}$Ce and $^{140}$Pr → $^{140}$Ce decays. The work before 1960 is compiled in ref. [3]) and the monograph by Dzhelepov *et al.* [4]). Later work includes that of Hisatake *et al.* [5]), Takekoshi *et al.* [6]), Dorikens-Vanpraet *et al.* [7]), Black and Mitchell [8]), Currie [17]) and Graham and Geiger [18]).

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## 2. Experimental Procedures

2.1. CURVED-CRYSTAL SPECTROMETER

The 2 m curved-crystal spectrometer (ccs) and the source techniques used in this investigation are described in ref. [9]). The measurements were made with the two crystals, Ge(0$\bar{2}$2) and Q(310), having effective areas of 4 $cm^2$ and 20 $cm^2$, respectively. Recently the Ge(0$\bar{2}$2) crystal has been recalibrated using the fourth-through-eighth order reflections of the 411.800 keV transition in the decay of $^{198}$Au. The resulting calibration constant $7297.989 \pm 0.025$ keV · screw-division (s.d.) is slightly smaller than the one previously determined [9]). (The calibration constant $k$, the $\gamma$-ray energy $E$ (keV), the crystal position $x$(s.d.) and the order of reflection are related by $E(x/n) = k$. Also for angles less than 3°, 1.0 s.d. ≈ 90 sec of arc.) The calibration constant for the $Q$(310) crystal is $12369.94 \pm 0.50$ keV · s.d.

The flat (ribbon) sources composed of a $La_2O_3$-epoxy mixture had effective widths of 76 μm or 130 μm. The total activity after thermal neutron irradiation in the University of Michigan Ford Reactor for 80–100 h at a flux of approximately $2 \times 10^{13}$ n/$cm^2$ · sec was estimated to be 0.2 to 0.8 Cur. The sources were aligned in the spectrometer using the second-order reflection from the Ge(0$\bar{2}$2) planes of the 487 keV gamma ray. The resolution widths (fwhm) of the diffraction profiles obtained with the Ge(0$\bar{2}$2) planes were approximately 10 sec and 13.5 sec of arc for the two different source widths. These correspond to an energy resolution of $\Delta E = 16 \times 10^{-6}\ E^2/n$ keV and $\Delta E = 20 \times 10^{-6}\ E^2/n$ keV, respectively, where $E$ is in keV and $n$ the order of reflection. The resolution width obtained with the $Q$(310) planes is 25 to 30 sec of arc for both source widths. Data were taken using the first-through-fifth order reflection from the Ge(0$\bar{2}$2) planes and the first-order reflection from the $Q$(310) planes.

2.2. LITHIUM-DRIFTED GERMANIUM SPECTROMETER

The Ge(Li) spectrometer consists of the following components: a Ge(Li) detector having a sensitive volume of 0.2 cm × 0.8 $cm^2$, a Tennelec 100C pre-amplifier and TC 200 amplifier and a Victoreen (SCIPP) 1600-channel pulse-height analyser. The detector is operated at liquid nitrogen temperature. Typical resolution widths (fwhm) obtained for three lines in the decay of $^{140}$La were 4.2 keV for the 487 keV line, 5.5 keV for the 1597 keV line and 9.0 keV for the 2522 keV line. The data accumulation time varied from 30 to 2500 min. It was possible to obtain the energy calibration from lines within the spectrum since energy measurements had been made with good accuracy using the ccs. The calibration was obtained from the three lines having energies $487.029 \pm 0.019$, $816.801 \pm 0.086$ and $1596.58 \pm 0.30$ keV.

The source consisted of several mg of $La(NO_3)_3$ dissolved in water and irradiated with thermal neutrons for 2–4 h in the University of Michigan Reactor. The activity was about 1 mCur.

## 3. Experimental Results

3.1. THE GAMMA-RAY SPECTRUM

The gamma-ray energies measured in this study are listed in table 1. All energies were measured at least twice and in most cases three or four times. The uncertainties correspond to the standard deviation of the mean.

The relative intensities of some of the observed gamma rays are given in table 2. In column two of this table are listed the relative intensities obtained from the present work. The intensity values in this column are separated into three subgroups and within each group the intensities are normalized to the most intense member of that group. In column four are listed the relative intensities reported in ref. [11]). All intensities in this column are relative to the 1597 keV $\gamma$-ray which was taken to have a

TABLE 1

Energy values for the gamma rays in the $^{140}La \rightarrow {}^{140}Ce$ decay

| | Energy [a]) (keV) | |
|---|---|---|
| 64.135 ± 0.010 | 487.029 ± 0.019 | 2348 ± 2 [b]) |
| 109.418 ± 0.007 | 618.2 ± 0.7 | 2522 ± 2 |
| 131.121 ± 0.008 | 751.827 ± 0.080 | 2547.5 ± 2.5 |
| 173.536 ± 0.012 | 815.801 ± 0.086 | 2900 ± 3 |
| 241.966 ± 0.012 | 867.82 ± 0.14 | 3123 ± 5 |
| 266.551 ± 0.014 | 919.64 ± 0.33 | |
| 306.9 ± 0.2 | 925.20 ± 0.17 | |
| 328.768 ± 0.012 | 950.88 ± 0.72 | |
| 397.79 ± 0.11 | 1596.58 ± 0.30 | |
| 432.530 ± 0.029 | 2522.6 ± 2.5 | |

[a]) All values are derived from data obtained with a 2 m curved-crystal spectrometer, except where noted.

