Eur. Phys. J. A **13**, 277–280 (2002)

THE EUROPEAN PHYSICAL JOURNAL A

Short Note

New yrast excited states of the N = 84 nucleus ^{142}Ce observed in deep inelastic reactions

Z. Liu[1,a], Y.H. Zhang[1], X.H. Zhou[1], M.L. Liu[1], W.J. Luo[1], Q.Y. Pan[1], Z.G. Gan[1], T. Hayakawa[2], M. Oshima[2], Y. Toh[2], T. Shizima[2], Y. Hatsukawa[2], A. Osa[2], T. Ishii[2], and M. Sugawara[3]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, 730000, PRC
[2] Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan
[3] Chiba Institute of Technology, Narashino, Chiba 275-0023, Japan

Received: 2 November 2001 / Revised version: 15 January 2002
Communicated by J. Äystö

Abstract. Excited states of ^{142}Ce, populated in deep inelastic reactions of ^{82}Se projectiles bombarding ^{139}La target, have been studied up to medium spins using in-beam γ spectroscopy techniques. Three new levels have been identified at 2625, 2995, 3834 keV, and assigned as 8^+, $9^{(-)}$ and $11^{(-)}$, respectively. These new yrast states follow closely the level systematics of the even mass $N = 84$ isotones. Their strctures have been discussed with the help of empirical shell model calculations.

PACS. 21.60.Cs Shell model – 23.20.Lv Gamma transitions and level energies – 27.60.+j $90 \leq A \leq 149$

The even mass $N = 84$ isotones have been the subject of many recent experimental and theoretical investigations into the collective and particle nature of yrast excitations. The yrast states in the isotones lighter than ^{142}Ce (Sn-Ba) have recently been identified in spontaneous fission [1,2]. For the heavier isotones (Nd-Gd), level structures have been well studied using fusion evaporation reactions [3,4]. Knowledge on the yrast levels of ^{142}Ce remains very limited due to the difficult access by fission or fusion evaporation reactions. It is now well established that deep inelastic reactions could populate yrast states in slightly neutron-rich nuclei [5] and provide an efficient way to study the structures of the most neutron-rich, stable isotopes such as ^{142}Ce. We have performed thick target γ-γ coincidence measurements using deep inelastic reactions between ^{139}La and ^{82}Se to explore the yrast spectroscopy of nuclei with $Z \sim 58$ and $N \sim 82$. In this short note, we report on the new results of the yrast excited states in ^{142}Ce.

The experiment was performed at Japan Atomic Energy Research Institute (JAERI), Tokai. A thick (~ 100 mg/cm^2) natural lanthanum target (abundance of ^{139}La is 99.9%) was bombarded with a 420 MeV ^{82}Se beam provided by the Tandem and the Booster accelerator system. All reaction products and beam could be stopped in the target. The beam energy is about 90 MeV above the Coulomb barrier for the ^{139}La + ^{82}Se system. Gamma-rays from both the target-like and projectile-like fragments were measured using the GEMINI multidetector array [6] consisting of twelve Compton-suppressed HPGe-detectors placed at $\pm 32°$, $\pm 58°$ and $90°$ with respect to the beam direction; six of them had an efficiency of 70% each and the others had 40% each relative to $3'' \times 3''$ NaI. The detectors were calibrated with ^{133}Ba and ^{152}Eu standard sources. About 350 million γ-γ coincidence events were recorded and sorted off-line into a total γ-γ coincidence matrix, which was used to extract coincidence relationships and relative intensities of γ-rays. In deep inelastic reactions, γ-rays from one specific fragment are not only coincident with each other themselves, they are also weakly cross coincident with γ-rays from the complementary fragments simultaneously produced with evaporation of zero, one, two or more neutrons. Isotopic assignments for previously unknown γ-rays were based on γ-γ coincidence and intensity relationships [5]. In order to extract information concerning γ-transition multipolarities, angular distribution [5,7] and directional correlation (DCO) analyses [8] have been done. The reliability of these analyses have been checked using known prompt γ-rays from the fusion evaporation reaction products between the ^{82}Se beam and ^{16}O deposited in the target (see table 1). In this short note, we only present the DCO results. A DCO matrix was sorted with the four detectors at $90°$ against the four detectors at $\pm 32°$. For typical stretched quadrupole

[a] e-mail: liuzh2001cn@yahoo.com.cn

Table 1. γ-ray transition energies, relative intensities and DCO ratios in ^{142}Ce.

