High-spin states in ^{135}Xe

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(Received 22 February 2007; published 18 May 2007)

The high-spin structure of the ^{135}Xe isotope was studied via prompt γ-ray spectroscopy in two different experiments: (i) as a fission fragment following the fission of the ^{226}Th compound nucleus formed in a fusion-fission reaction and (ii) as an evaporation residue in the ^{136}Xe$(n, 2n\gamma)^{135}$Xe reaction. The level scheme above the previously known $11/2^-$ isomer was established up to 3170-keV excitation energy. A strong sequence has been firmly assigned to ^{135}Xe and forms the yrast decay path including the $(15/2^-)$ and $(19/2^-)$ states. A much weaker sequence of γ rays has been observed and tentatively assigned to ^{135}Xe and is a candidate for the off-yrast sequence that includes the $(13/2^-)$ and $(17/2^-)$ states, expected in the weak coupling of the $h_{11/2}$ neutron to the even-A core. The experimental results are compared with predictions from shell-model calculations.

DOI: 10.1103/PhysRevC.75.054322 PACS number(s): 23.20.Lv, 27.60.+j, 25.40.−h, 28.20.−v

I. INTRODUCTION

The study of high-spin states in isotopes with $N \sim 82$ is of interest in order to enrich our knowledge in the vicinity of the $N = 82$ magic number. In particular, the high-spin level structure of the $^{135}\text{Xe}^{81}_{54}$ isotope with only one neutron hole in the $N = 82$ shell is very interesting because of the relatively limited number of single-particle configurations available for the construction of these levels. So far, the low-lying level information that exists for ^{135}Xe [1] was obtained in β-decay measurements and in single-nucleon pickup reactions.

At low excitation energies, ^{135}Xe is expected to have several states that originate from the coupling of single neutron-hole states to the phonon vibrations of the neighboring even-even core. The previously known $11/2^-$ isomer (527 keV, 15.29 min) is such a state that originates from the odd neutron occupying the $h_{11/2}$ orbital and is the highest spin known so far in this isotope [1] (the highest spin positive-parity state known is the 1781-keV level, but the 11/2 spin assignment is not firm). The high-spin level structure above the $11/2^-$ isomer remains unknown [1], although lower spin states are known up to ~2.5-MeV excitation energy.

Investigation of high-spin states in ^{135}Xe is very important for comparison with shell-model calculations [2,3]. Shell-model calculations in ^{135}Xe [2] predict the first high-spin excited states above the isomer at ~1450-, 1580-, and 1900-keV excitation energies ($15/2^-$, $13/2^-$, and $19/2^-$ states, respectively, in Fig. 3 of Ref. [2]). Such investigations contribute to our understanding of the interaction of the single valence neutron in a high-j orbital with the spherical core.

The shortage of information on high-spin states for ^{135}Xe is mainly due to the difficulty of studying this isotope as an evaporation residue in heavy-ion fusion reactions. The lack of suitable stable beam-target combinations is due to the proximity of ^{135}Xe to the line of stability. An alternative way to study this isotope would be the prompt γ-ray spectroscopy of fission fragments in fusion-fission reactions of much heavier nuclei. Such methods have been used several times recently to collect information on high-spin states of nuclei near the line of stability (see, for instance, Ref. [4] and references therein). Because of its proximity to the line of stability, ^{135}Xe can be populated as a fission fragment in such reactions. This method was used here together with the population of ^{135}Xe in a different experiment as the $x = 2$ channel in (n, xn) reactions on stable ^{136}Xe.

II. EXPERIMENTS

The beam for the fusion-fission experiment described in this work was provided by the 88-in. cyclotron facility at Lawrence Berkeley National Laboratory. The Gammasphere array was used to detect prompt-time coincidences between γ rays. Gammasphere comprised 100 Compton-suppressed large-volume high-purity Ge detectors. The ^{226}Th compound nucleus was populated in the ^{18}O+^{208}Pb reaction at 91 MeV, and the target was 45 mg/cm^2 in areal density. About 2.5×10^9 four-fold γ-ray coincidences were collected in the experiment. A symmetrized, three-dimensional cube was constructed to investigate the coincidence relationships between the γ rays.

