Eur. Phys. J. A **16**, 303–307 (2003)
DOI 10.1140/epja/i2002-10127-4

The European Physical Journal A

Short Note

The strength of octupole correlations in neutron-rich Xe isotopes

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Received: 18 November 2002 /

Communicated by D. Schwalm

Abstract. Excited levels in ^{140}Xe and ^{142}Xe nuclei, populated in the spontaneous fission of ^{248}Cm, were studied by means of prompt γ-ray spectroscopy, using EUROGAM2 array. We report the first observation of an octupole band in ^{142}Xe and extend the octupole band in ^{140}Xe. Level schemes of ^{140}Xe and ^{142}Xe obtained in this work show patterns characteristic of ocupole-vibrational bands. Properties of octupole bands in Xe isotopes indicate that octupole correlations in these nuclei are lower than in the corresponding Ba nuclei. The electric dipole moment of ^{142}Xe was found to be larger than in other Xe isotopes, contrary to theoretical predictions. This may be due to the special role of the $N = 88$ neutron number.

PACS. 23.20.Lv Gamma transitions and level energies – 21.60.Cs Shell model – 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$

When a very low electric dipole moment, D_0, was observed in the ^{146}Ba nucleus [1], expected to have the largest octupole deformation in the region [2], the theory explained this as a result of a *local* cancelling of D_0 moment [3]. The D_0 moment was calculated as a sum of the volume part, nearly constant over the region, and the shell-effect part, which varies with nucleon number. This allowed the reproduction of the observed D_0 moment, which is an order of magnitude larger in the ^{144}Ba nucleus than in the neighbouring ^{146}Ba nucleus. The theory predicted further, that the D_0 moment in the ^{148}Ba nucleus should again be as large as seen in ^{144}Ba. It was a great success of the theory of octupole deformation in nuclei, when experiment [4,5] confirmed these expectations.

The theory predicted low D_0 moments for $^{138\text{-}144}$Xe isotopes, with the minimum of $D_0 = 0.01$ e fm for ^{142}Xe [3,6]. It was also predicted that D_0 should increase with neutron number [6,7]. This was partly confirmed by the first, comprehensive study of $^{138\text{-}144}$Xe isotopes, populated in the spontaneous fission of ^{248}Cm [8]. It was concluded there that, although octupole collectivity is observed in the neutron-rich Xe isotopes, octupole effects are much weaker than in Ba isotopes. There were later claims [9], that at neutron number $N = 85$ octupole correlations increase from ^{141}Ba to ^{139}Xe, but as we have shown [10] and the authors of ref. [9] admitted [11], their conclusions were based on a wrong parity assignment to the 1086 keV level in ^{139}Xe. At that stage many experimental facts indicated that octupole effects are weak in the neutron-rich Xe isotopes. Therefore, it came as a surprise when strong octupole correlations were suggested in these nuclei [12], again. The authors of ref. [12] have proposed that the low D_0 value in ^{140}Xe [8,12] is due to a *local* minimum of the D_0 moment at the neutron number $N = 86$, in analogy to the minimum observed at $N = 90$ for Ba isotopes.

If the D_0 moment in Xe isotopes has a minimum for ^{140}Xe, then in analogy to Ba isotopes, one may expect larger D_0 values for the neighbouring neutron-rich Xe nuclei. It is not the case for the ^{139}Xe [10] and ^{141}Xe [13] nuclei. One could argue, however, that these two nuclei are too close to ^{140}Xe, to show a D_0 moment significantly larger than that observed in ^{140}Xe. The ^{142}Xe nucleus is located on the $N = 88$ line, where the strongest octupole effects are observed in the lanthanides. Therefore, one may expect that detailed spectroscopic studies of this nucleus could resolve the ambiguities highlighted above. We have performed a detailed investigation of octupole correlations in ^{140}Xe and ^{142}Xe nuclei. Below we report the first observation of an octupole band in the ^{142}Xe nucleus, extend the octupole band in the ^{140}Xe nucleus and discuss octupole correlations in Xe isotopes.