E_γ(keV)	$I_\gamma^{(a)}$	DCO ratio
641.3	108(6)	1.02(5)
578.0	100(5)	1.03(6)
523.5	90(5)	1.18(6)
881.9	50(3)	1.25(9)
369.9	41(2)	0.82(7)
839.3	30(2)	1.00(9)
$542(M1)^{(b)}$		0.66(9)
$156(M1)^{(b)}$		0.60(11)
$385(E2)^{(b)}$		0.95(6)
$1498(E2)^{(b)}$		0.95(10)

$^{(a)}$ See the text.
$^{(b)}$ Prompt γ transitions of ^{93}Nb [9].

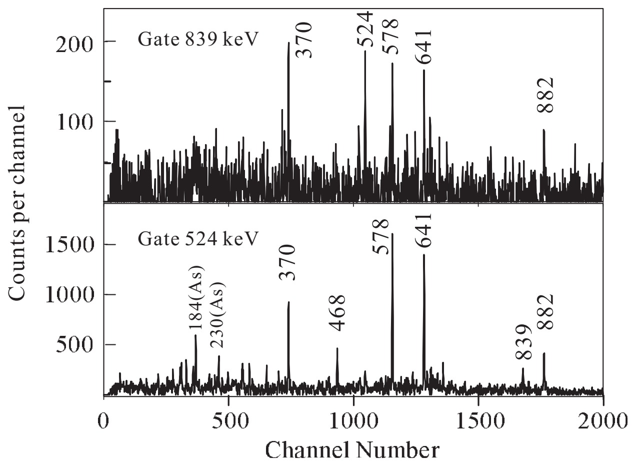

Fig. 1. Typical coincidence spectra gated on the 524 and 839 keV transitions.

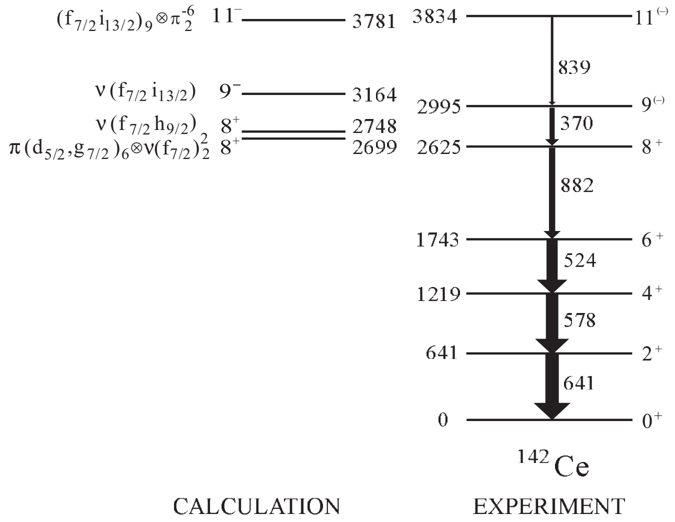

Fig. 2. The level scheme of ^{142}Ce obtained by the present work and the empirical shell model calculations for the levels identified in this work.

transitions from fusion evaporation reactions and deep inelastic reactions, their DCO ratios are both around 1.0. For stretched dipole transitions from fusion evaporation reactions, the DCO ratios are around 0.6, while in deep inelastic reactions their DCO ratios are in-between 0.6 and 1.0, depending on the degree of angular momentum alignment.