The (n, xn) experiment described in this work was performed at the Los Alamos Neutron Science Center Weapons Neutron Research (LANSCE/WNR) facility [5]. The γ rays were produced in the neutron bombardment of a ^{136}Xe gas target contained in an aluminum cell and were observed with the GEANIE spectrometer [6]. GEANIE is located 20.34 m

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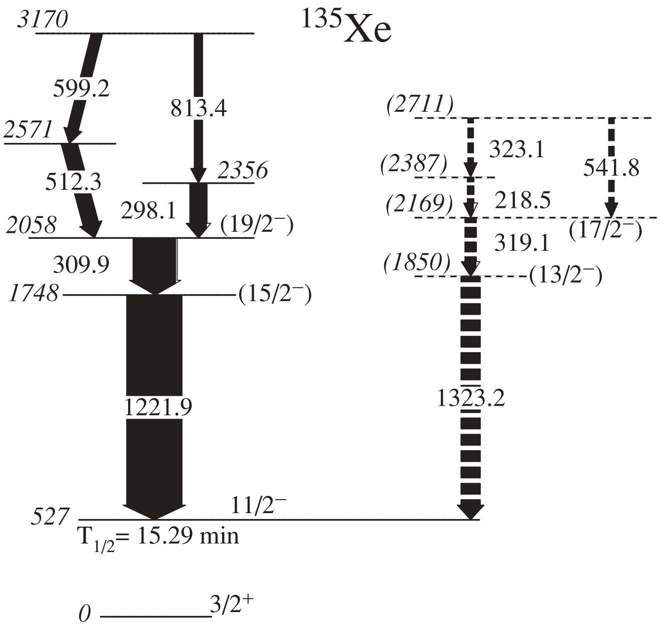

FIG. 1. Level scheme assigned to ^{135}Xe in the present work. Transition and excitation energies are given in keV. Arrow width represents transition intensity. Assignment of the weaker sequence on the right is still tentative (see text).

from the WNR spallation neutron source on the 60R (60°-right) flight path. The neutrons were produced in a ^{nat}W spallation target driven by an 800-MeV proton beam with a time structure that consists of 625-μs-long "macropulses," with each macropulse containing subnanosecond-wide "micropulses," spaced every 1.8 μs. The energy of the neutrons was determined using the time-of-flight technique. GEANIE is comprised of 11 Compton-suppressed planar Ge detectors

TABLE I. Energies, intensities, excitation energies, and spin-parity assignments of transitions assigned to ^{135}Xe in the present work.

Energy[a] (keV)	Intensity (%)	E_i (keV)	J_i^π	→	J_f^π
218.5[b]	11(3)	2387		→	$(\frac{17}{2}^-)$
298.1	30(5)	2356		→	$(\frac{19}{2}^-)$
309.9	77(7)	2058	$(\frac{19}{2}^-)$	→	$(\frac{15}{2}^-)$
319.1[b]	20(6)	2169	$(\frac{17}{2}^-)$	→	$(\frac{13}{2}^-)$
323.1[b]	3(1)	2711			
512.3	28(6)	2571		→	$(\frac{19}{2}^-)$
541.8[b]	<1	2711		→	$(\frac{17}{2}^-)$
599.2	20(6)	3170			
813.4	15(4)	3170			
1221.9	≡100	1748	$(\frac{15}{2}^-)$	→	$\frac{11}{2}^-$
1323.2[b]	35(9)	1850	$(\frac{13}{2}^-)$	→	$\frac{11}{2}^-$

[a]Uncertainty on γ-ray energies varies from 0.4 to 0.9 keV.
[b]Assignment to ^{135}Xe is tentative (see text).

