Eur. Phys. J. A **26**, 315–319 (2005)
DOI 10.1140/epja/i2005-10181-4

THE EUROPEAN PHYSICAL JOURNAL A

New high-spin states of ^{147}Nd and ^{145}Ce: Octupole correlation in the N = 87 isotones

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Received: 1 August 2005 /
Published online: 27 December 2005 –
Communicated by D. Schwalm

Abstract. High-spin states of the $N = 87$ nuclei, ^{147}Nd and ^{145}Ce, have been populated in the ^{12}C + ^{238}U and ^{18}O + ^{208}Pb fusion-fission reactions at 90 MeV and 85 MeV bombarding energy, respectively. The emitted γ-radiation was detected using the Euroball III and IV arrays. High-spin states of the ^{147}Nd isotope have been identified for the first time. The high-spin yrast and near-to-yrast structures of the ^{145}Ce nucleus have been considerably extended. The newly observed structures, discussed by analogy with the neighbouring isotones, show the coupling of an $h_{9/2}$ neutron to the quadrupole and octupole excitations of the core.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 21.10.Re Collective levels – 23.20.Lv γ transitions and level energies – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The study of the level structure of the $N = 87$ isotones can provide meaningful information on the nuclear shape changes occuring at $N = 90$, particularly the octupole correlations known in this mass region. For that purpose, the identification of the single-particle orbitals close to the Fermi levels and the behaviour of the structures built on them give important results. The high-spin states of the ^{151}Gd and ^{149}Sm isotopes have been already studied using (HI, $xn\gamma$) reactions [1,2]. Concerning the lighter isotones, the ^{145}Ce, ^{143}Ba, and ^{141}Xe [3–6] nuclei have been investigated using the spontaneous fission of transuranic ^{252}Cf and ^{248}Cm nuclei, since they cannot be populated in fusion-evaporation reactions.

In this paper, we report on new high-spin excited states in ^{147}Nd and ^{145}Ce populated in fission reactions induced by heavy ions. The new transitions have been identified using the fact that prompt γ-rays emitted by complementary fragments are detected in coincidence [7,8]. The high-spin level scheme of ^{147}Nd, which is identified for the first time, is very similar to the ones of the other $N = 87$ isotones. Moreover, the already known transitions [3] of ^{145}Ce have been reordered and new spin assignments are proposed. In addition, a completely new side band has been identified in ^{145}Ce. All the observed structures are discussed by analogy with the neighbouring isotones.

2 Experimental methods and results

The high-spin states in ^{147}Nd and ^{145}Ce have been populated using the two fusion-fission reactions, ^{12}C + ^{238}U and ^{18}O + ^{208}Pb at 90 MeV and 85 MeV incident energy, respectively. For the first experiment, the beam was provided by the Legnaro XTU tandem accelerator, and for the second one by the Vivitron accelerator at

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IReS (Strasbourg). The targets of 47 mg/cm^2 ^{238}U and 100 mg/cm^2 ^{208}Pb were thick enough to stop the recoiling nuclei. The γ-rays were detected with the Euroball III and IV arrays [9], respectively. The spectrometers contained 15 Cluster germanium detectors placed in the backward hemisphere with respect to the beam, 26 Clover germanium detectors located around 90°, and 30 tapered single-crystal germanium detectors located at forward angles. Each Cluster detector consists of seven closely packed large-volume Ge crystals [10] and each Clover detector consists of four smaller Ge crystals [11].

The data were recorded in an event-by-event mode with the requirement that a minimum of five (three) unsuppressed Ge detectors fired in prompt coincidence and about 1.9×10^9 (4×10^9) three- and higher-fold coincidence events were registered in the first (second) experiment. The data from the first experiment were sorted with the EURO14 software [12] and analysed using the Radware package [13]. For the second experiment, the offline analysis included both the usual γ-γ sorting and multi-gated spectra using the Fantastic software [14] and several three-dimensional "cubes" built and analysed with the Radware package [13].

The placement of the γ-ray transitions in a level scheme was based on γ-γ-γ coincidences and relative γ-ray intensities. Since the statistics of our ^{147}Nd and ^{145}Ce data was too low to perform γ-ray angular-correlation analysis, the spin assignments are based i) on the assumption that in the yrast decays spin values increase with excitation energy and ii) on the analogy with the level structure of the neighbouring isotones.

