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Band structure of ^{146}Ce studied through $\gamma-\gamma$ angular correlation measurements

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Abstract. The β-decay of ^{146}La was studied using the on-line isotope separator KUR-ISOL. Gamma-gamma angular correlation measurements were performed with a 4-Ge detectors system. Spin assignments of three levels were made: 3^+ for the 1576.5 keV level, 4^+ for the 1627.1 keV level and 5^+ for the 1810.2 keV level. The mixing ratios (E2/M1) were deduced to be $\delta_{183.2} = 0.25\pm0.08$, $\delta_{638.9} = 0.33\pm0.05$, $\delta_{959.0} = 1.19^{+0.16}_{-0.14}$, $\delta_{1015.9} = 5.4^{+3.1}_{-1.5}$ and $\delta_{1318.1} = 6.5^{+1.7}_{-1.1}$. These were compared to the calculated values obtained in three cases involving different Majorana force parameter values. The band structure of ^{146}Ce is discussed based on the results of calculation using the IBM-2 theory.

PACS. 21.10.Hw Spin and Parity – 23.20.En Angular distribution and correlation measurements – 23.20.Gq Multipole mixing ratios

1 Introduction

The rare earth region of deformed nuclei has been studied very extensively in recent years. Neutron-rich nuclei with $130 < A < 150$ have attracted continuing attention, since they provide an opportunity to study the transition from the spherical structure near the $N = 82$ closed shell to the deformed region beyond $N = 89$. The ^{146}Ce nucleus has $N = 88$ and is located at the onset of deformation of the mass 150 region. Two isomeric states in the parent nucleus ^{146}La (6.2 and 10.0 s) were reported by Monnand et al. [1]. Studies on the decay of the low-spin 2^- isomer of ^{146}La with $T_{1/2} = 6.2$ s were compiled in [2]. This isomer is predominantly produced through the β-decay of the 0^+ ground state of ^{146}Ba. On the other hand, the β-decay of the 10.0 s high-spin isomer of ^{146}La was investigated in detail by Sharshar *et al.* [3]. Wolf *et al.* [4] measured γ-γ angular correlations on rather strong cascades in ^{146}Ce generated through the β-decay of the low-spin isomer of ^{146}La. Studies of other even Ce isotopes ($N \neq 88$) have been carried out at several laboratories [5–8].

An isotope separator on-line (ISOL) of a gas-jet type installed at a nuclear reactor offers the capability to study relatively high-lying and high-spin states of ^{146}Ce which are fed following the β-decay of the high-spin isomer of ^{146}La, as the suggested spin and parity values are 6^- for this isomer and its Q_{β^-} value is rather high (6.53 MeV) [9]. The ground band of ^{146}Ce is established up to the 8^+ state. Although the quasi-β and -γ bands have been suggested by Sakai [10], members of these bands have not been clearly determined because the spin values of those levels have not been experimentally assigned except for that of the 1274.4 keV level which was previously determined to be 2^+ through our γ-γ angular correlation measurements [11]. It is of interest to investigate these higher excited states and compare the systematic behavior of Ce isotopes.

The present investigation of $\gamma-\gamma$ angular correlations in ^{146}Ce was undertaken in order to determine unambiguous spin values of higher excited states. A partial level scheme below 1.8 MeV, taken from [3], is shown in Fig. 1. The γ-transitions having the intensity less than 0.5 are little observed. The value (0.5) was taken as the observation limit for the γ-rays at the present experiment. Excitation levels calculated using the IBM-2 theory are compared to experimental ones and the band structure of ^{146}Ce is discussed.

2 Experimental details and results

Activities of ^{146}La were produced by the thermal neutron fission of ^{235}U, followed by use of the on-line mass separator KUR-ISOL [12] installed at a through-tube facility of the Kyoto University Reactor. As the target, 30 mg of ^{235}U was irradiated with the thermal neutron flux of 3×10^{12}n·cm^{-2}s^{-1}. The fission products were thermalized in a target chamber and transported by means of a gas-jet system to a surface-ionization type ion source coupled to a skimmer system. The thermalized fission products were ionized using an oxidation technique [13] by adding O_2 gas