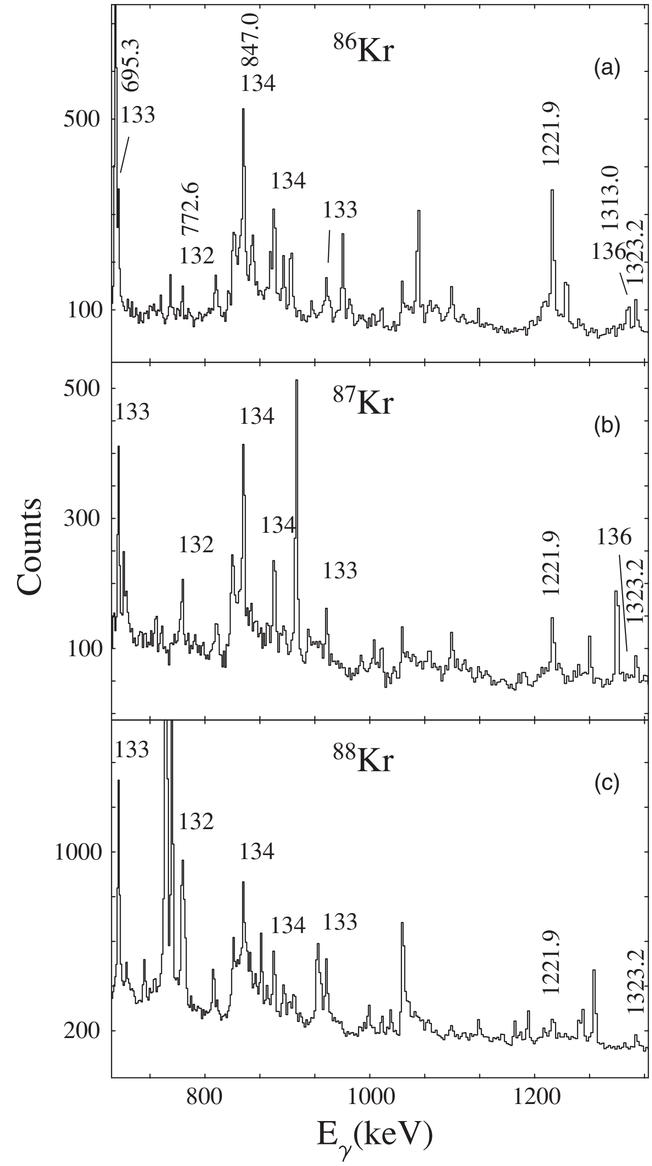

FIG. 2. Spectra gated on known transitions of ^{86,87,88}Kr [7–9] obtained in the fusion-fission experiment. Specifically, the spectra are double gates between the following transitions: (a) ^{86}Kr spectrum, between 1564.7- and 685.3-keV transitions, (b) ^{87}Kr spectrum, between 1419.7- and 421.5-keV transitions, and (c) ^{88}Kr spectrum, between 775.3- and 868.6-keV transitions. The 1221.9-keV transition assigned to ^{135}Xe can be clearly seen together with the 1323.2-keV transition that has been tentatively assigned to ^{135}Xe in the present work. Peaks of the other complementary ^{A}Xe isotopes are indicated by the number A. Peaks used to obtain the intensity ratios (shown in Fig. 3, see text) are additionally indicated in (a) by the transition energy (772.6 keV, ^{132}Xe [10]; 695.3 keV, ^{133}Xe [11]; 847.0 keV, ^{134}Xe [12]; 1313.0 keV, ^{136}Xe [13]). Additional transitions indicated only by A are the 947.8-keV transition of ^{133}Xe [11] and the 884.1-keV transition of ^{134}Xe [12].

(low-energy photon spectrometers, LEPSs), nine Compton-suppressed coaxial Ge detectors, and six unsuppressed coaxial Ge detectors. A total of ~2×10^8 γ singles and higher-fold data were recorded.

III. EXPERIMENTAL RESULTS

The present work is the first spectroscopic study of high-spin states above the previously known $11/2^-$ (527 keV, 15.29 min) isomer of ^{135}Xe. Six new transitions have been placed above the $11/2^-$ isomer, establishing the high-spin level scheme up to ∼3.2-MeV excitation energy. A second weaker sequence of four new transitions has been tentatively assigned to ^{135}Xe and placed in the level scheme above the isomer. The level scheme of ^{135}Xe deduced in the present work is shown in Fig. 1. The transitions in Fig. 1 and their measured intensity from the fusion-fission experiment are listed in Table I.

