Octupole Vibration and Influence of Shell Effects on the $E1$ Transition Rates in ^{140}Xe

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Spectroscopic studies of the β decay of ^{140}I have firmly established octupole collectivity in ^{140}Xe and evinced unique theoretical predictions of a quenched dipole moment. The first detailed investigations of an exotic Xe nucleus, including measurements of half-lives of levels in the ground and octupole bands, were made possible due to a new approach to produce beams of iodine with ISOL sources. [S0031-9007(99)09362-X]

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The low-energy structures of multifermion nuclear systems comprising of an even number of protons and neutrons can be largely described by collective degrees of freedom. These are dominated by the reflection symmetric quadrupole mode, while the reflection asymmetric octupole mode of excitation, when present, is much weaker. Consequently, the experimental information and systematics on properties of the negative parity bands, related to the latter mode of excitation, are quite limited. Octupole collectivity [1–5] is pronounced only in certain regions of the nuclear chart, just above the closed shells of heavy nuclei, where nuclei have only a few valence neutrons and protons and the competing quadrupole collectivity is weak. These regions, which provide the bulk of experimental data on the octupole mode, are associated with the filling of the unique parity orbitals, see, e.g., Refs. [6,7]. For the neutron-rich region above the doubly magic ^{132}Sn, the predicted [6], strong octupole collectivity has been verified experimentally [8] in several cases. Recent theoretical works [7,9] have explored the limits of octupole correlations, and suggest that the Xe ($Z = 54$) isotopes form the lower boundary of octupole collectivity, with ^{142}Xe being the most octupole soft of the $^{138-148}$Xe nuclei. Until now, it has been unclear whether the theoretical predictions for the Xe isotopes were in fact accurate.

Although atomic nuclei do not in general possess $E1$ moments, sizable moments of this type are associated with octupole collective states. The nuclide ^{140}Xe is, however, predicted [9,10] to exhibit a quenching of the dipole moment associated with the octupole correlations, similar in nature to the case of ^{146}Ba [8,11]. This prediction is of particular significance. Previous observations of the quenching of the dipole moments, a unique phenomenon that has been identified in only two cases, in ^{146}Ba and ^{224}Ra, have preceded the theoretical explanations. Current theoretical calculations [9,10] predict only one additional occurrence of dipole moment quenching: the Xe isotopes centered at ^{140}Xe. This nucleus thus constitutes a critical testing ground for a unique result of the theoretical studies; a result which is intimately linked to the basic parameters of the models being used.

Previous experimental work [12–14] has given much new information on the $^{138-144}$Xe nuclei, but has not been able to positively identify any octupole states. For ^{140}Xe, the ground state band was established up to the 16^+ level (with some degree of uncertainty for the higher-spin members), and one of the side bands observed was suggested to be an octupole band. We have performed a study of ^{140}Xe levels as populated in the decay of ^{140}I. The aim has been to identify the lower members of the first few excited bands and rigorously assign level parities and angular momenta. Crucial to the parity determination have been measurements of the relatively weak conversion electron lines of transitions in the ~1 MeV region. Equally important was the use of the $\beta\gamma\gamma(t)$ method [15] for direct measurements of level lifetimes in order to deduce the strengths of the intraband $E2$ transitions and to verify the possible quenching of the $E1$ transition rates as suggested independently by Butler and Nazarewicz [10] and by Martín and Robledo [9].

The data obtained are quite extensive, and a full report on the ^{140}I decay will be given elsewhere [16]. At least two low-lying collective bands were found in addition to the ground band. In the present paper we confirm the octupole nature of the band suggested by Bentaleb *et al.* [12,13] and focus on the observation of shell effects on the $E1$ rates of transitions between the octupole and the ground state bands. Furthermore, the ground state quadrupole collectivity has been clarified from the accurate measurement of the 2_1^+ level lifetime.

The ^{140}I activity was obtained as a mass separated fission product from thermal neutron-induced fission using the OSIRIS ISOL facility [17] at Studsvik. Prior to the present experiments, studies of exotic I isotopes have been severely hampered by the very strong production of isobaric Cs, due to the highly efficient surface ionization of the latter element. This problem was overcome by selecting doubly charged ions of $A = 140$, created by electron impact ionization [17], which suppressed the Cs contamination by a factor of at least 10^2 in comparison with the singly charged case. No activities other than the $A = 140$ isobars were present in the doubly charged beam.