^{142}Ce has previously been studied in the $\beta^\pm$ decay, (t, p) reaction, Coulomb excitation, inelastic neutron and electron scattering [10]. The yrast levels have been established up to the 6^+ state at 1743 keV [11]. The transition sequence (641-578-524 keV) decaying the yrast 2^+, 4^+ and 6^+ states is observed in the present work. Three new transitions with energies of 882, 370 and 839 keV are observed in distinct coincidence with the above-known transitions, and in weak coincidence with low-lying yrast transitions in As isotopes (^{77,79}As). By careful analyses of their coincidence intensities with the known 641, 578 and 524 keV lines, they have been firmly assigned to ^{142}Ce and placed above the yrast 6^+ state. These three new transitions are also coincident with each other (typical coincidence spectra gated on the 524 and 839 keV transitions are given in fig. 1). Based on their relative intensities, three levels at 2625, 2995 and 3834 keV are proposed. The relative γ-ray intensities were extracted from the coincidence data, by gating on the yrast $2^+ \to 0^+$ 641 keV transition; the relative intensity of the 641 keV transition itself was obtained from the coincidence with appropriate γ-rays of As isotopes.

For the products of the deep inelastic binary reactions the degree of spin alignment is much less compared to the fusion products. Nevertheless, the observed anisotropies are still high enough to extract information on the multipole character of γ-rays. The DCO ratios for the 882, 370 and 839 keV lines support that they are stretched quadrupole, dipole and quadrupole transitions, respectively. Quadrupole lines should be $E2$ transitions (since prompt $M2$ decays are very rare), so a spin and parity of 8^+ is assigned to the 2625 keV level. The 2995 keV state has a spin of 9 $\hbar$ and negative parity is tentatively assigned based on the level systematics of the yrast states in $N = 84$ isotones as discussed below. Similarly, the 3834 keV level is assigned as $11^{(-)}$. The level scheme proposed for ^{142}Ce by this work is presented in fig. 2. The excitation pattern in ^{142}Ce is similar to that observed in the heavier Nd-Gd isotones [3]. The properties of the observed transitions are listed in table 1.

With the presence of the higher-spin yrast levels of ^{142}Ce observed in this work, it is of interest to study the systematic trends of yrast excitations in the even-even $N = 84$ isotonic chain from the semi-magic ^{134}Sn ($Z = 50$) to the ^{148}Gd ($Z = 64$) nucleus. Figure 3 shows the yrast positive- and negative-parity levels in these $N = 84$ nuclei. The excitation energies of the 8^+, $9^{(-)}$,$11^{(-)}$ states in ^{142}Ce follow the systematics of this isotone chain quite well, strongly supporting the order, spin and parity assignments of these levels proposed above.

Only positive-parity states have been identified in the lighter isotones (Sn-Xe). In the heavier isotones (Ba-Gd),

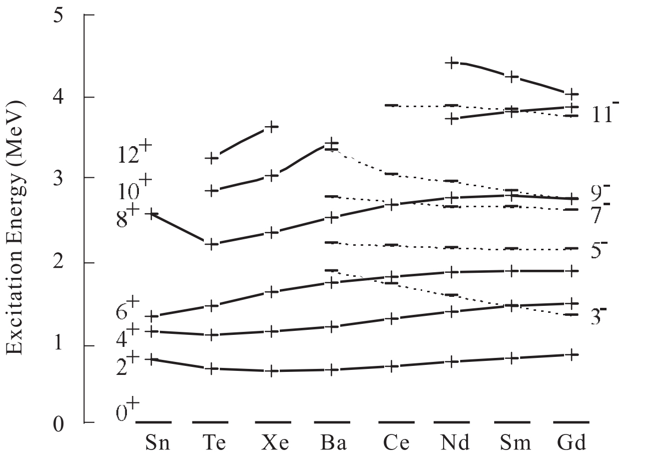

Fig. 3. Systematics of the yrast levels in the $N = 84$ isotones. Data are from this work and [1–4,10]. Solid lines connecting the positive-parity levels (represented by "+") and dashed lines connecting the negative-parity levels (represented by "−") are drawn to guide the eye.

negative-parity sequences consisting of 3^-, 5^-, 7^-, 9^-, 11^- levels are present as well. In the present study of ^{142}Ce, the previously known 3^- and 5^- states were not observed due to the non-yrast nature of them. In fig. 3, the 5^- state at 2125 keV is adopted for ^{142}Ce and it follows the systematics very well. Another 5^- state at a lower excitation energy of 1742 keV (just below the 1743 keV 6^+) [10] identified only in the electron scattering experiment deviates much from the systematics, implying that the assignment of this level was questionable. Up to now, the location of the yrast 7^- state is still unknown.