In the fusion-fission experiment, coincidences were established between the 1221.9-keV transition and previously known transitions of the complementary fission fragments ^{86,87,88}Kr [7–9] (from the 5, 4, and 3 neutron channels, respectively). The 1221.9-keV transition can be seen in Fig. 2, where spectra gated on ^{86,87,88}Kr are shown. In the same spectra, the weak 1323.2-keV transition can also be seen, which supports the assignment of this transition to a Xe isotope. The ratios of γ-ray intensities, observed in the ^{86,87}Kr-gated spectra in Fig. 2, for transitions in the known Xe isotopes, are summarized in Fig. 3, as well as the ratio for the 1221.9- and 1323.2-keV transitions. The ratio for

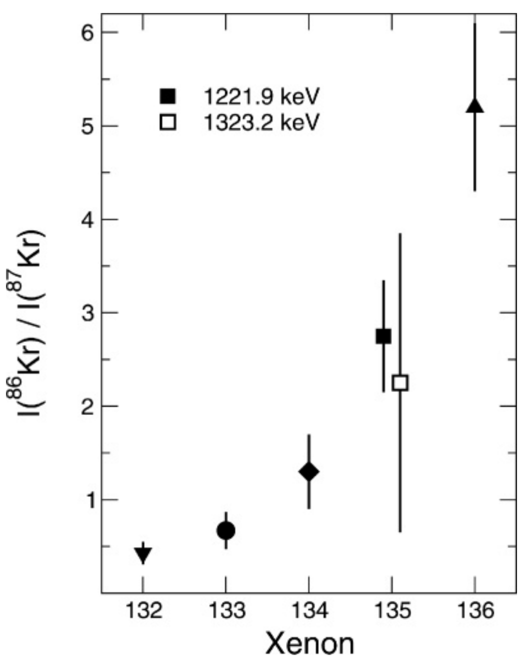

FIG. 3. Ratios of intensities of transitions in Xe isotopes observed in spectra gated on ^{86}Kr [Fig. 2(a)] and ^{87}Kr [Fig. 2(b)] obtained in the fusion-fission experiment. The known transitions in ^{132}Xe [10] (772.6 keV, reversed triangle), ^{133}Xe [11] (695.3 keV, circle), ^{134}Xe [12] (847.0 keV, diamond), and ^{136}Xe [13] (1313.0 keV, triangle) were used, together with the 1221.8-keV transition assigned to ^{135}Xe (filled square) and the 1323.2-keV transition tentatively assigned to ^{135}Xe (open square). The ratio for the 1221.8-keV transition, intermediate between values for ^{134}Xe and ^{136}Xe, supports this assignment. The ratio for the 1323.2-keV transition is also intermediate between values for ^{134}Xe and ^{136}Xe; however, because this transition is weak, the error on the ratio is rather large, preventing a definite assignment.