The singles spectra of γ rays following the decay of ^{140}I were studied using both large volume and low-energy photon Ge spectrometers, employing a multispectrum technique to identify the half-lives of individual γ lines. A moving tape system was used to repetitively remove the "old" sources collected on the tape. The rather short half-life of ^{140}I (0.9 s), as compared with the other $A = 140$ isobars, permitted easy identification of some 80 γ rays in ^{140}Xe, with energies up to about 2.8 MeV. We found no evidence for transitions in ^{139}Xe that could follow from the β-delayed neutron decay of ^{140}I. A majority of the observed transitions were placed in a decay scheme constructed using coincidence relations observed in a $\gamma\gamma$-coincidence measurement. A partial level scheme, relevant for the present discussion, is shown in Fig. 1.

An additional dual multispectrum experiment was made using a Ge detector and a high resolution Si(Li) detector (cooled to liquid nitrogen temperature) to simultaneously measure γ rays and conversion electrons. Partial results of the conversion electron measurements are given in Table I, and a section of the electron spectrum is shown in Fig. 2.

Level lifetimes were measured using a triple coincidence system [15] consisting of a plastic scintillator for β particles and a BaF_2 and a coaxial Ge detector for γ rays. Fast timing coincidences between the plastic scintillator and the BaF_2 crystal were gated by slower events obtained between the plastic scintillator and the Ge detector, thereby giving a means for selecting specific levels for the lifetime analysis. A crucial time calibration of the BaF_2 detector was obtained using a few calibration sources. Levels of particular interest here are the 1513 and 1772 keV states and the members of the ground state band.

Specifically, the lifetime of the 2_1^+ level was determined both by a centroid-shift method and by slope fitting. The centroid shift was determined by gating on the β detector, and on the 376 and 457 keV γ lines in the BaF_2 and the germanium detector, respectively, and then reversing the γ gates to find the shift in the centroid position. For slope fitting (see Fig. 3), a sum of time distributions, selected by germanium gates on the 927, 1136, 1194, 1587, and 1765 keV transitions, was used. The two methods yielded half-lives of 70.5(22) and 70(5) ps, respectively. The 4_1^+ level lifetime was determined with the centroid-shift method with gates on the β detector, and on the 457 keV transition in BaF_2 and the 376, 998, 1049, 2377, and 2413 keV transitions in the germanium detector. The gate on the 376 keV line is corrected for lifetimes of transitions feeding the 4^+ level (79% of the feeding intensity consists of transitions with lifetimes that were measured and could therefore be properly subtracted, whereas the transitions of higher energy, which constitute the remaining 21%, are effectively prompt). All higher excited states of interest here decay to either the 2_1^+ or 4_1^+ levels, and their half-lives were determined from the centroid shifts of the transitions deexciting these two levels when gating in Ge on the γ ray from the higher excited state. See Ref. [16] for further details on the fast timing analysis. A summary of the level half-lives obtained and of the deduced transition rates is given in Table II.

The previous experimental information on the excited states of ^{140}Xe is almost entirely based on studies of prompt γ rays following spontaneous fission. In these studies it was suggested that one band could be of octupole origin. Additional data on level lifetimes and parities were crucial for clarifying the nature of states and to identify collective bands, in particular for a nucleus such as ^{140}Xe that lacks well-developed rotational collectivity.

Specifically, several levels of the ground band have been proposed from the spontaneous fission studies [13].

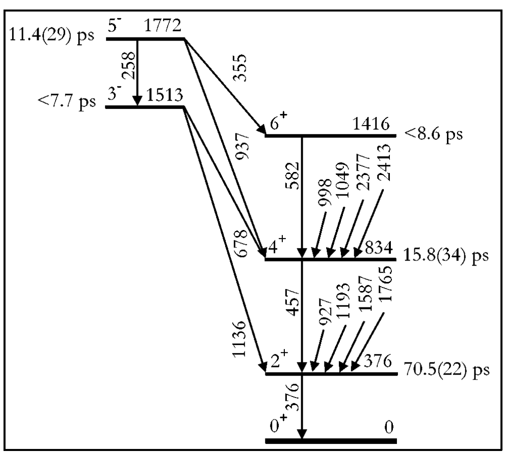

FIG. 1. Partial level scheme of ^{140}Xe illustrating the γ-ray decay of the octupole band. The 3^- (observed here for the first time) and 5^- levels of this band are well populated in the β decay of 4^- ^{140}I. The spins and parities shown are firmly supported by our conversion electron data. All level half-lives are from this work. Additional members of both bands shown here were reported in Ref. [13] although that work could not identify the octupole character of the excited band. Of special importance is the fact that the 258 and 937 keV transitions are of $M1/E2$ and of parity changing $E1$ multipolarity, respectively. This leads to unique assignments of parity and angular momenta for the negative parity states. A number of strong transitions used as gates in the half-life determination are schematically indicated by short arrows.

TABLE I. Experimental and theoretical conversion coefficients for selected transitions in ^{140}Xe. The $E1$ character of the 355.0 and 937.4 keV transitions was crucial for the identification of the octupole band.