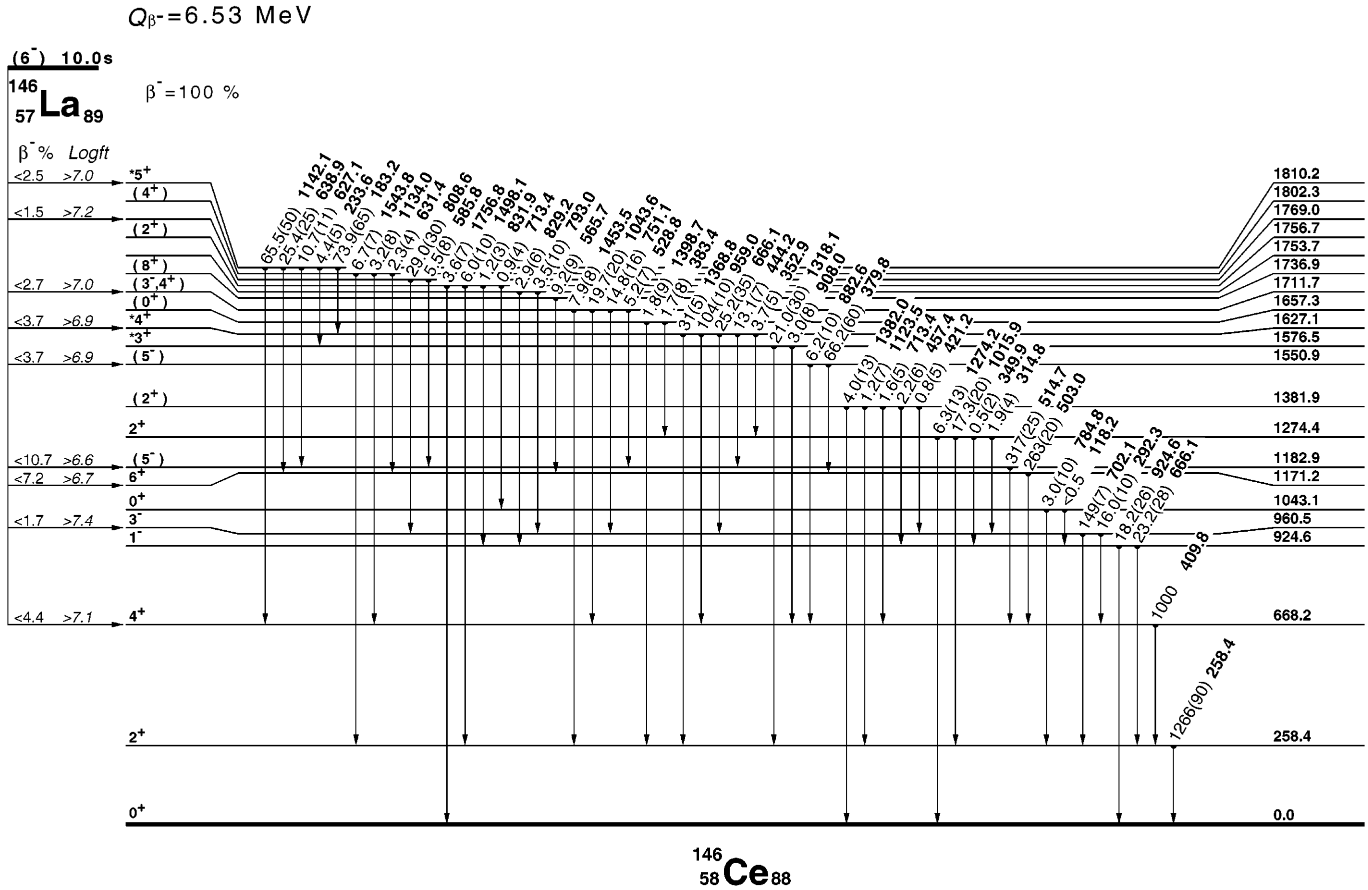

Fig. 1. A partial decay scheme of the high-spin isomer of ^{146}La taken from [3]. Spins having (*) are newly assigned by the present work

to the gas-jet. Several improvements on KUR–ISOL have been made: an increase in the beam intensity was attained using a He-N_2 mixed–gas–jet method [14], the capillary size was changed to 1.5mmϕ from 1.0 mmϕ to decrease the exchange over time of the transport gas through the target chamber, and stabilization of the beam intensity was attained using a PbI_2 aerosol. The total increase in beam intensity obtained was about a ten-fold increase. Low yield weak activities of rare earth nuclei could be measured. The ion beam of $A = 146$, which includes the high-spin isomer of ^{146}La produced directly by fission, was collected for 20 sec on an aluminized plastic tape. After the beam was deflected, the tape was moved to a measuring position 20 cm from the collecting position beneath a lead shield and then coincidence data were accumulated during the next 20 sec, while the next source was collected successively.

Gamma-gamma angular correlations were measured with a 4-Ge detectors system [15], with which measurements could be performed at six angles simultaneously. The coincidence efficiencies of various six pairs of detectors were different due to different detector characteristics. For example, the Ge detectors used were three closed-ended detectors (31%HPGe, 33%γX-HPGe, 34%HPGe) and a true coaxial detector(32%Ge(Li)), and the operating biases were 5000V, −3500V, 2000V and 4800V, respectively. Their resolutions were about 2 keV FWHM at 1332 keV. When the coincidence efficiency of detectors pair (m,n) is ε_{mn}, the angular correlation function W is as follows,

$$W(\theta_{\rm mn}, \varepsilon_{\rm mn}) = \varepsilon_{\rm mn} W(\theta_{\rm mn}).$$

In order to eliminate differences in coincidence efficiency of each pair of detectors, measurements were performed twice with different arrangements of the Ge detectors as shown in Fig. 2. The measuring angles for the first arrangement ($\theta_{\rm mn}$) were 90°, 105°, 120°, 135°, 150° and 165°, and those for the second arrangement ($\theta'_{\rm mn}$) were 100°, 110°, 127.5°, 137.5°, 152.5° and 170°. The results of the angular correlation of the 244-121 keV cascade of ^{152}Eu are shown in Fig.3(a) for the first arrangement and in Fig.3(b) for the second arrangement. These data were corrected with single counts. As seen in Figs. 3(a) and (b), the coincidence counts at 120° in the first arrangement and 170° in the second arrangement are small. This means that the coincidence efficiency ε_{12} of the pair Ge(1) and Ge(2) is small. This $\varepsilon_{\rm mn}$ can be cancelled by taking a ratio.

$$\frac{W(\theta_{\rm mn}, \varepsilon_{\rm mn})}{W(\theta'_{\rm mn}, \varepsilon_{\rm mn})} = \frac{\varepsilon_{\rm mn} W(\theta_{\rm mn})}{\varepsilon_{\rm mn} W(\theta'_{\rm mn})} = \frac{W(\theta_{\rm mn})}{W(\theta'_{\rm mn})}$$

When the experimental ratio of coincidence counts at the angles $\theta_{\rm mn}$ and $\theta'_{\rm mn}$ is $y^{\rm mn}$, the following equation is obtained.

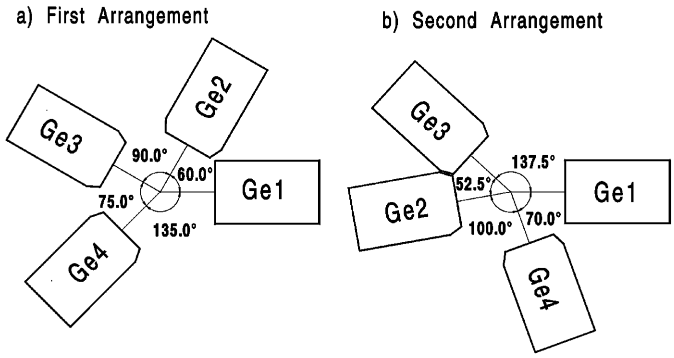

Fig. 2. Arrangements of the four Ge detectors. The front corners of the detectors 2, 3 and 4 were cut in order to set each of them at a short distance (6cm) from the center of the source

$$R \cdot \frac{1 + \sum_{\ell=2,4} Q^{\rm m}_{\ell}(1) Q^{\rm n}_{\ell}(2) A_{\ell\ell} P_{\ell}(\cos\theta_{\rm mn})}{1 + \sum_{\ell=2,4} Q^{\rm m}_{\ell}(1) Q^{\rm n}_{\ell}(2) A_{\ell\ell} P_{\ell}(\cos\theta'_{\rm mn})} = y^{\rm mn}_{12}. \quad (1)$$