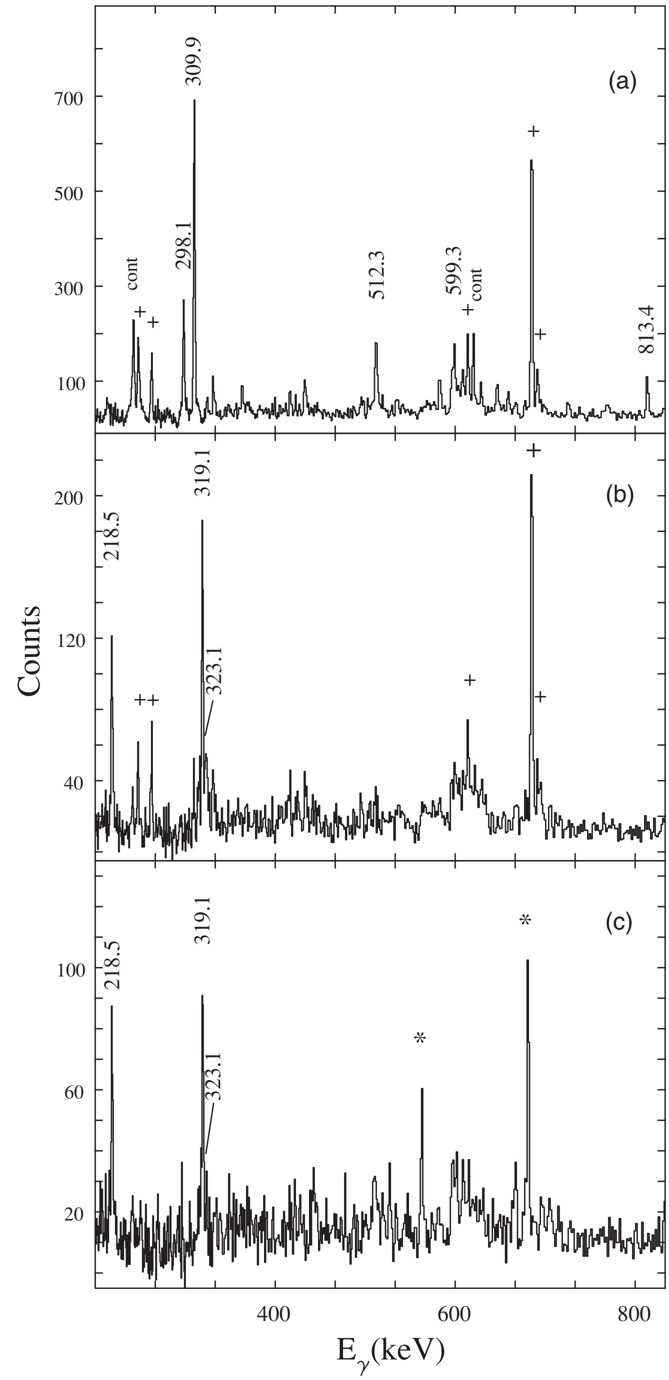

FIG. 4. Example of typical spectra of transitions assigned to ^{135}Xe in the present work and obtained in the fusion-fission experiment. (a) Double gate on 1221.9-keV transition of ^{135}Xe, and 1564.7-keV transition of ^{86}Kr [7] complementary fragment; all new transitions above 1748 keV in Fig. 1 are clearly indicated; other known ^{86}Kr transitions are indicated by "+", while transitions from other isotopes (contaminants) are indicated by "cont." (b) Double gate on 1323.2-keV transition assigned tentatively to ^{135}Xe, and 1564.7-keV transition of ^{86}Kr [7] complementary fragment, and other known ^{86}Kr transitions (+). (c) Same as (b), but with the 1577.6-keV transition of ^{87}Kr [8] complementary fragment and other known ^{87}Kr transitions (*). All new transitions above 1850 keV in Fig. 1 are clearly indicated in both (b) and (c). Transition energies are in keV.