		Theoretical α_K			
Transition	Empirical α_K	$E1$	$E2$	$M1$	Multipolarity
258.6	0.078(7)	0.03	0.055	0.053	($M1$ or) $E2$
355.0	<0.007	0.006	0.02	0.023	$E1$
376.7	0.018(1)	0.005	0.018	0.02	$E2$
457.7	0.0085(5)	0.003	0.012	0.0095	($M1$ or) $E2$
582.4	0.0046(14)	0.0018	0.005	0.0065	$E2$
937.4	0.00057(20)	0.0007	0.0017	0.0023	$E1$

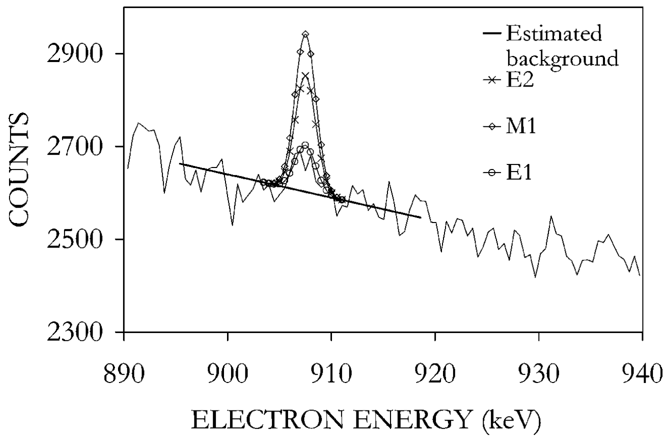

FIG. 2. A section of the conversion electron spectrum showing the weak K line of the 937 keV transition. The expected peak size, as derived from theoretical conversion coefficients for different multipolarities, is shown with symbols. The experimental data is compatible only with an $E1$ multipolarity.

The first few of these are well established on grounds of the transition intensities. Our results for transition multipolarities and transition strengths fully confirm the collective nature of the band up to the 1417 keV 6^+ level, which is the highest one observed by us in that band. Our value for the half-life of the 2_1^+ level, 70.5(22) ps, is almost a factor of 2 lower than the preliminary value of 113(5) ps from a survey by Cheifetz *et al.* [18], and brings the $B(E2; 2^+ \rightarrow 0^+)$ of ^{140}Xe into agreement with the systematics of Grodzins (as quoted by Raman *et al.*) [19] as well as with the global systematics of Raman *et al.* [19]. Our deduced $B(E2; 2^+ \rightarrow 0^+)$ and Q_0 of 24.9(8) W.u. and 2.32(4) e b, respectively, are typical of vibrational nuclei in this region. The quadrupole deformation parameter β_2 is obtained as 0.146(3), which is near the upper boundary of predictions [7,9,10].

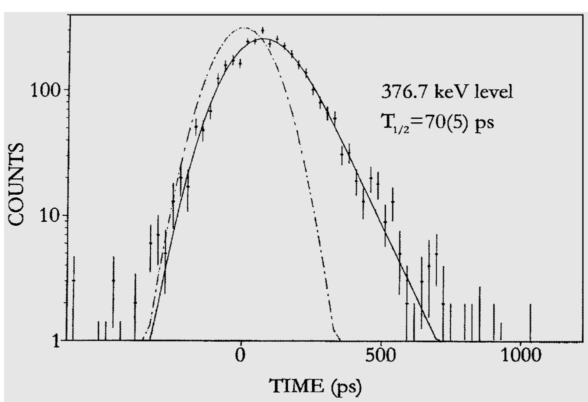

FIG. 3. A time-delayed spectrum with a slope due to the half-life of the 2_1^+ level. The dashed and solid lines represent the prompt Gaussian response function and the χ^2 fit to the spectrum, respectively. See the text for details.

Our β-decay data also show that the new level at 1513 keV and the level at 1772 keV observed previously [13] can be firmly identified as the spin 3 and 5 members of a collective band having a negative parity. Thus, we agree with Bentaleb *et al.* concerning the octupole nature of the 5^- state. The parity is given by the $E1$ multipolarities of the relatively strong 355 and 937 keV transitions depopulating the higher level. Additionally, the internal conversion data gave a $M1$ or $E2$ multipolarity for the connecting transition of 258 keV. The level lifetime and γ-ray branching show that this intraband transition has a $B(E2)$ value [37(10) W.u.] comparable to that of the ground band.