Here, $A_{\ell\ell} = A_{\ell}(1)A_{\ell}(2)$ is the product of the angular correlation coefficients [16] and P_{ℓ} is the Legendre function. The suffixes m and n correspond to the detectors (1∼4). Coincident γ-rays are indicated as 1 and 2. The parameter R is the source intensity ratio between the first and second measurements. The geometrical correction factors (Q^{m}_{ℓ} and Q^{n}_{ℓ}) of the Ge detectors were measured by a collimated beam method [17]. The above equations were fitted to the experimental data with the free parameters R, A_{22} and A_{44}. The results obtained through this analysis are shown in Fig. 3(c). Although the A_{22} values were not so different among the three cases, the A_{44} value (-0.007 ± 0.011) at (c) was as small as the theoretical value (0.009).

In the case of measurements of ^{146}Ce, coincident events were recorded in event by event mode for the first two days in the first arrangement and for the next two days in the second arrangement. Four cycle measurements were performed in all, and the data were analyzed off-line. The event mode data were sorted for desired energy gates at each of the 12 angles according to detector pairs. Each spectrum gated with a specified γ-ray peak was normalized for the detector efficiency using the singles spectrum of each detector accumulated simultaneously during the run. Spectra gated above and below the γ-ray peak were used to subtract the contributions from the Compton tails of other coincident γ-rays.

The $\gamma - \gamma$ angular correlations of 6-cascades, having the known spin and parity of $4^+ - 2^+ - 0^+$ ($409.8 - 258.4$ keV), $1^- - 2^+ - 0^+$ ($666.1 - 258.4$ keV), $3^- - 2^+ - 0^+$ ($702.1 - 258.4$ keV), $0^+ - 2^+ - 0^+$ ($784.8 - 258.4$ keV), $6^+ - 4^+ - 2^+$ ($503.0 - 409.8$ keV) and $5^- - 4^+ - 2^+$ ($514.7 - 409.8$ keV), were analyzed. The angular correlation coefficients obtained are listed in Table 1 together with the previous and theoretical ones. As an example, the obtained pattern of the 784.8-258.4 keV(0-2-0) cascade is shown in Fig. 4. As the values obtained agreed with the previous and theoretical values for the pure multipole γ-rays, the total reliance of the system was confirmed.

Mixing ratios, δ(E2/M1), were determined directly from the minimum point of the following S^2 equation

$$S^2(\delta) = \sum_{m,n} w_{\rm mn} \left[y^{\rm mn}_{12} - R \times \frac{1 + \sum_{\ell=2,4} Q^{\rm m}_{\ell}(1) Q^{\rm n}_{\ell}(2) A_{\ell\ell}(\delta) P_{\ell}(\cos\theta_{\rm mn})}{1 + \sum_{\ell=2,4} Q^{\rm m}_{\ell}(1) Q^{\rm n}_{\ell}(2) A_{\ell\ell}(\delta) P_{\ell}(\cos\theta'_{\rm mn})} \right]^2 ,$$

where the value of R was adopted from the value obtained using equation (1) and $w_{\rm mn}$ is the inverse of the square of

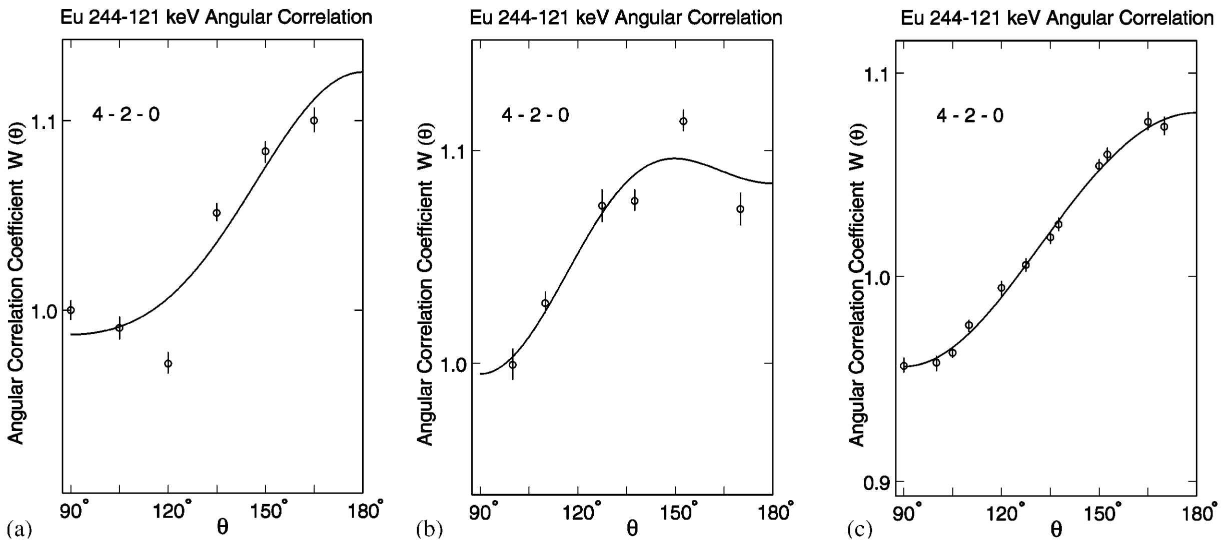

Fig. 3. (a) The result ($A_{22} = 0.099 \pm 0.005$ and $A_{44} = 0.035 \pm 0.012$) of the first arrangement. (b) The result ($A_{22} = 0.088 \pm 0.005$ and $A_{44} = 0.077 \pm 0.012$) of the second arrangement. (c) The result ($A_{22} = 0.102 \pm 0.005$ and $A_{44} = -0.007 \pm 0.011$) of the ratio analysis