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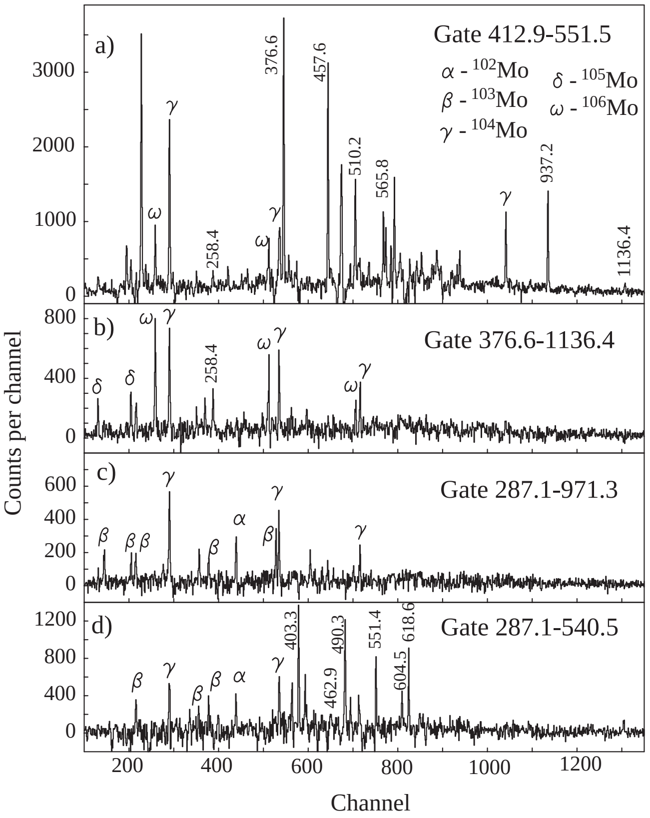

Fig. 1. Double-gated spectra of prompt-γ radiation following fission of ^{248}Cm, as obtained in the present work.

To study ^{140}Xe and ^{142}Xe isotopes we used high-fold coincidences between prompt γ-rays following the spontaneous fission of ^{248}Cm, measured with the EUROGAM2 array of anti-Compton Ge spectrometers. For more details on the experiment and data analysis see ref. [14].

Taking the γ-ray energies of ref. [8], it was a straightforward task to extend the level schemes of ^{140}Xe and ^{142}Xe. Figure 1 shows some relevant γ-ray spectra obtained by double gating on γ-γ-γ-coincidence data, which allowed identification of new excited levels in both nuclei. The double gate set on the known [8] 412.9 keV and 551.5 keV lines in ^{140}Xe, shown in fig. 1a contains transitions belonging to ^{140}Xe and to ^{104,106}Mo, the two most abundant fission fragments complementary to ^{140}Xe. In fig. 1a one can also see lines at 1136.4 keV, 937.2 keV and 258.4 keV. In fig. 1b, displaying a double gate set on the 376.6 keV and 1136.4 keV lines the 258.4 keV line appears as well. These and some further gates allow the introduction in ^{140}Xe of the 1513.0 keV level and the 655.8 keV and 543.3 keV transitions, as shown in fig. 2. The 1513.0 keV level has also been proposed in ref. [12].

Similarly, a double gate set on the known 287.1 keV and 971.3 keV lines in ^{142}Xe [8], shown in fig. 1c, contains lines belonging to ^{102,103,104}Mo, the three most abundant fission fragments complementary to ^{142}Xe. This indicates that the 971.3 keV transition feeds the 287.1 keV level in ^{142}Xe and allows the introduction of the 1258.4 keV level in ^{142}Xe. The double gate on the 540.5 keV and 287.1 keV lines shows that the 540.5 keV transition feeds the 2350.8 keV level in ^{142}Xe. These and further gates allowed to propose the partial level scheme of ^{142}Xe, as shown in fig. 3 (transitions in brackets are tentative).