[b]) Values in this column derive from data obtained with the Ge(Li) spectrometer.

value 1.00. The numbers in this column closely correspond to the values for quanta/decay reported by Dzhelepov *et al.* [4]) when multiplied by 0.96. In column five the relative intensities of ref. [11]) are renormalized to the scale of column two.

The relative intensities measured in the present work and listed in the first two subgroups were obtained with the ccs using the Ge(022) planes in second-order reflection. The reflection efficiency of this crystal in second order, $R(E_\gamma, 2)$, has been investigated [10]) in the energy range from 130 to 2110 keV and is reasonably described by $R(E_\gamma, 2) \propto E_\gamma^{-k}$ with $0.6 \leqq k \leqq 1.2$. A value of $k = 1.0$ was used for the present work. The relative intensities were obtained from the relative peak counting rates corrected for crystal reflection efficiency and photopeak detection efficiency. The uncertainties in intensity values (column three) are derived from the uncertainty in the crystal reflection efficiency and the statistical fluctuations in the peak counting rates. The relative intensities of the third subgroup derive from the data taken with the Ge(Li) spectrometer. The ratio of full-energy peak amplitudes corrected for detection efficiency was used. The correction for detection efficiency was based on the relative photoelectric cross sections.

The following energy measurements are of special interest:

TABLE 2

The relative intensities of some $\gamma$-rays in the $^{140}La \rightarrow {}^{140}Ce$ decay

| Gamma-ray energy present work (keV) | $I_\gamma$ [a]) present work | $\Delta I_\gamma$ present work | $I_\gamma$ [b]) Prikhodtseva and Khol'nov [11]) | $I_\gamma$ [c]) Prikhodtseva and Khol'nov [11]) |
|---|---|---|---|---|
| 306.9 | 0.044 | 0.023 | | |
| 328.768 | 45 | 10 | 0.21 | 50 |
| 397.79 | 0.11 | 0.050 | 0.03 | 7 |
| 432.530 | 6.1 | 1.5 | 0.025 | 6.0 |
| 487.029 | 100 | | 0.419 | 100 |
| 618.2 | 0.090 | 0.045 | | |
| 751.826 | 19 | 3.8 | 0.0337 [d]) | 17.2 |
| 815.801 | 100 | | 0.196 | 100 |
| 867.82 | 22.5 | 4.5 | 0.053 | 27 |
| 919.64 | 11 | 2.7 | | |
| 925.20 | 30 | 6.0 | 0.096 [e]) | 49 |
| 950.88 | 2.6 | 0.65 | | |
| 2348 | 33 | 9.0 | 0.0078 | 21 |
| 2522 | 100 | | 0.037 | 100 |
| 2547.5 | 3.5 | 1.0 | | |

[a]) The intensities of the present work are given relative to the most intense member within each subgroup.

[b]) The values in this column are reported in ref. [11]) and correspond closely to the quanta/decay reported by Dzhelepov *et al.* [4]) when multiplied by 0.96.

[c]) The values of ref. [11]) renormalized to the scale of column two.

[d]) Intensity of a reported 748 keV transition [11]).

[e]) Intensity of a reported 923 keV transition [11]).

919.64 and 925.20 keV. Previously these two transitions have been reported as a single transition with an energy of approximately 923 keV. The diffraction profiles for this doublet obtained with two different source widths and dispersions are represented in fig. 1. Fig. 1(b) shows that these two lines are well separated in the fourth-order reflection from the Ge(0$\bar{2}$2) planes using a source of 76 $\mu$m width. The separation of the composite profile into two separate peaks was somewhat less in the Ge(Li) spectrum. Using the data of both instruments, the relative gamma-ray intensity value $I_\gamma(919.64)/I_\gamma(925.20) = 0.37 \pm 0.04$ is obtained.

950.88 keV. The diffraction profile for this previously unreported transition is shown in fig. 1a). The energy was determined using the second-order reflection from the Ge(0$\bar{2}$2) planes. The intensity of this gamma ray relative to the 920–925 keV doublet was constant with time. On this basis the 950.88 keV transition is assigned to the $^{140}La \rightarrow {}^{140}Ce$ decay.

618.2 keV. The measurement on this weak transition had to be made in first-order reflection since the second-order diffraction profile contains a contribution of the relatively strong third-order reflection of the 920–925 keV lines. The first-order diffraction profile of this gamma-ray line is shown in fig. 2a; in the same figure the

487 keV diffraction profile is shown for comparison. Since the 487 keV transition occurs in about 40 % of the decays [4]), the 618.2 keV transition occurs only in approximately $4 \times 10^{-4}$ decays. It could not be seen in the singles spectrum obtained with the Ge(Li) spectrometer due to the presence of the Compton distributions of intense high-energy lines in the region of the 618.2 keV photopeak.

306.9 keV. This transition has not been reported previously in the decay of $^{140}$La though it has been observed in the $^{140}$Pr → $^{140}$Ce decay [5]).