Table 1. $\gamma - \gamma$ angular correlation coefficients

Cascade	present		previous[a]		theory	
	A_{22}	A_{44}	A_{22}	A_{44}	A_{22}	A_{44}
$4^+ \to 2^+ \to 0^+$ 409.8—258.4	0.10(1)	0.02(1)	0.105(11)	−0.001(14)	0.10	0.01
$1^- \to 2^+ \to 0^+$ 666.1—258.4	−0.22(3)	−0.02(2)	−0.261(24)	−0.12(3)	-0.25	0.0[b]
$3^- \to 2^+ \to 0^+$ 702.1—258.4	−0.08(2)	−0.01(4)	−0.071(24)	−0.05(4)	-0.07	0.0[b]
$0^+ \to 2^+ \to 0^+$ 784.8—258.4	0.30(7)	0.96(13)	0.31(9)	1.02(20)	0.36	1.14
$6^+ \to 4^+ \to 2^+$ 503.0—409.8	0.10(2)	0.00(4)	—	—	0.10	0.01
$5^- \to 4^+ \to 2^+$ 514.7—409.8	−0.07(2)	0.01(3)	—	—	-0.07	0[b]

[a] [4]. [b] M2 mixing is assumed to be zero.

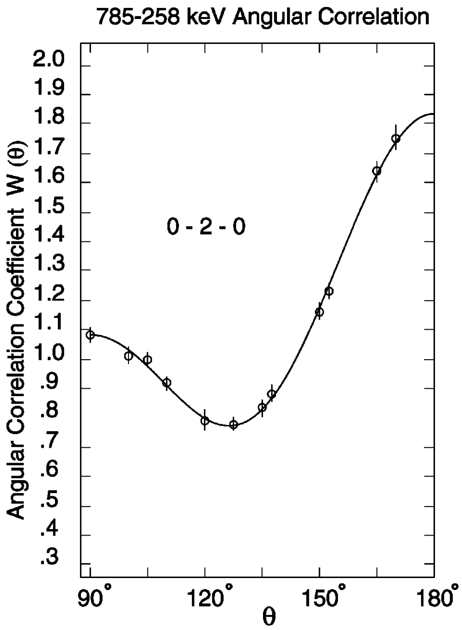

Fig. 4. Angular correlation of the 784.8–258.4 keV cascade

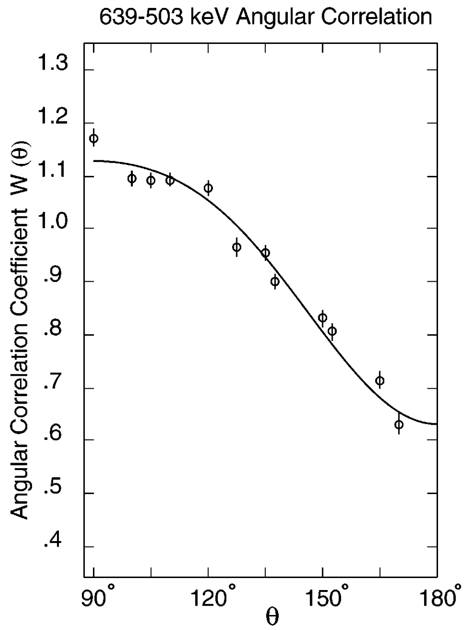

Fig. 5. Angular correlation of the 638.9–503.0 keV cascade

the standard deviation $(1/\sigma^2(y_{12}^{mn}))$. The error of δ was estimated [18] from the equation

$$S^2 = S^2_{\min} + 1.$$

The obtained angular correlation coefficients and mixing ratios are listed in Table 2 together with the calculated values of δ.

The angular correlation of the $638.9 - 503.0$ keV cascade is shown in Fig. 5. The fitted value of R was 1.43 and the correlation coefficient was $A_{22} = -0.36 \pm 0.14$. The spin and parity of 4^+ or 5^+ for the 1810.2 keV level are expected from the γ-decay pattern. If they are 4^+, the A_{22} coefficient is expected to be a positive value (0.102). It disagrees with the obtained negative value. Thus, the J^π value of 5^+ was deduced. The S^2 for this cascade is plotted versus $\tan^{-1}\delta$ in Fig. 6, in which two curves and one point for the assumed three spin sequences (6–6–4), (5–6–4) and (4–6–4) are shown. The (4–6–4) sequence is one point at the center of the circle. The (6–6–4) sequence is above the 99% confidence line and is not acceptable. The minimum points of the (5–6–4) sequence were under the 95% confidence line, and the mixing ratio $\delta_{638.9} = 0.33 \pm 0.05$ or $2.37^{+0.32}_{-0.26}$ was obtained for the (5–6–4) sequence.

For the 1627.1 keV level, the spin and parity of 3^- or 4^+ are expected from the γ-decay pattern. Since the 183.2 keV γ-feeding from the above determined 5^+ level at 1810.2 keV existed and the 183.2 keV γ-ray was deemed to have the M1(E2) character as indicated by the conversion electron measurement [3], J^π was determined to be 4^+ for the 1627.1 keV level. The obtained angular correlation coefficient of the 1368.8–258.4 keV cascade was $A_{22} = 0.10 \pm 0.07$, which agreed well with the theoretical value, $A_{22} = 0.102$.

The spin and parity of 2^+, $3^\pm$ or 4^+ for the 1576.5 keV level are expected from its γ-decays. The existence of the 233.6 keV γ-ray feeding from the 5^+ level (1810.2keV) re-

Table 2. γ-γ angular correlation coefficients and mixing ratios. The Majorana parameter values $\xi = 0.03,\ 0.18$ and 0.35 MeV were used for cases I, II and III, respectively. Case II was adopted in the present calculation.