The relatively low excitation energies of the first band members, too low to originate from noncollective excitations, imply that the band is of octupole origin. It is thereby the first firmly identified octupole structure observed in the neutron-rich xenon isotopes, and constitutes the first experimental verification that octupole collectivity occurs at modest excitation energies already at $Z = 54$. The energy of the 3^- level of ^{140}Xe is actually comparable to that of the $Z = 56$ isotope ^{142}Ba. The 1^- band head can be expected near 1350–1400 keV, assuming a reasonably regular band structure. Our data show no indications for such a level, probably due to its very low population in the β decay of ^{140}I. The significant β-particle population of the 2^+, 4^+, and 6^+ levels of the ground band is compatible only with $J^\pi = 4^-$ for the β-decaying state of ^{140}I. The relatively strong β transitions observed to the 3^- and 5^- states are thus of the allowed Gamow-Teller type. Note that previous information on the decay properties of ^{140}I is very limited [20].

The $E1$ transition rates deduced from the half-lives of the 3^- and 5^- levels, Table II, are exceptionally low. For ease of comparison it is convenient [10] to express the $E1$ strength in terms of the intrinsic dipole moment D_0. The deduced values of D_0 in ^{140}Xe are in the range 0.019 to 0.023 e fm and thus comparable to the lowest observed in the regions of octupole correlations. [Note that the significantly revised value of $B(E2; 2^+ \rightarrow 0^+)$ has implications on the previous attempts [13] at extracting the intrinsic dipole moment from the reduced

TABLE II. Level half-lives and reduced transition probabilities for selected transitions in ^{140}Xe.

Level (keV)	Transition (keV)	γ intensity	$T_{1/2}$ (ps)	$B(\lambda)$ (W.u.)
376	376.7	98.2(1)	70.5(22)	24.9(8)
834	457.7	68.3(36)	15.8(34)	40(9)
1416	582.4	9.3(6)	<8.6	>19.7
1513	678.7	1.7(2)	<7.7	$>2.91 \times 10^{-5}$
1513	1136.7	4.4(5)	<7.7	$>1.58 \times 10^{-5}$
1772	258.6	0.7(1)	11.4(29)	37(10)
1772	355.0	1.3(1)	11.4(29)	$3.1(8) \times 10^{-5}$
1772	937.4	18.8(11)	11.4(29)	$2.4(6) \times 10^{-5}$

transition probabilities via rotational model formulas.] Both macroscopic and microscopic contributions play a role in the dipole moment, but the macroscopic contribution is not expected [6,10] to be significant outside the actinide region. The very low values of D_0 should thus be attributed to a vanishing microscopic part, which has separate contributions from neutrons and protons. These contributions vary strongly as a function of the respective particle numbers (see illustration in Ref. [11]), reflecting the filling of the shells. Measured $E1$ rates in ^{146}Ba [11] showed that this nucleus had a drastically smaller dipole moment than those of neighboring nuclei, which was explained [7,10] as being due to a cancellation resulting from the variations mentioned above. The first predictions of a quenched dipole moment, performed within the same theoretical frameworks, locate it at the very onset of octupole correlations, in the $Z = 54$ Xe isotopes. The self-consistent calculations of Martín and Robledo [9] show a sharp minimum of $D_0 = 0.01$ e fm at ^{140}Xe, whereas the shell correction approach [10] gives low values of $|D_0| \leq 0.04$ e fm over a range of the heavy Xe isotopes. In both cases, the predictions are of a different order of magnitude than for the nearby barium nuclei and other nuclei in this region. For comparison, ^{142}Ba has a quadrupole collectivity and general structure similar to ^{140}Xe, but its dipole moment of $\sim$0.2 e fm is a factor of 10 higher than for ^{140}Xe. Our single datum at ^{140}Xe cannot distinguish between the slightly different predictions of self-consistent and shell correction calculations, but does provide a verification of the correctness of the physical assumptions underlying the calculations.

In summary, exceptionally low $B(E1)$ rates have been measured for ^{140}Xe, corresponding to a dipole moment among the lowest observed in the regions of octupole collectivity. It represents the first verification of predicted quenching of the dipole moment in an atomic nucleus. The experimental results on the β decay of ^{140}I have been possible due to a novel technique for the extraction of highly pure I beams. It represents a breakthrough event that will open up detailed studies of a whole class of nuclei, namely, those populated in the decay of neutron-rich I and Br that previously were inaccessible. This technique was applied here for the first time. The β decay of ^{140}I (the I^π of which was deduced as 4^-) has been studied in detail for the first time, resulting in a firmly established negative parity of the low-lying octupole band suggested by Bentaleb *et al.* Furthermore, this study has drastically improved the evidence for a relatively low-lying octupole band in ^{140}Xe. The new data have established ^{140}Xe as the nearest octupole collective nucleus to the doubly magic ^{132}Sn. The 2_1^+ half-life determination represents a correction of a previous, tentative, result and restores agreement with systematics for the dynamic quadrupole deformation of the ground band, which is crucial for the interpretation of the $B(E1)/B(E2)$ ratios measured in prompt fission experiments as well as for model calculations for the Xe nuclei.

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