Although the 306.9 keV transition is very weak the measurement on this line necessitated using the second-order reflection from the Ge(022) planes for the fol-

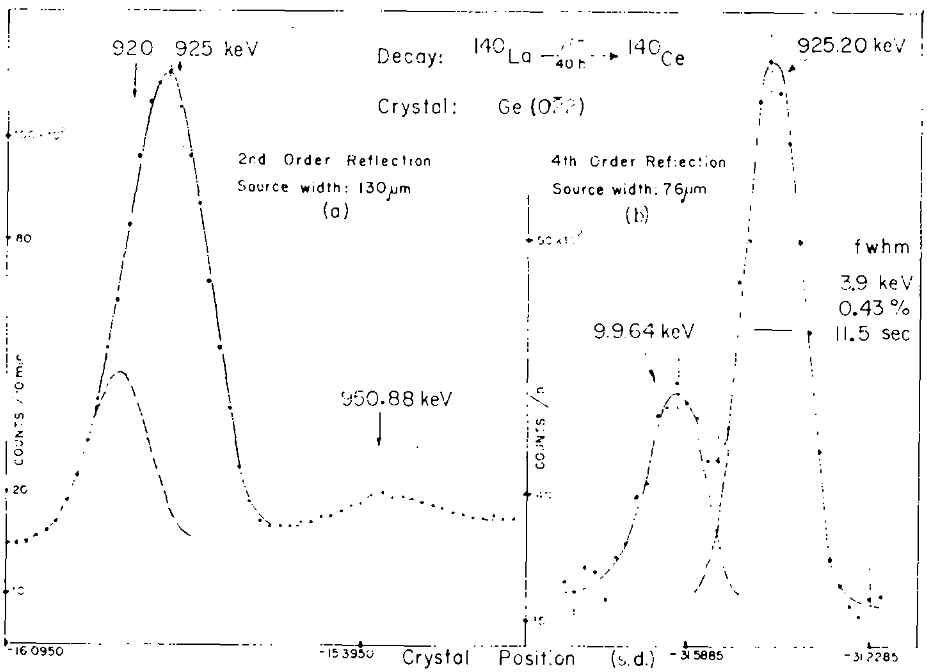


Fig. 1. Diffraction profiles of the 920–925 keV gamma-ray doublet occurring in the decay of $^{140}$La obtained with two different source widths and dispersions. The solid line merely indicates the trend of the data points.

lowing reason. The first-order reflection of the 306.9 keV gamma ray occurs at nearly the same Bragg angle as the third-order reflection of the 920–925 keV doublet. Thus the diffraction spectrum consists of three different gamma rays in various proportions of intensity. By setting the amplifier-discriminator to accept the photopeak of the 306.9 keV gamma ray, a portion of the Compton distribution due to the 920–925 keV gamma rays is also accepted. In the region of the first-order reflection of the 306.9 keV line (and so the third-order reflection of the 920–925 keV doublet) the relative intensities of these two contributions to the count rate is large enough to produce serious distortions to the diffraction profile of the 306.9 keV line. By measuring the 306.9 keV gamma ray in second order this distortion is greatly reduced since the diffraction profile intensity of the 920–925 keV lines (sixth-order reflection now) is reduced by about a factor of ten, whereas the 306.9 keV line is only reduced in intensity by about a factor of two. In this manner a good energy determination of

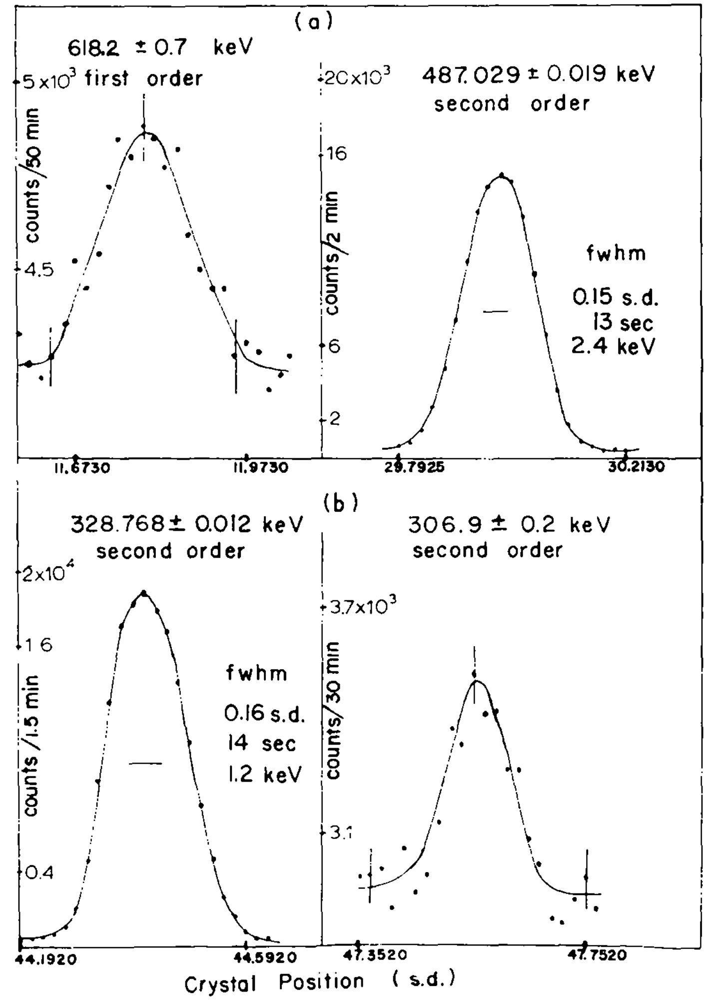


Fig. 2. Diffraction profiles of the weak 306.9 and 618.2 keV gamma rays occurring in the decay of $^{140}$La. The profiles of the intense 487 and 329 keV lines are shown for comparison. The crystal was Ge($0\bar{2}2$) and the source activity was about 0.8 Cur.

this transition was possible, though it occurs only in approximately $2 \times 10^{-4}$ of the decays. Fig. 2b shows the second order diffraction profile of the 306.9 keV line; the diffraction profile for 328.768 keV line is shown for comparison. The 306.9 keV line could not be observed in the singles spectrum obtained with the Ge(Li) spectrometer.