3 Experimental results

3.1 Study of ^{147}Nd

Very few high-spin levels were known in ^{147}Nd prior to this work. From transfer reactions, the first-excited state at 49.9 keV has been assigned as $7/2^-$, and the excited state at 190.2 keV as $(9/2)^-$. The latter is not directly linked to the $5/2^-$ ground state, but is depopulated by a 139.9 keV transition to the first-excited state [15].

The search for new transitions in ^{147}Nd (from the C + U data set) was performed using spectra gated on the two most intense transitions in the complementary fragments $^{92-95}$Sr [16]. Besides the γ-lines belonging to the Sr isotopes, these spectra exhibit a strong 139.9 keV line which we assigned to ^{147}Nd. From the spectra in double coincidence with the 139.9 keV and the first or the second strongest transitions in the complementary fragments, new transitions of 405.9, 593.8, 309.2 and 531.1 keV have been identified.

An example of double-gated spectrum used for the construction of the level scheme is shown in fig. 1 (top panel). The coincidence spectrum gated on the 139.9 and 681.2 keV lines shows, besides a few transitions emitted by Sr isotopes, the 405.9, 593.8, 309.2, 531.1 and 793.2 keV yrast transitions, the new lines of 611.8 and 686.2 keV belonging to the side band, as well as the 484.1 and 302.9 keV linking transitions. Moreover, the two paths, consisting of the 309.2-593.8 keV and 383.9-518.9 keV transitions which de-excite the 1499 keV level, could be identified.

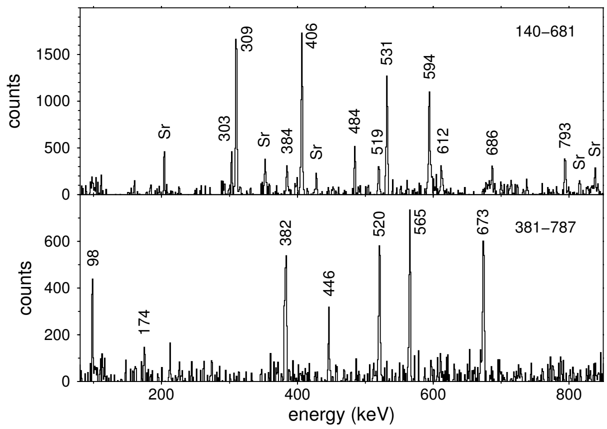

Fig. 1. Double-gated spectra set on the 140 and 681 keV transitions of ^{147}Nd (top) and on the 381 and 787 keV transitions of ^{145}Ce (bottom), built from the data obtained in the ^{12}C + ^{238}U reaction at 90 MeV beam energy. Transitions emitted by the Sr complementary fragments are marked.

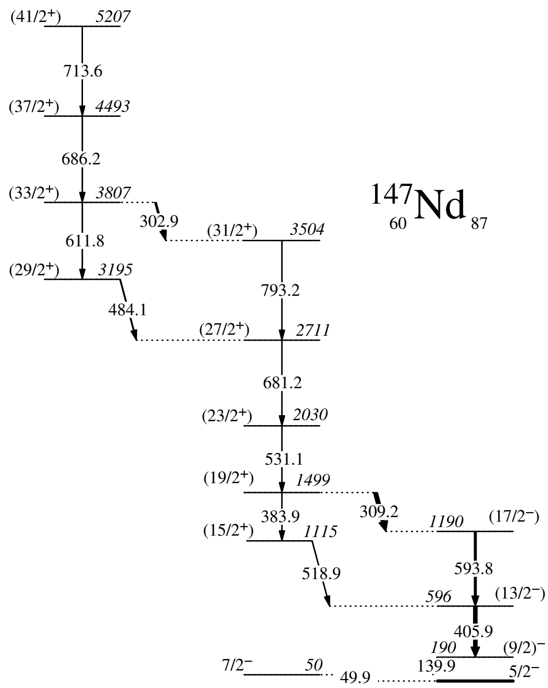

Fig. 2. Level scheme of ^{147}Nd obtained as fission fragment in the fusion reaction ^{12}C + ^{238}U at 90 MeV beam energy. The two first transitions (50 and 140 keV) were already known [15].