The $N = 84$ isotones around the doubly magic ^{132}Sn ($Z = 50$) and ^{146}Gd ($Z = 64$) behave as closed-shell nuclei. While in the middle of these two proton shells, with the increasing number of valence protons, collectivity is expected. These $N = 84$ isotones provide a particular interesting case for studying the competition between collective and single-particle degrees of freedom. ^{134}Sn and ^{148}Gd have only two valence neutrons outside their doubly magic cores. Their low-lying yrast levels are formed by the two valence neutrons, or the coupling of the collective octupole states with the two-neutron states. The 2^+, 4^+, 6^+ sequences in these two nuclei originate from a $\nu(f_{7/2})^2$ configuration. In the isotones between them, the excitation energies of the 2^+, 4^+ and 6^+ levels show a smooth change, suggesting that these excitations have a substantial contribution from the $\nu(f_{7/2})^2$ configuration. In the middle of this isotone chain, the excitation energies of the 2^+, 4^+ and 6^+ levels become approximately equidistant, indicating the presence of a collective vibration. Theoretical and experimental studies show, however, that the collective excitations decrease with spin [12–16]. It is demonstrated in ^{144}Nd, for example, that 2 qp configurations already dominate the 5^- and 6^+ states [16,13, 14]. So higher-spin states are expected to be better described in a single-particle picture.

To gain insight into the structures of the new states of ^{142}Ce observed in this work, we have performed empirical shell model calculations. This method allows the decomposition of a shell model configuration into substructures corresponding to specific levels in neighboring nuclei, in which empirical interaction energies are included automatically [17]. The empirical single-particle energies and interaction energies are almost complete in the ^{146}Gd region, while the spectroscopic information in the ^{132}Sn region is still very limited. We chose ^{146}Gd as a core. The calculation results are shown in the left side of fig. 2.

The yrast 8^+ state may have $\nu(f_{7/2}h_{9/2})_8$ and/or $\nu(f^2_{7/2})_2 \otimes \pi(g^{-1}_{7/2}d_{5/2})_6$ configurations. The first one is a pure two-neutron configuration proposed in ^{134}Sn and ^{148}Gd. It is decomposed as follows:

$$E(^{142}\mathrm{Ce}, 8^+, \nu(f_{7/2}h_{9/2})) = S + E\left(^{141}\mathrm{Ce}, \frac{7}{2}^-, \nu f_{7/2}\right) + E\left(^{141}\mathrm{Ce}, \frac{9}{2}^-, \nu h_{9/2}\right) + E(^{148}\mathrm{Gd}, 8^+, \nu(f_{7/2}h_{9/2})) - E(^{140}\mathrm{Ce}, 0^+) - E\left(^{147}\mathrm{Gd}, \frac{7}{2}^-, \nu f_{7/2}\right) - E\left(^{147}\mathrm{Gd}, \frac{9}{2}^-, \nu h_{9/2}\right) = 2748\ \mathrm{keV}.$$

The mass window S is

$$S = M(^{146}\mathrm{Gd}) + M(^{148}\mathrm{Gd}) + 2M(^{141}\mathrm{Ce}) - M(^{140}\mathrm{Ce}) - M(^{142}\mathrm{Ce}) - 2M(^{147}\mathrm{Gd}) = 97\ \mathrm{keV}.$$

The $\pi(g^{-1}_{7/2}d_{5/2})_6 \otimes \nu(f^2_{7/2})_2$ configuration is estimated to be 2699 keV. The experimental energy of the $\nu(f^2_{7/2})_2 \otimes \pi d_{5/2}, \frac{9}{2}^+$ level in ^{143}Pr is unknown. In the calculation it is taken as 640 keV based on the weak coupling behavior observed in neighboring ^{145}Pm [18]. The calculated energies of both configurations reproduce the experimental data satisfactorily, suggesting that there is substantial contribution from these two single-particle excitations in this 8^+ state. ^{142}Ce has 8 protons outside the $Z = 50$ closed shell. This yrast 8^+ level is interesting for testing the $\pi g_{7/2}$ subshell closure, as addressed in [1]. The second configuration involving the excitation of the $\pi g_{7/2}$ subshell closure seems more favorable in energy, indicating that this subshell closure is not important.