2348, 2522 and 2547.5 keV. The photopeaks of these three gamma rays in the Ge(Li) spectrum are shown in fig. 3. The 2547.5 keV gamma ray has not been reported previously. The positions of the photopeaks and double escape peaks were both used to determine the energies. The relative intensities of these three lines in the Ge(Li) spectrum stayed constant in time and thus were attributed to the decay of $^{140}$La.

2900 keV. The best energy determination of this gamma ray could be made from the position of the double escape peak in the Ge(Li) spectrum. The photopeak was observed, but it was not used in the energy determination due to very low counting rates. The intensity of the double escape peak fell off with the same time constant as the 2522 keV line.

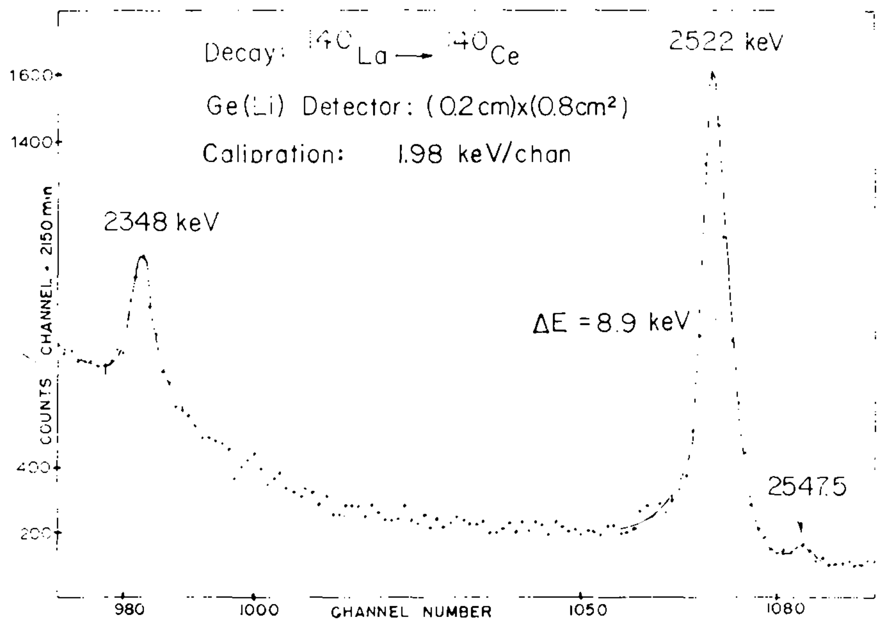


Fig. 3. The singles spectrum obtained with a Ge(Li) spectrometer in the energy region 2320-2570 keV for the gamma rays which follow the decay of $^{140}$La.

3123 keV. A good energy measurement of this previously reported gamma ray [4]) could not be made due to the low detection efficiency of the Ge(Li) detector at this energy. However, the presence of a small peak at 2101 ± 5 keV could correspond to the double escape peak of a 3123 keV gamma ray.

## 4. Discussion of the Level Scheme for $^{140}$Ce

In fig. 4 is presented a level scheme for the excited states of the nucleus $^{140}$Ce populated through the beta decay of $^{140}$La which is consistent with the present energy measurements and much of the work of previous investigators. To the level scheme of ref. [3]) two new levels at 2516.14 and 2547.5 keV have been added and the tentatively proposed level at 2348.41 keV is further supported. Angular momenta and parities were taken from ref. [3]), the compilation of data by Dzhelepov *et al.* [4]) and more recent angular correlation measurements [5, 7, 8]). The $\beta$-ray end-point energies were obtained using the value $Q_\beta$ = 3.769±0.005 MeV given by Mattauch *et al.* [12])