The analysis of all coincidence relationships has led to the new level scheme of the ^{147}Nd isotope drawn in fig. 2. Additional support to the assignment of the new γ-rays comes from their coincidence relationships with the 37 keV X-ray of Nd. Since this level scheme is very similar to the ones of the $N = 87$ isotones ^{149}Sm and ^{151}Gd [2], the same spin values can be assigned to the excited levels, as given in fig. 2. It is worth pointing out that the 49.9 keV transition could not be observed in our experiment because of its very large conversion coefficient ($\alpha_{\rm tot} = 10.3$).

3.2 Study of ^{145}Ce

First of all it has to be noticed that the high-spin levels of ^{145}Ce which have been recently identified [3] do not follow the general trend of the $N = 87$ isotones, but they bear strong resemblance to the excited levels of the neighbouring ^{147}Ce isotope [17]. Above 1 MeV excitation energy, the ^{145}Ce yrast band has been interpreted [3] as built on a $13/2^+$ state coming from the $\nu i_{13/2}$ sub-shell, which is known to be involved at low excitation energy in the $N = 89$ isotones.

From our data sets, the 381, 565, 98, 382, 520 and 673 keV lines, reported in ref. [3], are confirmed to belong to the low part of the ^{145}Ce yrast structure. They are observed in coincidence with the transitions emitted by its complementary fragments, ^{95,96,97}Zr in the ^{12}C + ^{238}U reaction and ^{76}Ge in the ^{18}O + ^{208}Pb reaction. Nevertheless, the observation of several other coincidence relationships leads us to reorder these transitions. Our new level scheme is drawn in fig. 3 and an example of double-gated spectrum is given in fig. 1 (bottom panel), showing that the 738 keV transition previously reported in ref. [3] does not belong to the yrast band.

The 97.5 keV transition has to be placed at the bottom of the level scheme because of its strong total intensity. Moreover, two transitions (368.8 and 578.0 keV) have been found to be located in parallel with the 382.2-564.6 cascade. The group of 6 transitions (97.5, 380.7, 564.6, 382.2, 578.0, and 368.8 keV) is very similar to the one located between 50 keV and 1499 keV in ^{147}Nd (see fig. 2). Furthermore, a weak transition at 70 keV has been observed in several spectra double-gated by the low-lying transitions of ^{145}Ce. It is worth pointing out that an excited level at 70 keV is known from the study of the ^{145}La β-decay. It is fed by the most intense β-branch ($\log ft = 5.8$), the ground state being also populated by a strong β-branch ($\log ft = 6.2$) [18]. As discussed in the next paragraph, the ground state and the first-excited state of ^{145}Ce observed in this work can be assigned as $5/2^-$ and $7/2^-$, respectively, as in ^{147}Nd.

In the last compilation [19], the spin value of the ground state of ^{145}Ce has been evaluated to be $(3/2)^-$ from an argument based on its β-decay to ^{145}Pr. It is reported that the very strong branch having $\log ft = 5$ is only compatible with a $\nu 3/2[532]$ configuration for the ^{145}Ce ground state and a $\pi 5/2[532]$ configuration for the ^{145}Pr excited state [19]. Such a statement can be withdrawn as the $5/2^-$ ground state of the neighbouring ^{147}Nd isotone is known to strongly decay ($\log ft = 5$) to an excited state of ^{147}La, which has been assigned as a $5/2^-$ state [15].

The spin value of the ground state of ^{145}Ce had been proposed to be $5/2^-$ by the authors of ref. [18], from an extensive study of the $A = 145$ chain β-decay (particularly ^{145}La $\to$ ^{145}Ce $\to$ ^{145}Pr) and an analysis of the systematics of the first-excited levels of the $N = 87$ isotones.

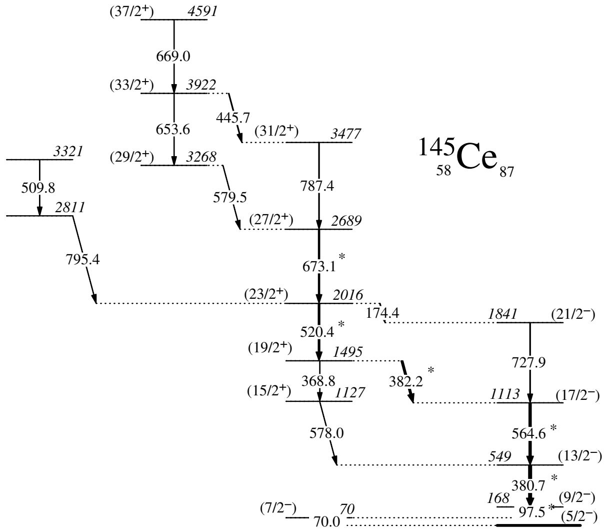

Fig. 3. Level scheme of ^{145}Ce obtained as fission fragment in the fusion reactions ^{12}C + ^{238}U at 90 MeV beam energy and ^{18}O + ^{208}Pb at 85 MeV beam energy. The transitions marked with a star had been previously identified from fission experiments [3] and have been reordered (see text).