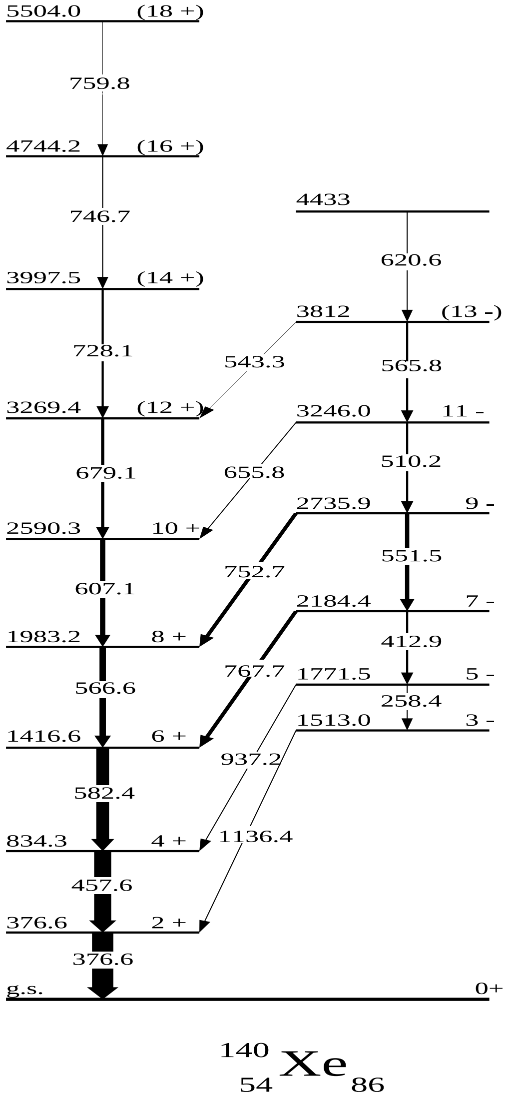

Fig. 2. Partial level scheme of ^{140}Xe, as obtained in this work.

Further discussion of the non-yrast bands in ^{140}Xe and ^{142}Xe requires determination of spins and parities. Spins and parities of levels in ^{140}Xe and ^{142}Xe were determined from angular correlations and directional-polarization measurements performed with EUROGAM2 [14,15]. The γ-γ angular correlations of the 1136.4, 937.2, 767.7, 752.7 and 655.8 keV transitions in ^{140}Xe with the stretched quadrupole transitions of the ground-state band, shown in table 1, indicate a $\Delta I = 1$ character for these transitions and therefore spins as shown in fig. 2. The linear polarization values for the 767.7 keV and 752.7 keV transitions are also shown in table 1. Together with the angular correlations, these data indicate a stretched $E1$ character for both transitions and, hence, spins and parities of $I^{\pi} = 7^{-}$ and $I^{\pi} = 9^{-}$ for the 2184.4 keV and 2735.9 keV levels, respectively. Because of the $I = 5$ and $I = 3$ spin assignment

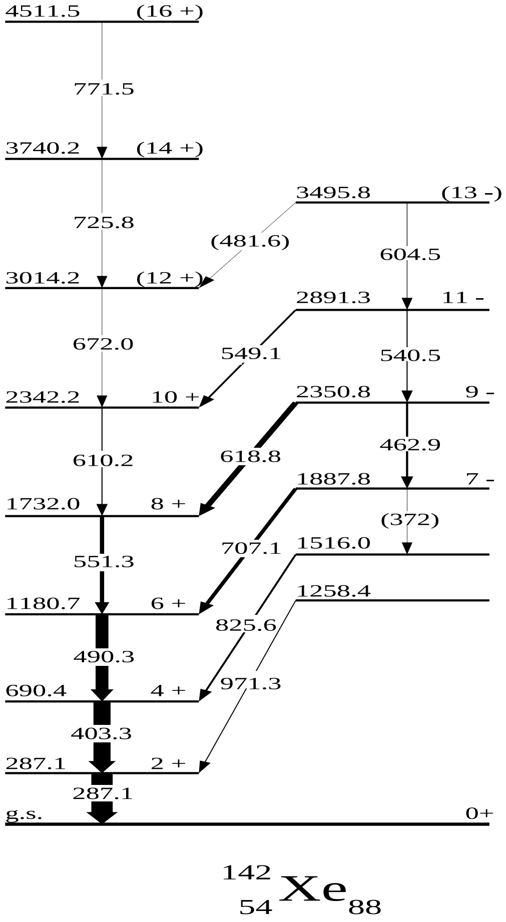

Fig. 3. Partial level scheme of ^{142}Xe as obtained in this work.

to the 1513.0 keV and 1771.5 keV levels, respectively, and due to non-observance of any half-life of these levels longer than 10 ns, we conclude that the 412.9 keV and 258.4 keV transitions are of a stretched $E2$ character. Therefore, the two discussed levels have negative parities, as has also been reported in ref. [12]. The present, direct measurement of spin value $I = 3$ for the 1513.0 keV level is an important confirmation of ref. [12], where this spin has been deduced from a half-life measurement.