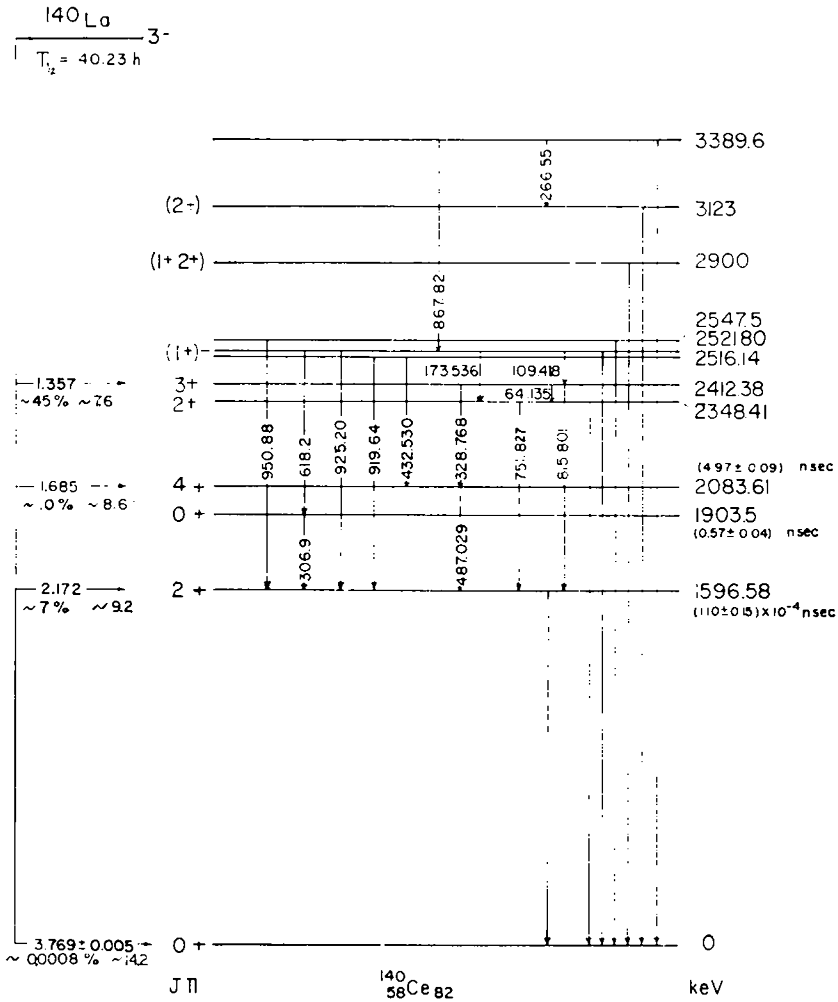


Fig. 4. The proposed level scheme for $^{140}$Ce using the results of the present investigations.

and the level excitation energies from the present work. Only part of the $\beta$-decay feeding is shown since the softer $\beta$-ray components have not yet been clearly identified. The mean lives for the first three excited levels are taken from refs. [16-18]). The average value of the four measurements [19]) of the gyromagnetic ratio $g$ of the first $4^+$ level is 1.07±0.05. A discussion of some of the levels follows.

1903.5 keV. The absence of a $\gamma$-ray with this energy and the measurements on the conversion electrons and internal-pair positons emitted in the direct transition to the ground state led to a $J^{\pi} = 0^{+}$ assignment [4]) to this level. A weak 0.63 MeV $\gamma$-ray populating this level in the decay of $^{140}$La has been reported [6, 21]) and a $\gamma$-ray of energy 0.306 MeV depopulating this level was found [5]) in the decay of $^{140}$Pr. On this basis the 618.2±0.7 and 306.9±0.2 keV transition measured in this work have been assigned to the $^{140}$La decay. Hisatake *et al.* [5]) have measured the $\gamma$-ray directional correlation for the 0.306–1.597 MeV cascade occurring in the decay of $^{140}$Pr and found it consistent with the (0–2–0) angular momentum sequence.

2348.41 keV. A level at this energy is established since a $\gamma$-ray of this energy has been observed in the spectrum. (Any transition in this decay with energy $\geqq$ 2.172 MeV must be a ground state transition since $Q_{\beta}$ = 3.769 MeV and the first excited state is at 1.597 MeV.) The internal conversion electrons and internal-pair positons for a transition of this energy have also been observed [4]). Dzhelepov *et al.* [4]) have proposed a $J^{\pi} = 2^{+}$ assignment for this level. In addition to the transitions which are shown in ref. [3]) to populate and depopulate this state it is proposed that the 64.135 keV transition proceeds to this level from the 2412.4 keV level. The measured energy 815.801±0.086 keV of the crossover transition from the 2412.4 to the 1596.6 keV state compares favourably with the sum of the measured transition energies 751.827±64.135 = 815.962±0.081 keV.

2412.38 keV. Many investigators [7, 17]) have attributed a value $J^{\pi} = 3^{+}$ to this level on the basis of the 329–487, 816–1597, 329–1597 keV $\gamma$-ray directional correlation measurements and earlier electron conversion studies [3]). However, the quadrupole admixture (0.1–0.5 %) in the 329 keV transition which is obtained from the $\gamma\gamma(\vartheta)$ data [19]) does not agree with the admixtures which Bashilov *et al.* [20]) reported based on a comparison of the experimental value of $\alpha_K$ and K/L with the theoretical values of Sliv and Band. This apparent discrepancy can be partially resolved if instead one uses the revised table of theoretical conversion coefficients of Sliv and Band[22]) from which the following values of $\alpha_K$ and K/L are obtained for the different types of transitions (at 329 keV):

| | E1 | E2 | E3 | M1 | M2 | M3 |
|---|---|---|---|---|---|---|
| $\alpha_K(\times 10^3)$ | 8.5 | 30 | 92 | 38 | 155 | 530 |
| K/L | 7.45 | 5.3 | 2.8 | 7.1 | 6.3 | 4.8 |

The experimental value $\alpha_K = 29\times10^{-3}$ reported by Bashilov *et al.* still seems most consistent with the theoretical values for an E2 transition, though an appreciable M1 admixture might not be excluded (no uncertainties were reported in ref. [20])). The earlier theoretical value [20]) for $\alpha_K$(M1) was $47\times10^{-3}$. This appeared to have eliminated the possibility of an appreciable M1 admixture in the 329 keV transition. Using the relative $\gamma$-ray intensity of the present work, $I_{\gamma}(329)/I_{\gamma}(487) = 0.45\pm0.10$, the K-conversion relative electron intensity of Bashilov *et al.*, $I_{Ke}(329)/I_{Ke}(487) = 1.6$

and the theoretical value $\alpha_K(487\text{ keV; E2}) = 9.5\times10^{-3}$, the value $\alpha_K(329\text{ keV}) = (34\pm7)\times10^{-3}$ is obtained. This value is consistent with an M1+E2 transition, though the admixture cannot be specified. The experimental value [20] K/L = 6.2±0.5 is also consistent with the new theoretical value for a M1+E2 transition. Since the 329 keV transition proceeds to the 2083.6 keV ($2^+$) state, the assignment $J^\pi = 3^+$ is not excluded by conversion electron data and is in fact most consistent with all available data.