Cascade (keV–keV)	A_{22}	A_{44}	Present δ (E2/M1)	IBM-2 $\|\delta\|$ I	II	III
$2^+ \to 2^+ \to 0^+$ 1015.9—258.4	-0.18 ± 0.04	0.35 ± 0.09	$\delta_{1015.9} = \begin{cases} 0.54 \pm 0.07 \text{ or} \\ 5.4^{+3.1}_{-1.5} \end{cases}$	1.1	4.5	9.2
$3^+ \to 2^+ \to 0^+$ 1318.1—258.4	-0.13 ± 0.06	-0.04 ± 0.12	$\delta_{1318.1} = \begin{cases} -0.05 \pm 0.04 \text{ or} \\ 6.5^{+1.7}_{-1.1} \end{cases}$	0.05	1.8	4.9
$4^+ \to 2^+ \to 0^+$ 1368.8—258.4	0.10 ± 0.07	—	pure E2	—	—	—
$4^+ \to 4^+ \to 2^+$ 959.0—409.8	-0.12 ± 0.06	-0.01 ± 0.06	$\delta_{959.0} = 1.19^{+0.16}_{-0.14}$	0.45	1.2	3.2
$5^+ \to 6^+ \to 4^+$ 638.9—503.0	-0.36 ± 0.14	-0.10 ± 0.03	$\delta_{638.9} = \begin{cases} 0.33 \pm 0.05 \text{ or} \\ 2.37^{+0.32}_{-0.26} \end{cases}$	0.13	0.45	1.3
$5^+ \to 4^+ \to 4^+$ 183.2—959.0	0.13 ± 0.03	0.02 ± 0.06	$\delta_{183.2} = \begin{cases} 0.25 \pm 0.08 \text{ or} \\ 2.7^{+0.9}_{-0.6} \end{cases}$	0.01	0.37	1.1

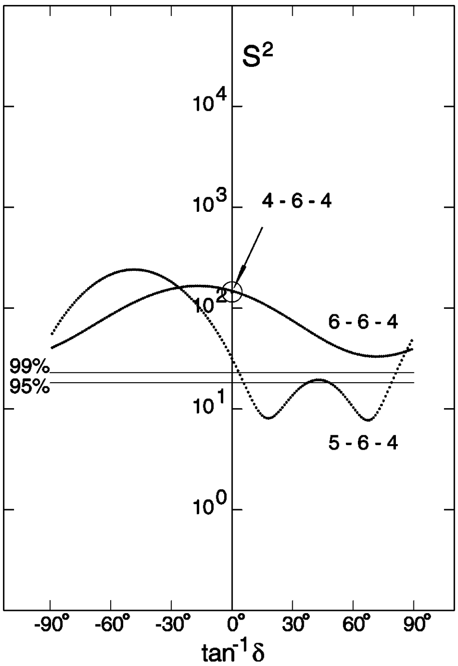

Fig. 6. S^2 versus $\tan^{-1}\delta$ for the 638.9–503.0 keV cascade. Three spin sequences are shown

stricts its spin and parity to 3^+ or 4^+. If they are 4^+, the expected A_{22} value (0.102) does not agree with the experimental value (–0.13) for the cascade of 1318.1-258.4 keV. Thus, the spin and parity 3^+ were adopted and $\delta_{1318.1} = -0.05 \pm 0.04$ or $6.5^{+1.7}_{-1.1}$ was obtained.

The value $\delta_{1015.9} = 0.54 \pm 0.07$ or $5.4^{+3.1}_{-1.5}$ was obtained from the angular correlation of the 1015.9–258.4 keV cascade, and, from the 183.2-959.0 keV cascade, the mixing ratio $\delta_{183.2}$(E2/M1) $= 0.25 \pm 0.08$ or $2.7^{+0.9}_{-0.6}$ was deduced using the $\delta_{959.0}$ value (1.19) obtained on the basis of the results of the 959.0-409.8 keV cascade.

3 Discussion

Excitation level energies for the ^{146}Ce nucleus were calculated using the neutron-proton interacting boson model (IBM-2) [19]. The effects of the proton subshell closure at $Z = 64$ were taken into account in the calculation. The neutron shell closure was also assumed to be unaffected by the $Z = 64$ proton subshell. Thus, both numbers of neutron and proton bosons were $N_\nu = N_\pi = 3$. Gill *et al.* [20] studied the parameters for IBM-2 calculations near the $Z = 64$ subshell and they suggested acceptable regions of the d-boson energy parameter (ϵ_d), the quadrupole force strength parameter (κ) and the quadrupole coefficient (χ_ν and χ_π) for the nuclei of Ba, Ce, Nd and Sm. In the present calculation, the NPBOS program by Otsuka and Yoshida [21] was used. The parameters $\kappa = -0.1$ MeV, $\epsilon_d = 0.5$ MeV, $\chi_\nu = -0.9$ and $\chi_\pi = -1.5$ were found to give a good fit to the experimental levels. These parameters were within the ranges suggested by Gill *et al.* [20] except for the value of χ_π. The Majorana force parameter $\xi = 0.18$ MeV was used. The results are shown in Fig. 7, where some of the positive-parity levels experimentally observed are classified and compared with the calculated levels. The calculated F-spin values of $(\langle F\rangle^2/\langle F_{\max}\rangle^2)$% are presented on the calculated levels. The F-spin is the isospin for the proton and neutron bosons. The IBM-2 predicts enhanced M1 transitions between states with F-spin quantum numbers of $F_{\max}$ and $(F_{\max} - 1)$ [22]. As the mixture of the component of the $(F_{\max} - 1)$ state causes enhancement of M1 transition probability, the Majorana parameter significantly influences the mixing ratios, δ(E2/M1). In three cases , with the Majorana force parameters 0.03(I), 0.18(II) and 0.35(III) MeV, the values of the mixing ratio δ were calculated. For example, the $\langle F\rangle^2/\langle F_{\max}\rangle^2$ values for the 2_3^+ state were 53.7%, 97.9% and 99.1% in case I, II and III, respectively. The calculated δ values for the three cases are listed in Table 2. Case II was adopted in the present calculation. The B(E2) values were calculated with the effective boson charges $e_\nu = 0.069$ and $e_\pi = 0.157$, which were determined to reproduce the measured B(E2) value (41 ± 5 W.u. [2]) of the 2_1^+ state at 258.4 keV. Experimen-