In the even-A $N = 84$ isotones, the yrast 9^- states have been proposed to involve the excitation of one neutron from the $f_{7/2}$ orbital to $i_{13/2}$. The excitation energy has been calculated with this configuration:

$$E(^{142}\mathrm{Ce}, 9^-, \nu(f_{7/2}i_{13/2})) = S + E\left(^{141}\mathrm{Ce}, \frac{7}{2}^-, \nu f_{7/2}\right) + E\left(^{141}\mathrm{Ce}, \frac{13}{2}^+, \nu i_{13/2}\right) + E(^{148}\mathrm{Gd}, 9^-, \nu(f_{7/2}i_{13/2})) - E(^{140}\mathrm{Ce}, 0^+) - E\left(^{147}\mathrm{Gd}, \frac{7}{2}^-, \nu f_{7/2}\right) - E\left(^{147}\mathrm{Gd}, \frac{13}{2}^+, \nu i_{13/2}\right) = 3164\ \mathrm{keV}.$$

The calculated result is about 170 keV above the experimental value. Similar calculations have been done for the 11^- state under several possible configurations. The calculated excitation energy is 3781 keV for the $\nu(f_{7/2}i_{13/2})_9 \otimes (\pi^{-6})_2$ configuration, 4128 keV for the two-neutron configuration $\nu(h_{9/2}i_{13/2})$, and 4352 keV for the $\pi(g_{7/2}^{-1}h_{11/2}d_{5/2}^{0})_9 \otimes \nu(f_{7/2}^{2})_2$ configuration. Based on the excitation energy arguments, the $\nu(f_{7/2}i_{13/2})_9 \otimes (\pi^{-6})_2$ configuration seems a best candidate for the observed 11^- level. The same configuration has been assigned for the yrast 11^- state in ^{144}Nd [4].

^{142}Ce has eight and ten valence nucleons relative to the doubly magic ^{132}Sn and ^{146}Gd, respectively. It is expected that this nucleus may manifest collective properties. But as displayed in fig. 2, the new excited states observed in the present work could be reasonably reproduced in energy by the empirical shell model calculations, indicating that single-particle excitations dominate these medium-spin yrast states in this nucleus.

The authors gratefully acknowledge the crew of the JAERI tandem and booster accelerator system. This work was supported by the National Natural Science Foundation of China under Grant No. 19705011, the Major Basic Research Development Program (G2000077400), and the Chinese Academy of Sciences.

References

1. A. Korgul *et al.*, Eur. Phys. J. A **7**, 167 (2000).
2. W. Urban *et al.*, Nucl. Phys. A **613**, 107 (1997).
3. L. Bargioni *et al.*, Phys. Rev. C **51**, R1057 (1995).
4. J.K. Jewell *et al.*, Phys. Rev. C **52**, 1295 (1995).
5. C.T. Zhang *et al.*, Nucl. Phys. A **628**, 386 (1998).
6. K. Furuno *et al.*, Nucl. Instrum. Methods A **421**, 211 (1999).
7. J.F.C. Cocks *et al.*, Nucl. Phys. A **645**, 61 (1999).
8. K.S. Krane *et al.*, Nucl. Data Tables A **11**, 351 (1973).
9. C.M. Baglin, Nucl. Data Sheets **80**, 1 (1997).
10. J.K. Tuli, Nucl. Data Sheets **89**, 671 (2000).
11. J.R.Vanhoy *et al.*, Phys. Rev. C **52**, 2387 (1995).
12. J. Copnell *et al.*, Phys. Rev. C **46**, 1301 (1992).
13. J. Holden *et al.*, Phys. Rev. C **63**, 024315 (2001).
14. S.J. Robinson *et al.*, Phys. Rev. C **62**, 044306 (2000).
15. P.D. Cottle *et al.*, Phys. Rev. C **40**, 2028 (1989).
16. P.D. Cottle *et al.*, Phys. Rev. C **43**, 59 (1991).
17. J. Blomqvist *et al.*, Z. Phys. A **312**, 27 (1983).
18. T. Glasmacher *et al.*, Phys. Rev. C **45**, 1619 (1992).