<u>2516.14 keV.</u> A level with this excitation energy is proposed for the following two reasons. The measured γ-ray energy 919.64±0.33 keV closely corresponds to the energy sum 487.029+432.530 = 919.559±0.035 keV. Bolotin *et al.* [23]) have reported coincidences between γ-rays with energies of approximately 487 and 433 keV. Six transitions from the 2516.14 keV level to lower levels are possible and a search was made for some of the corresponding γ-rays. The energies of these transitions and the intensity limits determined for the unobserved γ-rays are as follows:

| | transition | relative intensity limits |
|---|---|---|
| $J^\pi \to 3^+$ | 2516.14−2412.38 = 103.76 keV, | $I_\gamma(104\text{ keV}) < 0.03 I_\gamma(131\text{ keV})$, |
| $J^\pi \to 2^+$ | 2516.14−2348.41 = 167.71, | $I_\gamma(168) < 1.5\times10^{-3} I_\gamma(432.5)$, |
| $J^\pi \to 4^+$ | 2516.14−2083.61 = 432.53, | measured (table 2) |
| $J^\pi \to 0^+$ | 2516.14−1903.5 = 612.6, | $I_\gamma(613) < 5\times10^{-3} I_\gamma(432.5)$, |
| $J^\pi \to 2^+$ | 2516.14−1596.58 = 919.56, | measured (table 2), |
| $J^\pi \to 0^+$ | 2516.14− 0 = 2516.14, | $I_\gamma(2516) < 0.1\, I_\gamma(2522)$. |

The data available for a $J^\pi$ assignment to this new level are the values $\alpha_K(432.5) = (10\pm4)\times10^{-3}$ and the relative intensity $I_\gamma(432.5)/I_\gamma(919.6) = 1.2\pm0.4$. The value for $\alpha_K$ was obtained using the relative K-conversion intensities $I_{eK}(432.5)/I_{eK}(487) = 0.06\pm0.016$ of Bashilov *et al.* (the uncertainty in this number is our estimate), the relative γ-ray intensity of the present work $I_\gamma(432)/I_\gamma(487) = 0.060\pm0.015$ and the theoretical value $\alpha_K(487;\text{ E2}) = 9.5\times10^{-3}$. The relative γ-ray intensity was obtained using the value $I_\gamma(487)/I_\gamma(816) = 2.14$ of ref. [11]) and the values $I_\gamma(432.5)/I_\gamma(487) = 0.061\pm0.015$ and $I_\gamma(919.6)/I_\gamma(815.8) = 0.11\pm0.027$ of the present work. The theoretical values [22]) of $\alpha_K(432.5)$ for the different types of transitions are:

| | E1 | E2 | E3 | M1 | M2 | M3 | experiment |
|---|---|---|---|---|---|---|---|
| $\alpha_K(\times10^3)$ | 4.4 | 13.2 | 37 | 19 | 64 | 195 | 10±4. |

Thus the experimental value is compatible with the theoretical values for transitions of type E1+M2, E2+M1 and pure E2. Since the 432.5 keV transition populates a $4^+$ state, the values of $J^\pi$ for the 2516 keV level may be $3^-, 4^-, 5^-$ or $2^+, 3^+, 4^+, 5^+$. Since the $^{140}$La ground state has $J^\pi = 3^-$, the apparent absence of β-ray feeding [3,4]) to the 2516 keV level tends to exclude the negative parity states. The observed γ-ray intensity $I_\gamma(432.5;\ J^\pi \to 4^+)/I_\gamma(919.6;\ J^\pi \to 2^+) = 1.2\pm0.4$ tends to exclude the high angular momentum states $5^+, 6^+$. Thus the values $J^\pi = 2^+, 3^+, 4^+$ appear to be most compatible with the data. It might further be argued, that a $2^+$ assignment is unlikely since the transition probability $\lambda$ (2516; E2) should be much larger than the transition probability $\lambda$ (432.5, E2), and yet the 2516 keV transition is not observed. A $3^+$ assignment would lead to the unusual circumstance of having two $3^+$ levels separated by 103.8 keV with one (2412 keV) being fed in about 50% of the $\beta$-decays, [3]) the other fed very little (if at all). The assignment $J^\pi = 4^+$ to the 2516 keV level does not seem to violate any of these elementary notions. On the basis of these weak arguments the value $J^\pi = 4^+$ is favoured.

2521.80 keV. The $\gamma$-rays, electron conversion electrons and internal pair positons corresponding to the direct transition from this level to the ground state have been observed [3,4]). Heretofore the $J^\pi$ assignment [3,4]) has been $2^+$ and this was based on data from the "923"–1597 keV $\gamma$-ray directional correlation and electron conversion data on the 433 and "923" keV transitions. Now that the 433 keV transition can no longer be considered to depopulate the 2522 keV level and the "923" keV $\gamma$-ray has been resolved into two components with energies 919.64 and 925.20 keV with a relative intensity of $I_\gamma(919.6) = 0.37\, I_\gamma(925.2)$, the $J^\pi = 2^+$ assignment must be re-evaluated. The data available for a determination of $J^\pi$ for the 2522 keV level are the measurements [13]) $\alpha_K(2522) = 3.91 \times 10^{-4}$ and the ratio of internal-pair positons to K-shell conversion electrons [15]) $I_{e^+}/I_{e^-} = 1.05$. Both of these measurements, when compared to the theoretical values [13,15]), indicate that the 2522 keV transition to the ground state ($0^+$) is of type M1. Thus the assignment $J^\pi = 1^-$ to the 2522 keV level is most likely. Also, the measured value [20]) of K/L for the 109.42 keV transition from the 2522 keV to the 2412 keV ($3^+$) level is consistent with the theoretical value for a pure E2 transition. This measurement is therefore also compatible with a $1^+$ assignment to the 2522 keV state.