The configuration of their ground states is $\nu f_{7/2}^{-3}$, with a spin value evolving from $7/2^-$ in the heavy-mass isotones ($A \geq 149$) to $5/2^-$ in the light-mass ones ($A = 147, 143$ and 141). The lowering in energy of the $j-1$ level below the j level of a j^{+3} or j^{-3} configuration is a well-known phenomenon [20] (see, for instance, the $7/2^+$ ground state of the $_{47}$Ag isotopes corresponding to the $\pi g_{9/2}^{-3}$ configuration, or the $5/2^+$ ground state of the $_{53}$I isotopes corresponding to the $\pi g_{7/2}^{-3}$ configuration): the crossing of the $j-1$ and j levels is a function of the core collectivity. Considering that i) the $7/2^-$-$5/2^-$ crossing in the $N = 87$ isotones takes place between ^{149}Sm and ^{147}Nd and ii) the spin values of the ^{143}Ba and ^{141}Xe ground state are known to be 5/2, the 5/2 value can be safely assigned to the ground state of ^{145}Ce, whereas a change to 3/2 is questionable.

Taking into account these arguments, as well as the strong similarity of the high-spin structures of ^{147}Nd, ^{145}Ce, ^{143}Ba [4,5], and ^{141}Xe [6], we have assigned all the spin and parity values reported in fig. 3.

4 Discussion

The high-spin structures of the $N = 87$ isotones are expected to involve the high-j sub-shells located above the $N = 82$ shell closure, namely $\nu f_{7/2}$, $\nu h_{9/2}$, and $\nu i_{13/2}$. Moreover, the octupole correlations are known to play an important role in this mass region (see, for instance, [21]), because of several pairs of opposite-parity orbitals lying close in energy around the Fermi levels, such as $\nu f_{7/2}$-$\nu i_{13/2}$ and $\pi d_{5/2}$-$\pi h_{11/2}$.

As said before, the lowest configuration of the ^{147}Nd and ^{145}Ce isotones is $\nu f_{7/2}^{-3}$ leading to a $5/2^-$ ground state and a $7/2^-$ state at 50 and 70 keV, respectively. The $\nu h_{9/2}$

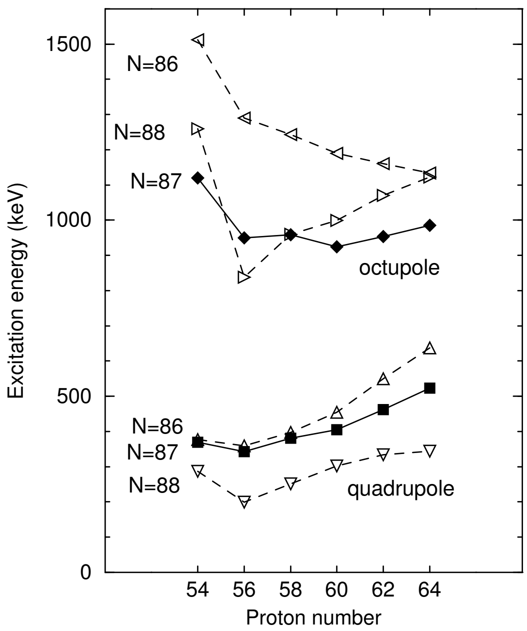

Fig. 4. Excitation energy of the quadrupole and octupole modes in the $N = 86, 87$, and 88 isotones as a function of proton number, from $_{54}$Xe to $_{64}$Gd. The energies of the 2^+ states of the $N = 86$ isotones (empty triangle-up) and of the $N = 88$ isotones (empty triangle-down) are compared to the excitation energies of the $13/2^-$ states relative to the $9/2^-$ states of the $N = 87$ isotones (filled square). The energies of the 3^- states of the $N = 86$ isotones (empty triangle-left) and of the $N = 88$ isotones (empty triangle-right) are compared to the excitation energies of the $15/2^+$ states relative to the $9/2^-$ states of the $N = 87$ isotones (filled diamond).