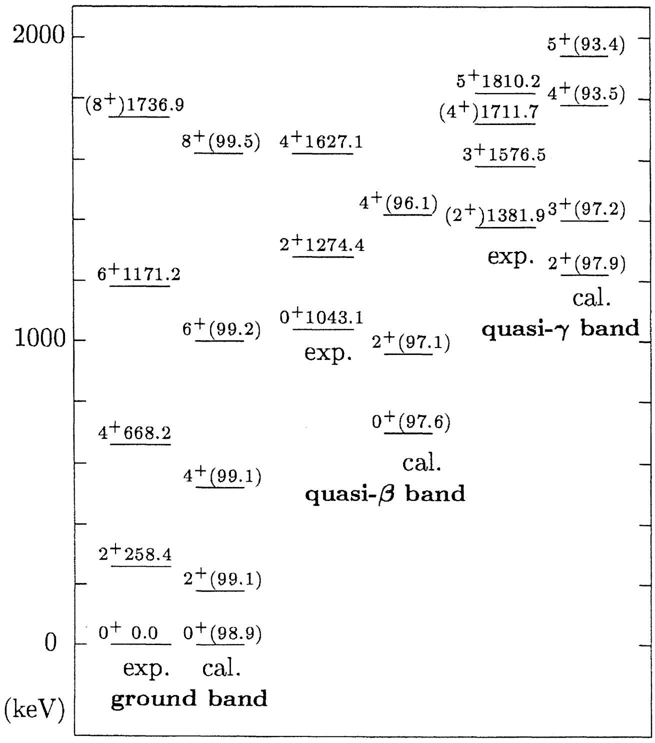

Fig. 7. Band structure of levels in ^{146}Ce. The experimental and calculated excitation energies are shown. Values written on the calculated levels are $\langle F\rangle^2/\langle F_{\max}\rangle^2$ %

Table 3. B(E2) ratios. The suffix 1 corresponds to the ground band members. The 2_2 level indicates the 1274.4 keV level and 2_3 indicates the 1381.9 level. The 4_2, 4_3 and 4_4 states indicate 1627.1, 1711.7 and 1802.3 keV levels, respectively

B(E2) ratios	Experimental	IBM-2
$\frac{B(\mathrm{E2}: 2_2 \longrightarrow 2_1)}{B(\mathrm{E2}: 2_2 \longrightarrow 0_1)}$	1.8 ± 0.4	62 (β state)
$\frac{B(\mathrm{E2}: 2_3 \longrightarrow 2_1)}{B(\mathrm{E2}: 2_3 \longrightarrow 0_1)}$	$< 0.9 \pm 0.6^a$	0.02 (γ state)
$\frac{B(\mathrm{E2}: 4_2 \longrightarrow 2_2)}{B(\mathrm{E2}: 4_2 \longrightarrow 2_1)}$	105 ± 22	1311 (β state)
$\frac{B(\mathrm{E2}: 4_3 \longrightarrow 2_2)}{B(\mathrm{E2}: 4_3 \longrightarrow 2_1)}$	$< 26^b$	0.1 (γ state)
$\frac{B(\mathrm{E2}: 4_4 \longrightarrow 2_2)}{B(\mathrm{E2}: 4_4 \longrightarrow 2_1)}$	$< 16^b$	

^{a} E2 mixing is not clear. ^{b} No observation (< 0.5).

tal B(E2) ratios are compared with the calculated values in Table 3.

3.1 The ground band

Four levels, 258.4, 668.2, 1171.2 and 1736.9 keV were assigned to constitute the ground band with J^π = 2^+, 4^+, 6^+ and (8^+), respectively [3,8]. The (8^+) level is reported to be 1737.9 keV as determined in a study on ^{252}Cf fission fragments [23] and also it was calculated to be 1735.9 keV in [2]. These levels perhaps corresponds to the 1736.9 keV level.

3.2 The quasi-β band

The 1043.1 and 1274.4 keV levels were assigned as members of a quasi-β band [3,10,11]. The isotopes ^{142}Ce, ^{144}Ce, ^{146}Ce and ^{148}Ce have gradually decreasing quasi-β band head (0_2^+) energies as seen in Fig. 8. As the 2_2^+ state behaves in the same way as the 0_2^+ state, the 2_2^+ level, 1274.4 keV, of ^{146}Ce was systematically confirmed to be the 2^+ member of the quasi-β band. The large value obtained for the E2 mixing ratio ($\delta_{1015.9} = 5.4^{+3.1}_{-1.5}$) of the 1015.9 keV γ-transition ($2_2^+ \rightarrow 2_1^+$) agrees with the calculated value (4.5), and the experimental B(E2) ratio $B(\mathrm{E2}: 2_2 \rightarrow 2_1)/(\mathrm{B}(\mathrm{E2}: 2_2 \rightarrow 0_1) = 1.8 \pm 0.4$ is also preferable to the quasi-β band assignment as seen in Table 3. The transition intensity of the γ-ray (231.3 keV) in the case of the $2_2 \rightarrow 0_2$ transition is estimated to be about 0.3 and it could not be seen in the present measurement because it is less than the observation limit of 0.5.

Three candidates, the 1627.1 (4_2), 1711.7($3^-, 4_3$) and 1802.3 keV((4_4)) levels exist for the 4^+ member of the quasi-β band, although the assignments of 4^+ for the last two levels are not definite. As the experimental ratio $B(\mathrm{E2}: 4_2 \rightarrow 2_2)/B(\mathrm{E2}: 4_2 \rightarrow 2_1)$ was large (105 ± 22) and the calculated value was also large for the β state as seen in Table 3, the 1627.1 keV(4_2) level was assigned as the 4^+ member of the quasi-β band. The E2/M1 mixing ratio of 959.0 keV γ-ray ($4_2 \rightarrow 4_1$) was $1.19^{+0.16}_{-0.14}$ which agreed with the calculated value 1.2.