It is seen from the level scheme (fig. 4) that the $\gamma$-rays for five out of the seven possible transitions depopulating the 2522 keV level have been observed. The $\gamma$-ray of the transition going to the 2084 keV ($4^-$) level was not observed. The intensity limit $I_\gamma(438.14) < 0.03 I_\gamma(432.5)$ was determined.

2547.5 keV. A new level is proposed at this excitation energy because a $\gamma$-ray of this energy is observed in the spectrum. Further, the previously unreported $\gamma$-ray with an energy of 950.88 keV could correspond to the transition from this level to the first excited state at 1596.58 keV. The sum $1596.58 + 950.88 = 2547.5 \pm 0.77$ keV agrees well with the measured energy $2547.5 \pm 2.5$ keV. There are no data available for a direct determination of $J^\pi$ for this level. Some weak arguments based on the observed $\gamma$-ray intensities favour the values $J = 1, 2$.

A search was made for a 199 keV $\gamma$-ray corresponding to the transition from the 2547.5 keV to the 2348.4 keV level. With the curved crystal spectrometer, a peak could be seen at the crystal setting for the first-order reflection (Ge(022)) of this line. However, the second-order reflection of the 397.79 keV $\gamma$-ray occurs at nearly the same Bragg angle and therefore could account for the observed peak. Unfortunately, the available intensity was insufficient to go to a higher order reflection where an identification of the peak would be possible. Nevertheless, the intensity limit $I_\gamma$ (199 keV) $< 1.9 \times 10^{-4}$ $I_\gamma$(487 keV) could be set.

2900, 3123 and 3389.6 keV. These levels are included in the decay scheme since the direct transitions to the ground state have been observed [4]). Also there is at least one soft component in the $\beta$-ray spectrum with a reported [3,4]) end-point energy of 0.42 MeV which could feed into one of the upper levels. The $J^\pi$ values for these levels shown on the level scheme are those given by Dzhelepov *et al.* [4]). In this investigation the 2900 and 3123 keV $\gamma$-rays were observed. A search was made for various $\gamma$-rays which would be emitted when these levels depopulate to lower-lying levels; however none was observed. Intensity limits could be set as follows: for $\gamma$-rays corresponding to the transitions 2900 $\rightarrow$ 2348, 1597 keV the limits are $I_\gamma$(566–534 keV) $< 3 \times 10^{-4}$ $I_\gamma$(487 keV) and $I_\gamma$(1263–1345 keV) $< 3 \times 10^{-3}$ $I_\gamma$ (1597 keV); for $\gamma$-rays corresponding to the transitions 3123$\rightarrow$2348, 1597 keV, the limits are $I_\gamma$(788–772 keV) $< 3 \times 10^{-2}$ $I_\gamma$(751.8 keV) and $I_\gamma$(1560–1500 keV) $< 1 \times 10^{-2}$ $I_\gamma$(1597). The $\gamma$-ray for a previously reported 730 keV transition [20]) could not be found and the intensity limit $I_\gamma$(743–718 keV) $< 5 \times 10^{-2}$ $I_\gamma$(751.8 keV) was determined.

The moderately strong 867.82 keV $\gamma$-ray could correspond to the transition between the 3389.6 and 2521.80 keV levels. This would account for the extensive depopulation of the 2521.8 keV level. From the data on the $\beta$-ray spectrum it is not clear to what extent (if any) the 2521.80 keV level is fed. The soft component in the $\beta$-ray spectrum with an end-point energy 0.42 MeV could be feeding the 3389.6 keV level. The observed 266.551 keV $\gamma$-ray could correspond to the transition from the 3389.6 keV to the 3123 keV level since the two sums $3123+266.5 = 3189.5 \pm 5$ keV and $867.82+2521.80 = 3389.6 \pm 0.4$ keV are in good agreement.

It could not be determined where the $\gamma$-rays with energies 397.79, 131.121 and 241.966 keV should be placed in the proposed level scheme. The measured energy $397.79 \pm 0.11$ keV agrees well with the sum $131.121 \pm 266.551 = 397.672 \pm 0.014$ keV, suggesting that there may be a level at $3123-131 = 2992$ keV or at $3389.6+131.1 = 3520.7$ keV. However, no further support for the existence of such levels was found.