Angular correlations between the 707.1 keV and 618.8 keV transitions in ^{142}Xe and the stretched quadrupole transitions of the ground-state band as well as the 462.9 keV and 540.5 keV transitions of the excited band, shown in table 1, demonstrate a $\Delta I = 1$ character of the 707.1 keV and 618.8 keV transitions and the stretched quadrupole character of the 540.5 keV transition. This indicates spins $I = 7$, $I = 9$ and $I = 11$ for the levels at 1887.8 keV, 2350.8 keV and 2891.3 keV, respectively. The linear polarization value for the 618.8 keV line indicates an electric character for this transition and, consequently, a negative parity for the 2350.8 keV level. Due to the non-observance of any half-life of the 2891.3 keV and 2350.8 keV levels, longer than 10 ns we assume that the 540.5 keV and 462.9 keV, $\Delta I = 2$ transition are of an electric character and, consequently, the 2891.3 keV and 1887.8 keV levels have negative parity. For transitions depopulating the 1258.4 keV and 1516.0 keV levels neither angular correlations nor linear polarization are available. From fig. 1c it is evident that the 1258.4 keV level is populated in fission, because of the prompt coincidence with Mo isotopes. We also know that fission populates levels up to about 700 keV above the yrast line. Therefore, the spin of the 1258.4 keV level is most likely higher than two units. Excitation energies of the 1258.4 keV and 1516.0 keV levels, which fit a regular, rotational pattern of other levels in the negative-parity band, suggest the octupole character of the two excitations and spins $I = 3$ and $I = 5$, respectively. Even without spin and parity assignment to these levels the octupole band in ^{142}Xe is firmly established in this work.

Table 1. Angular correlations and linear polarization for transitions in the ^{140}Xe and ^{142}Xe nuclei. "Sum" denotes the summed correlation with several g.s. band transitions.

$E_{\gamma 1} - E_{\gamma 2}$ (keV - keV)	A_2/A_0	A_4/A_0	$P(E_{\gamma 1})$
^{140}Xe			
1136.4 - 376.6	−0.11(2)	−0.06(4)	
937.2 - sum	−0.10(3)	0.02(4)	
937.2 - 412.9	−0.05(2)	−0.07(3)	
767.7 - sum	−0.07(3)	0.01(1)	+ 0.08(4)
767.7 - 551.5	−0.04(3)	−0.02(1)	
752.7 - sum	−0.13(2)	−0.02(1)	+ 0.16(8)
752.7 - 510.2	−0.07(2)	−0.01(3)	
655.8 - sum	−0.11(3)	0.01(4)	
^{142}Xe			
707.1 - sum	−0.14(4)	−0.02(5)	
618.8 - sum	−0.08(1)	0.02(1)	+ 0.3(1)
618.8 - 540.5	−0.10(5)	0.00(5)	

Table 2. The $B(E1)/B(E2)$ branching ratios for transitions de-exciting levels in octupole bands of ^{140}Xe and ^{142}Xe, obtained in the present work.