sub-shell is more favourable for the yrast excited states of the $N = 87$ isotones. The excitation energies of the levels in the bands based on the states at 168 keV in ^{145}Ce and at 190 keV in ^{147}Nd are very similar to those observed in their respective core, ^{146}Nd [22] and ^{144}Ce [23]. Therefore, the negative-parity band above the $(9/2^-)$ state can be interpreted as a decoupled band, in which the $h_{9/2}$ neutron with an angular momentum closely aligned with the rotational angular momentum plays a spectator role. The comparison of the excitation energy of the quadrupole mode in the $N = 86, 87$, and 88 isotones is given in fig. 4. The behaviour of the $N = 87$ isotones is closer to that of the $N = 86$ isotones. This can be easily understood since the neutron configuration of the $9/2^-$ band of the $N = 87$ isotones is a neutron-particle excitation, $\nu h_{9/2} \otimes \nu f_{7/2}^{-4}$.

In the light [4–6] and heavy [1,2] $N = 87$ isotones, a side band built on a $15/2^+$ state is strongly connected to the yrast band (by $E1$ transitions). A similar behaviour has been measured in the present work for ^{147}Nd and ^{145}Ce (see figs. 2 and 3). Then the corresponding levels can be interpreted as the result of the coupling of the $h_{9/2}$ neutron to the octupole modes of the core. The comparison of the excitation energy of the octupole mode in the $N = 86, 87$, and 88 isotones is given in fig. 4. The octupole excitation energies of the $N = 87$ isotones are lower than the ones of their $N = 86$ cores and of some of the $N = 88$ isotones, too. This can be due to the mixing of the octupole excitation with the single-particle $\nu i_{13/2}$ excitation. Moreover, we can remark that only one structure of the parity doublet has been observed in ^{147}Nd and ^{145}Ce, contrary to the lighter isotones [5,6] which exhibit the two expected structures with the simplex quantum number $s = \pm 1$. This can be due to the experimental limitations.

An important finding of the present work is the observation of the side bands which start at 3195 and 3268 keV in ^{147}Nd and ^{145}Ce, respectively (see figs. 2 and 3). Once more we can rely on the similarity with the behaviour of the neighbouring even-even nuclei. In these nuclei, above 3 MeV excitation energy, the octupole band is no longer the negative-parity yrast band. It is crossed by another $\Delta I = 2$ band built on a 11^- state. Such a band head has been observed at 3405 keV in ^{146}Nd and at 3422 keV in ^{148}Sm and has been interpreted as a $\nu i_{13/2} \nu h_{9/2}$ state [24]. Since a similar pair breaking can be expected in the neighbouring isotopes, we propose the three-neutron configuration $\nu f_{7/2} \nu h_{9/2} \nu i_{13/2}$ for the new levels at 3195 and 3268 keV in ^{147}Nd and ^{145}Ce, respectively.

5 Summary

In the present work, new high-spin states forming three bands in ^{147}Nd, as well as in ^{145}Ce, have been established. As in the other $N = 87$ isotones, the two first structures are due to the coupling of an $h_{9/2}$ neutron to the quadrupole and octupole modes of the core. Moreover, a three-neutron $\nu f_{7/2} \nu h_{9/2} \nu i_{13/2}$ configuration has been suggested for the new side bands located above 3 MeV in ^{145}Ce and ^{147}Nd.

The Euroball project was a collaboration between France, the United Kingdom, Germany, Italy, Denmark and Sweden. This work has been supported in part by the collaboration agreement BAS-CNRS under contract No. 16946. The Euroball III experiment has been performed under U.E. contract (ERB FHGECT 980 110) at Legnaro. The Euroball IV experiment has been supported in part by the EU under contract HPRI-CT-1999-00078 (EUROVIV). We thank the crews of the tandem of Legnaro and of the Vivitron. We are very indebted to M.-A. Saettle for preparing the Pb targets, P. Bednarczyk, J. Devin, J.-M. Gallone, P. Médina, and D. Vintache for their help during the Euroball IV experiment.

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