An application of the quasi-particle theory for single-closed shell nuclei (in BCS plus Tamm-Dancoff approximation) has recently been made by Rho [2]) to calculate the level spectra for $J^\pi = 2^+, 3^+, 4^+$ states of some spherical even-mass nuclei with a closed neutron shell at $N = 82$. The nucleus $^{140}$Ce was of special interest. In $^{140}$Ce the two quasi-particle states having mostly

$$(g^2\tfrac{7}{2})_{J=2}, \qquad (g^2\tfrac{7}{2})_{J=4}, \qquad (d^2\tfrac{5}{2})_{J=2}, \qquad (d^2\tfrac{5}{2})_{J=4}$$

configurations are predicted to be the first four excited states respectively (ignoring $J = 0, 1$ states). In the presently proposed level scheme (fig. 4) these four states might be identified with the levels at excitation energies of 1.596 ($2^+$), 2.084 ($4^+$), 2.348 ($2^+$), 2.516 ($4^+$?) MeV in the same order as above. The $J^\pi = 3^+$ level at 2.412 MeV is likely the first of the $(d\tfrac{5}{2}, g\tfrac{7}{2})_J$ states and the 2.522 MeV level may correspond to the $(d\tfrac{5}{2}, g\tfrac{7}{2})_{J=1}$ state. The theoretical value of Rho for the gyromagnetic ratio of the 2.084 ($4^+$) keV state is $g = 0.92$ which compares favourably with the experimental value $g = 1.07 \pm 0.05$ (average of the four measurements given in ref. [19]). This supports the hypothesis that the 2.084 ($4^+$) keV level has a predominantly $(g^2 \frac{7}{2})_{J=4}$ configuration. Further points of comparison are $B$(E2) values. The measured $B(\mathrm{E2}; 2^+ \rightarrow 0^+; 1597\ \mathrm{keV})$ and $B(\mathrm{E2}; 4^+ \rightarrow 2^+; 487\ \mathrm{keV})$ are 16 and $\frac{1}{28}$ Weisskopf units, respectively, whereas the calculations predict 13 and $\frac{1}{17}$ Weisskopf units for the same quantities. In view of the experimental uncertainties, this agreement is good.

Although the comparison between theory and experiment that is at present available in the nucleus $^{140}$Ce is modest, it should be mentioned that this nucleus has properties favourable to experimental and theoretical investigations which could with further investigation lead to a fruitful comparison.

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*Note added in proof.* The calculated (M. Rho, private communication) excitation energy of the two quasi-particle state $(g_{\frac{7}{2}\frac{5}{2}})_{J^\pi=1^-}$ is approximately 2.5 MeV and the $(g_{\frac{7}{2}\frac{5}{2}})_{J^\pi=3^+}$ state is at a slightly lower energy. These states might correspond to the 2521.8 and 2412.4 keV levels of the presently proposed level scheme.

## References


1) L. S. Kisslinger and R. A. Sorensen, Mat. Fys. Medd. Dan. Vid. Selsk. **32**, No. 9 (1960)
2) M. Rho, Congrès International de Physique Nucléaire, Vol. II, ed. by P. Gugenberger (Éditions du Centre National de la Recherche Scientifique, Paris, 1964) p. 440;
M. Rho, Nuclear Physics **65** (1965) 497
3) Nuclear Data Sheets, National Academy of Sciences, National Research Council, Wash. 25, D.C.
4) B. S. Dzhelepov, V. P. Prikhodtseva and Yu. V. Khol'nov, Isobaric nuclei with the mass number $A = 140$ (Pergamon Press, New York, 1963)
5) K. Hisatake, Y. Yoshida, K. Etoh and T. Murata, Nuclear Physics **56** (1964) 625
6) H. Takekoshi, N. Shikazono and P. Tseng, J. Phys. Soc. Japan **16** (1961) 1674
7) L. Dorikens-Vanpraet, O. Segaert, M. Dorikens and J. Demuynck, Proc. Phys. Soc. **82** (1963) 488
8) W. W. Black and A. C. G. Mitchell, Phys. Rev. **132** (1963) 1193
9) J. J. Reidy and M. L. Wiedenbeck, Nucl. Instr. **33** (1965) 213
10) J. J. Reidy and M. L. Wiedenbeck, Nuclear Physics **70** (1965) 518
11) V. P. Prikhodtseva and Iu. V. Khol'nov, Izv. Akad. Nauk SSSR (ser. fiz) **22** (1958) 176
12) J. H. E. Mattauch, W. Thiele and A. H. Wapstra, Nuclear Physics **67** (1965) 1
13) B. S. Dzhelepov, Yu. V. Khol'nov and V. P. Prikhodtseva, Nuclear Physics **9** (1958) 665
14) V. A. Balalaev, B. S. Dzhelepov, A. I. Medvedev, A. Meshter and I. F. Uchevatkin, JETP (Soviet Phys). **16** (1963) 1425
15) S. F. Antonova, S. S. Vasilenko, M. G. Kaganskii and D. L. Kaminskii, JETP (Soviet Phys.) **11** (1960) 554
16) S. Ofer and A. Schwarzschild, Phys. Rev. **116** (1959) 725
17) W. M. Currie, Nuclear Physics, **32** (1962) 574; **48** (1963) 561
18) R. L. Graham and J. S. Geiger, Bull. Am. Phys. Soc. **11** (1966) 11
19) M. Schmorak, H. Wilson, P. Gatti and L. Grodzins, Phys. Rev. **134** (1964) B718
20) A. A. Bashilov, B. S. Dzhelepov, N. D. Novosil'tseva and L. S. Chervinskaya, Izv. Akad. Nauk SSSR (ser. fiz) **22** (1958) 179
21) P. Salling, Nuclear Physics **65** (1965) 520
22) L. A. Sliv and I. M. Band, in Alpha-, beta- and gamma-ray spectroscopy, Vol. II, ed. by K. Siegbahn (North-Holland Publ. Co., Amsterdam, 1965) appendix 5, p. 1639
23) H. H. Bolotin, C. H. Pruett, P. L. Roggenkamp and R. G. Wilkinson, Phys. Rev. **99** (1955) 62