$E_{\mathrm{exc.}}$ (keV)	E_γ ($E1$) (keV)	E_γ ($E2$) (keV)	$B(E1)/B(E2)$ ($10^{-6}\mathrm{fm}^{-2}$)
^{140}Xe			
1771.5	258.4	937.2	0.04(1)
2184.4	412.9	767.7	0.05(1)
2735.9	551.5	752.7	0.06(1)
^{142}Xe			
1887.8	372	707.1	0.3(1)
2350.8	462.9	618.8	0.5(1)
2892.3	540.5	549.1	0.7(1)

The identification of new octupole levels in ^{140}Xe and ^{142}Xe allows more definite conclusions about the strength of octupole correlations in Xe isotopes. In table 2 we show the $B(E1)/B(E2)$ branching ratios for transitions de-exciting octupole levels in the ^{140}Xe and ^{142}Xe nuclei. Average values of the $B(E1)/B(E2)$ branching ratios, calculated from these data are $0.05(1)\times10^{-6}\mathrm{fm}^{-2}$ and $0.5(1)\times 10^{-6}\mathrm{fm}^{-2}$ for ^{140}Xe and ^{142}Xe, respectively. We note here that one observes in ^{142}Xe an increase of $B(E1)/B(E2)$ ratios by an order of magnitude, compared to lower-mass Xe isotopes.

The obtained values can be used to estimate electric dipole moments in both nuclei using the rotational formula $D_0 = \sqrt{5B(E1)/16B(E2)} \times Q_0$. The electric quadrupole moment, Q_0, needed for this calculation, has been obtained from ref. [16]. For ^{140}Xe $Q_0 = 1.80(4)$ b. For ^{142}Xe, we estimated its value from the extrapolation of the Q_0 values observed for other Xe isotopes and the $N = 88$, Ba and Ce isotones [16], adopting $Q_0 = 2.5(5)$ b. The error bar has been enlarged to account for the uncertainty of the extrapolation. Electric dipole moments calculated in this way are $D_0 = 0.03(1)$ e fm for ^{140}Xe and $D_0 = 0.10(2)$ e fm for ^{142}Xe. In a similar way we calculated D_0 moments for ^{139}Xe and ^{141}Ba nuclei, taking average $B(E1)/B(E2)$ branching ratios in these nuclei of $0.28(4) \times 10^{-6}$ fm^{-2} and $1.3(1) \times 10^{-6}$ fm^{-2}, as reported in ref. [11]. We have obtained quadrupole moments for both nuclei from interpolation between values for the neighbouring even-even isotopes [16], adopting values of $Q_0 = 1.1(3)$ b for ^{139}Xe and $Q_0 = 2.0(3)$ b for ^{141}Ba. Error bars have been enlarged to account for the uncertainty of the interpolation. With this input we obtain electric dipole moments $D_0 = 0.03(1)$ e fm for ^{139}Xe and $D_0 = 0.12(2)$ e fm for ^{141}Ba. Even with such an estimate of Q_0, one can conclude that the D_0 in ^{141}Ba is significantly larger than that in^{139}Xe. A similar difference has been observed at $N = 87$ for ^{141}Xe [13] and ^{143}Ba [5].

In fig. 4 we show the newly obtained D_0 values together with D_0 moments in other lanthanide nuclei available in the literature [5,17]. One observes a sharp decrease of the D_0 moment from Ba to Xe isotopes along the $N = 85$, 86 and 87 lines. This is not the case for $N = 88$. The D_0 moment in ^{142}Xe is comparable to that in ^{144}Ba. If the D_0 moment in ^{144}Xe is as high as in ^{142}Xe, then the scenario of a local decrease of D_0, proposed in ref. [12] holds, at least partly. If it is again low, as in ^{140}Xe then we have an interesting situation, not predicted theoretically, of a local *increase* of the D_0 moment at $N = 88$, a "magic" number for octupole correlations.

The ^{144}Xe nucleus has been studied in ref. [8]. No octupole excitations were found there. The present data also do not reveal any alternating-parity band in this nucleus at low and medium spins. Therefore, no strong octupole correlations are expected there. More definite conclusions about ^{144}Xe will require a better measurement but already now the available data indicate that, generally, there is a decrease of octupole correlations in Xe as compared to Ba nuclei. Apart from the variation in D_0 moments, there are other signatures of this decrease, as illustrated in figs. 5 and 6. In fig. 5 one observes an increase of octupole excitation energies from Ba to Xe isotopes at both $N = 86$ and $N = 88$ neutron numbers, a sign of weaker octupole correlations in Xe. In fig. 6 the quantity ω^-/ω^+ [17] is shown, which measures whether the octupole band corresponds to the octupole deformation or octupole vibrations. One notices that the two Xe isotopes deviate towards the octupole vibrational limit more than Ba nuclei.