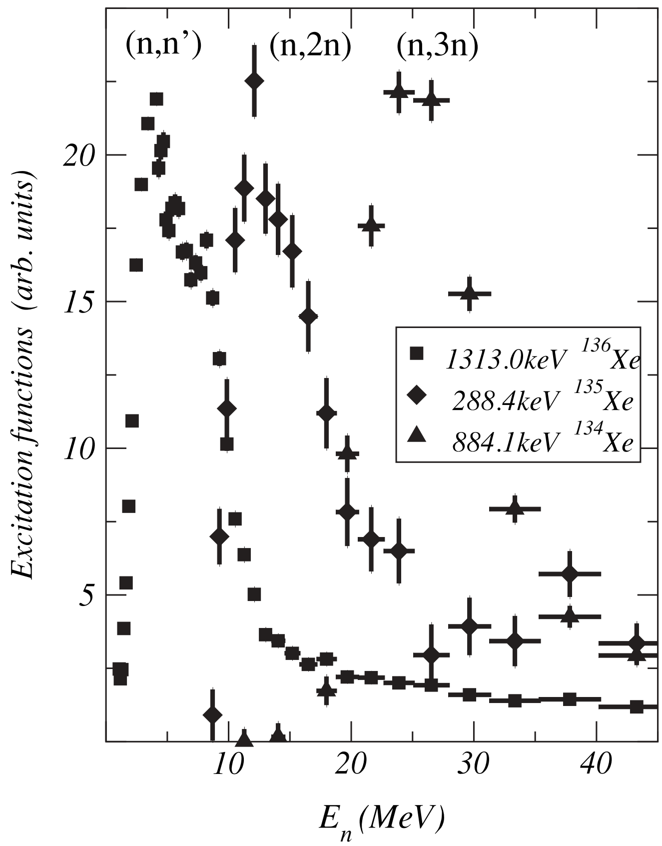

FIG. 5. Examples of excitation functions for neutrons with energies up to 45 MeV deduced in the (n, xn) experiment for previously known transitions of ^{134}Xe [12] [the $(n, 3n)$ reaction channel], ^{135}Xe [1] [the $(n, 2n)$ reaction channel], and ^{136}Xe [13] [the (n,n′) reaction channel]. The 884.1-keV, $4^+ \rightarrow 2^+$ transition of ^{134}Xe (triangles); 288.4-keV, $\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$ transition of ^{135}Xe (diamonds); and 1313.0-keV, $2^+ \rightarrow 0^+$ transition of ^{136}Xe (squares) are shown.

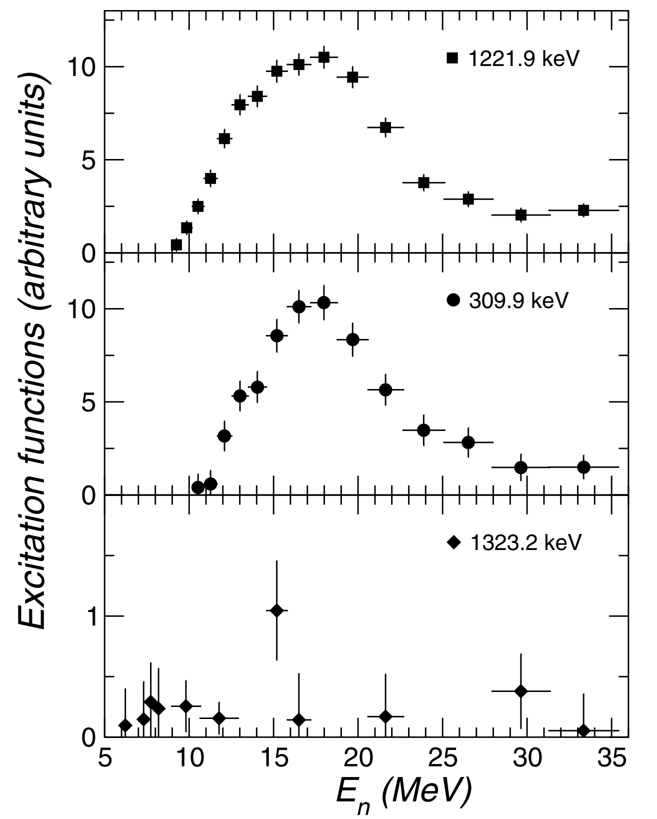

FIG. 6. Excitation functions for neutrons with energies up to 36 MeV deduced in the (n, xn) experiment for the 1221.9- (squares) and 309.9-keV (circles) transitions assigned to ^{135}Xe in the present work and the 1323.2-keV transition (diamonds) tentatively assigned to ^{135}Xe in the present work.

the 1221.9-keV transition, intermediate between the values for ^{134}Xe and ^{136}Xe, supports the isotopic assignment to ^{135}Xe. Because of the large error on the ratio obtained for the weak 1323.2-keV transition, an assignment to ^{135}Xe can be tentatively suggested for this transition without entirely excluding the possibility of an assignment to ^{134}Xe. The other transitions assigned (tentatively or not) to ^{135}Xe can be seen in the gated spectra in Fig. 4.

The assignment of the 1221.9- and 309.9-keV transitions to ^{135}Xe was deduced independently in the (n, xn) experiment, where the excitation functions for these transitions were obtained versus neutron energy. Examples of typical excitation functions obtained for previously known transitions of ^{134,135,136}Xe in the (n, xn) experiment are shown in Fig. 5. As shown in Fig. 5, a typical excitation function for a transition of ^{136}Xe [the (n, n') reaction channel] peaks at neutron energies $E_n < 10$ MeV; that of ^{135}Xe [the $(n, 2n)$ reaction channel] peaks at neutron energies between 10 and 20 MeV, and so on. The excitation functions for the 1221.9- and 309.9-keV transitions are shown in Fig. 6, and both exhibit the typical characteristics of transitions in the ^{136}Xe$(n, 2n)$ reaction channel, confirming their assignment to ^{135}Xe. All the other transitions in Fig. 1 are much weaker than the 1221.9- and 309.9-keV transitions and were not observed in the (n, xn) experiment, probably because of insufficient statistics (see, for example, the excitation function obtained for the 1323.2-keV transition in Fig. 6). Hence, the assignment to ^{135}Xe of the 1323.2-keV transition, as well as the whole sequence built above this transition in Fig. 1, remains tentative.