3.3 The quasi-γ band

The (2_3^+) level, 1381.9 keV, was assigned as a band head of the quasi-γ band [3,10] from the systematics. The energy separation between the 1576.5(3_1^+) and 1381.9(2_3^+) keV levels is similar to the energy difference $E(3_1^+ - 2_3^+)$ of ^{144}Ce and ^{148}Ce. The 3_1^+ level, 1576.5 keV, is possibly the quasi-γ 3^+ state. The deduced mixing ratio of the $3_1 \rightarrow 2_1$ γ-transition (1318.1 keV) was $\delta_{1318.1}(\mathrm{E2/M1}) = -0.05 \pm 0.04$ or $6.5^{+1.7}_{-1.1}$. The larger value is preferable as the calculated value is $|\delta|$=1.8.

One of the two levels 1711.7 and 1802.3 keV is considered to be the 4^+ member of the quasi-γ band; although their 4^+ assignments are not yet definite, they are tentatively denoted as 4_3(1711.7 keV) and 4_4(1802.3 keV) in this paper. Transitions from these levels to the 2_2 level are not observed, that is, these intensities are less than 0.5 [3]. Therefore, the limit value of the B(E2) ratio can be estimated as $B(\mathrm{E2}: 4_3 \rightarrow 2_2)/B(\mathrm{E2}: 4_3 \rightarrow 2_1) < 26$ and $B(\mathrm{E2}: 4_4 \rightarrow 2_2)/B(\mathrm{E2}: 4_4 \rightarrow 2_1) < 16$. As the calculated value is 0.1, the 4_γ level can not be decided. However, the ratio of estimated transition probabilities of $(4_\gamma \rightarrow 2_1)/(4_\gamma \rightarrow 4_1)$ was about 0.5 and

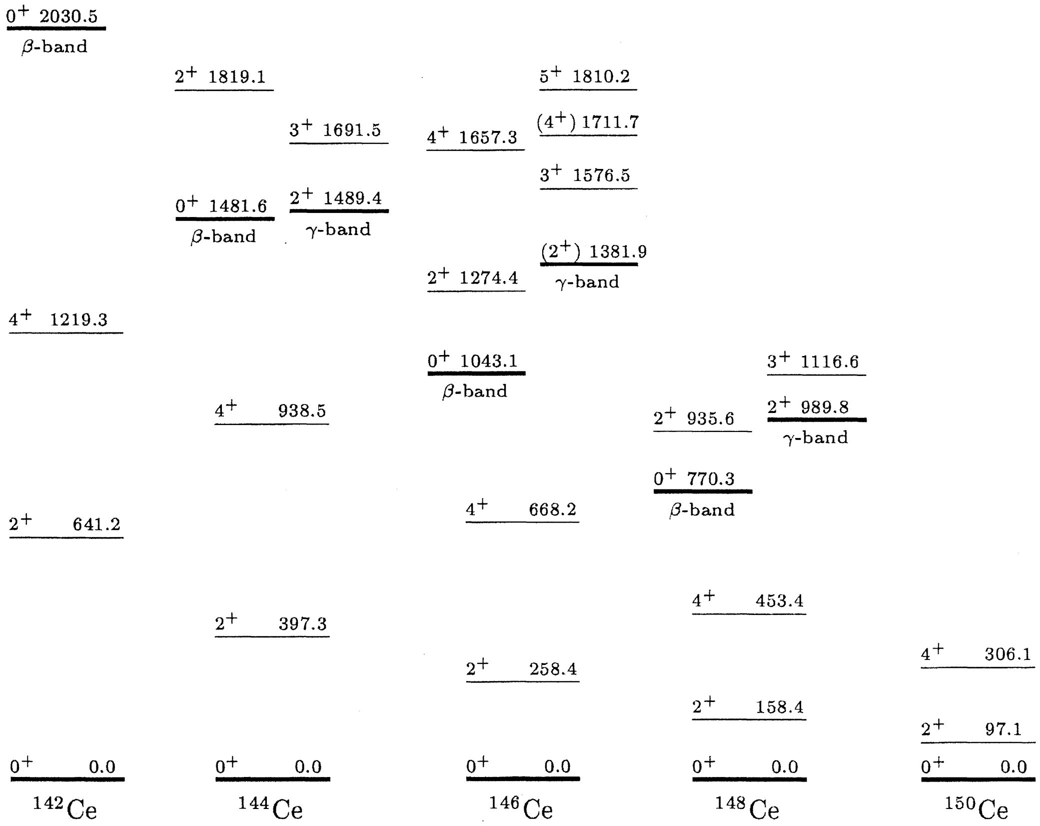

Fig. 8. Systematics of the quasi-β and -γ bands in Ce isotopes. ^{142,144}Ce from [5,6], ^{146}Ce from the current work, ^{148}Ce from [7] and ^{150}Ce from [8]

the corresponding experimental value of ($4_3 \rightarrow 2_1$ 1453.5 keV)/($4_3 \rightarrow 4_1$ 1043.6 keV) was about 0.4, while ($4_4 \rightarrow 2_1$ 1543.8 keV)/($4_4 \rightarrow 2_1$ 1134.0 keV) was about 2.1. The assignment of the 4_3 level as the quasi-γ state is consistent with the intensity ratio. Thus, the 4_3 level was tentatively assigned as the member of the quasi-γ band. Although the γ-transition (329.8 keV) $4_3 \rightarrow 2_3$ is not observed, it is plausible because the estimated transition intensity (0.2) is less than the observation limit. The 1810.2 keV level assigned as 5^+ is considered to correspond to the 5^+ member of the quasi-γ band. The B(E2) ratios decaying from the 5^+ level are listed in Table 4, and these are in good agreement with the calculations. The estimated γ-transition intensity for the $5_\gamma \rightarrow 4_\gamma$ (98.5 keV) transition was about 0.2 and it could not be observed because of the observation limit (0.5). The mixing ratio of the 183.2 keV γ-ray deduced as $\delta = 0.25 \pm 0.08$ from the angular correlation of the 183.2 – 959.0 keV cascade, agrees with the calculated value, 0.37.