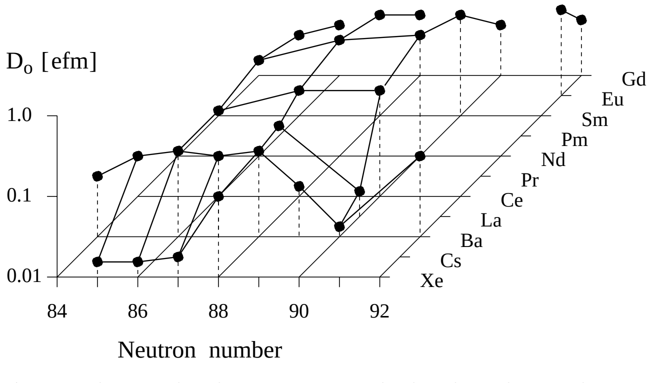

Fig. 4. Electric dipole moments in the lanthanides as obtained in this work and quoted in the literature [5,13,17].

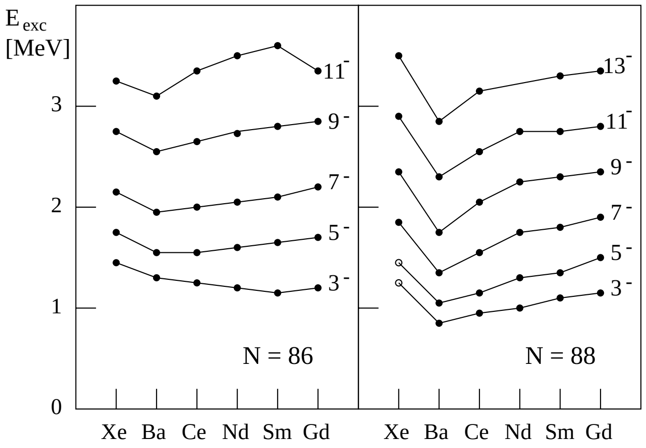

Fig. 5. Excitation energies in octupole bands of the neutron-rich lanthanide nuclei with $N = 86$ and $N = 88$ neutrons.

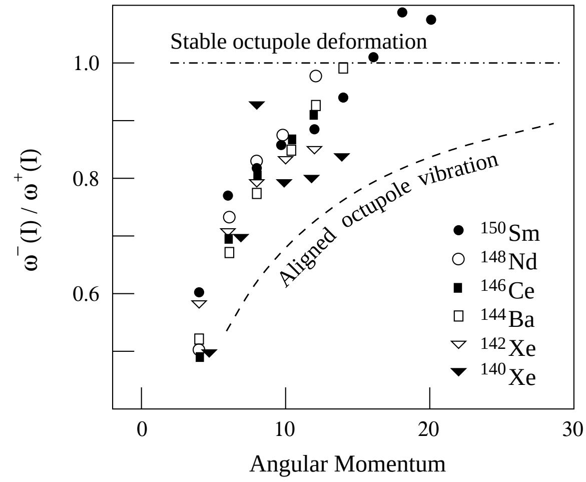

Fig. 6. Plot of ω^-/ω^+ *versus* spin, I, for the neutron-rich lanthanide nuclei.

In summary, we conclude that there is a significant decrease of octupole correlations in Xe isotopes as compared to Ba isotopes. The exception appears to be the ^{142}Xe nucleus, where we have found an electric dipole moment as large as in ^{144}Ba. It is of a great interest to measure the D_0 moment in the ^{144}Xe. If it is small, as suggested both by theory and experiment, then there is a local increase of the D_0 moment in ^{142}Xe, probably due to the special role of the $N = 88$ neutron number in generating octupole correlations.

This work was supported by the Polish Research Council, KBN, under grant no. 2P03B02622, by the SERC of the UK under grant no. GRH71161 and by the US Department of Energy under contract no. W-31-109-ENG-38. The authors are also indebted for the use of ^{248}Cm to the Office of Basic Energy Sciences, US Department of Energy, through the transplutonium element production facilities at the Oak Ridge National Laboratory.

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