Table 4. B(E2) ratios of the γ-rays decaying from the 5_1^+ state. The $3_1, 4_1, 5_1$ and 6_1 indicate the 1576.5, 668.2, 1810.2 and 1171.2 keV levels, respectively

Cascade	Experimental	Calculation IBM-2
$\frac{B(\mathrm{E2}: 5_1 \longrightarrow 4_1)}{B(\mathrm{E2}: 5_1 \longrightarrow 3_1)}$	$< (5.4 \pm 0.7) \times 10^{-3}$ [a]	4.1×10^{-3}
$\frac{B(\mathrm{E2}: 5_1 \longrightarrow 4_2)}{B(\mathrm{E2}: 5_1 \longrightarrow 3_1)}$	3.3 ± 0.7	0.27
$\frac{B(\mathrm{E2}: 5_1 \longrightarrow 6_1)}{B(\mathrm{E2}: 5_1 \longrightarrow 3_1)}$	$(1.3 \pm 0.3) \times 10^{-3}$	8.6×10^{-2}

[a] E2 mixing is not clear.

4 Conclusion

Levels of ^{146}Ce as populated in the β-decay of ^{146}La were investigated. The spins and parities of three levels were determined from the present measurements. The calculated levels of the ground, quasi-β and -γ bands were compared with the experimental levels. The levels 1043.1, 1274.4 and 1627.1 keV were assigned as 0^+, 2^+ and 4^+ members, respectively, of a quasi-β band. Also, the levels 1381.9, 1576.5, (1711.7) and 1810.2 keV were assigned as 2^+, 3^+, 4^+ and 5^+ members, respectively, of a quasi-γ band. It was found that the excitation energies of low-lying positive-parity levels of ^{146}Ce could be fairly well reproduced by an IBM-2 calculation with appropriate values of the parameters, although no overall agreement was obtained especially for higher-lying levels. The Majorana interaction parameter strongly influenced E2/M1 mixing ratios. The E2/M1 mixing ratio is expected to be an indicator of the Majorana force. For extended studies on the band structure of ^{146}Ce, definite spin and parity assignments for levels from 1.3 to 3 MeV are required. As a lot of negative-parity levels have been identified experimentally, analyses including f-bosons and calculations of γ-transition rates including negative parity states are also needed.

References

1. E. Monnand, J. Blachot, J. P. Bocquet, F. Schussler, H. Lawin, G. Sadler, K. Sistemich, G. Jung and K. D. Wünsch, Verh. Dtsch. Phys. Ges. **4**, 845 (1978)
2. L. K. Peker and J. K. Tuli, Nuclear Data Sheets **82**, 187 (1997)
3. T. Sharshar, S. Yamada, K. Okano and K. Aoki, Z. Phys. A **345**, 377 (1993)
4. A. Wolf, C. Chung, W. B. Walters, G. Peaslee, R. L. Gill, M. Shmid, V. Manzella, E. Meier, M. L. Stelts, H. I. Liou, R. E. Chrien and D. S. Brenner, Nucl. Instrum. and Methods 206, 397 (1983)
5. A. Wolf, C. Chung, W. B. Walters, R. L. Gill, M. Shmid, R. E. Chrien and Peaslee, Phys. Rev. C **28**, 352 (1983)
6. E. Michelakakis, W. D. Hamilton, P. Hungerford, G. Jung, P. Pfeiffer and S. M. Scott, J. Phys. G **8**, 111 (1982)
7. R. L. Gill, M. Shmid, R. E. Chrien, Y. Y. Chu, A. Wolf, D. S. Brenner, K. Sistemich, F. K. Wohn, H. Yamamoto, C. Chung and W. B. Walters, Phys. Rev. C **27**, 1732 (1983)
8. J. B. Wilhelmy, S. G. Thompson, R. C. Jared and E. Cheifetz, Phys. Rev. Lett. **25**, 1122 (1970)
9. G. Audi and A. H. Wapsara, Nucl. Phys. **A595**, 409 (1995)
10. M. Sakai, Atomic Data and Nuclear Data Tables **31**, 399 (1984)
11. S. Yamada, K. Aoki and T. Sharshar, Y. Kawase and K. Okano, Annu. Rep. Res. Reactor Inst. Kyoto Univ. **24**, 56 (1991)
12. K. Okano, Y. Kawase, K. Kawade, H. Yamamoto, M. Hanada, T. Katoh and I. Fujiwara, Nucl. Instrum. and Methods. **186**, 115 (1981)
13. Y. Kawase and K. Okano, Nucl. Instrum. and Methods. Phys. Res. B **37/38**, 116 (1989)
14. A. Taniguchi, K. Okano, T. Sharshar and Y. Kawase, Nucl. Instrum. Methods. Phys. Res. A **351**, 378 (1994)
15. S. Yamada, T. Sharshar, K. Aoki and K. Okano, Nucl. Instrum. Methods Phys. Res. A **316**, 276 (1992)
16. A. J. Becker and R. M. Steffen, Phys. Rev. **180**, 1043 (1969)
17. S. Yamada, K. Aoki and T. Hayashi, Annu. Rep. Res. Reactor Inst. Kyoto Univ. **7**, 1 (1974)
18. S. J. Robinson, Nucl. Instrum. and Methods Phys. Res. A **292**, 386 (1990)
19. T. Otsuka, A. Arima and F. Iachello, Nucl. Phys. **A309**, 1 (1978)
20. R. L. Gill, R. F. Casten, D. D. Warner, D. S. Brenner and W. B. Walters, Phys. Lett. B **118**, 251 (1982)
21. T. Otsuka and N. Yoshida, Japan Atomic Energy Research Institute Report, JAERI-M 85-094(1985)
22. N. Pietralla, C. Fransen, D. Belic, P. von Brentano, C. Frießner, U. Kneissl, A. Linnemann, A. Nord, H. H. Pitz, T. Otsuka, I. Schneider, V. Werner and I. Wiedenhöver, Phys. Rev. Lett. **83**, 1303 (1999)
23. W. R. Phillips, R. V. F. Janssens, I. Ahmad, H. Emling, R. Holzmann, T. L. Khoo and M. W. Drigert, Phys. Lett. B **212**, 402 (1988)