Spin and parity assignments of all levels reported in this work are difficult to deduce experimentally because of the lack of directional correlation information for the fission products in the fusion-fission experiment and insufficient statistics in the (n, xn) experiment. The only experimental deduction is that the spin of the 2058-keV level is likely higher than that of the 1748-keV level, supported by the fact that the threshold of the excitation function of the 309.9-keV transition in Fig. 6 is ~1 MeV larger than the threshold for the 1221.9-keV transition in the same figure. Given that the excitation energy difference between these two levels is only 310 keV, the 1-MeV threshold difference could be attributed to a higher spin of the higher level.

Based on the comparison with probable assignments for the first high-spin excited states above the corresponding $11/2^-$ isomers in the neighboring isotones (^{133}Te [14], ^{137}Ba [15], ^{139}Ce [16], and ^{141}Nd [17]) and in the lighter odd-A

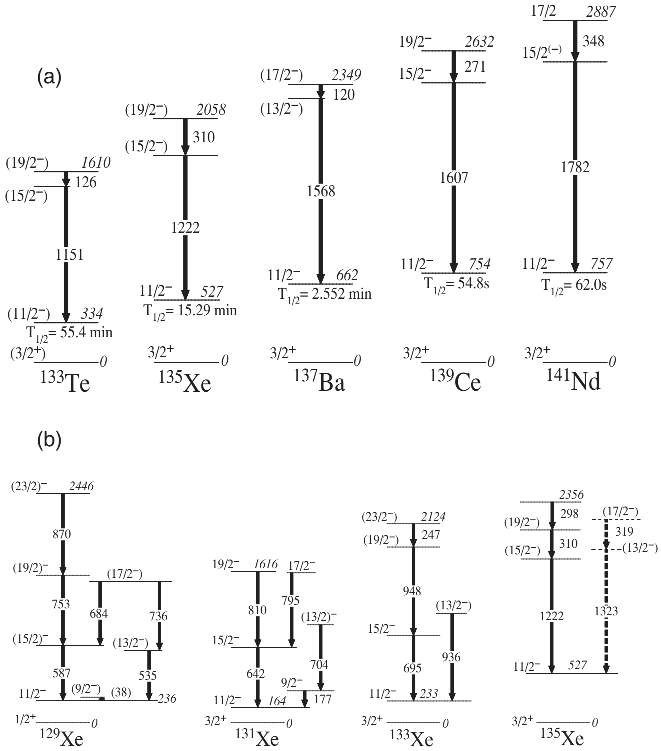

FIG. 7. Comparison of high-spin states assigned to ^{135}Xe in the present work with known high-spin states in (a) the $N = 81$ isotones (^{133}Te [14], ^{137}Ba [15], ^{139}Ce [16], and ^{141}Nd [17]) and (b) the lighter odd-A Xe isotopes (^{129}Xe [18], ^{131}Xe [19], and ^{133}Xe [11]).

Xe isotopes (^{129}Xe [18], ^{131}Xe [19], and ^{133}Xe [11]), displayed in Fig. 7, spin and parity assignments for some of the levels assigned to ^{135}Xe in the present work have been tentatively suggested, as discussed next.

IV. DISCUSSION

In Fig. 7, the level schemes above the $11/2^-$ isomers in the $N = 81$ Te, Ba, Ce, and Nd isotones are summarized together with those in the odd-A Xe isotopes with $N \leqslant 81$. In all these cases, the first excited states above the isomers are understood as originating from the coupling of the $h_{11/2}$ neutron hole to the first excited states in the cores, and the similarities in the experimentally observed structures confirm this interpretation. Indeed, the first four excited states above the $11/2^-$ isomer assigned (tentatively or not) to ^{135}Xe in the present work fit the systematics very well. Moreover, the underlying structure evolves from the weak-coupling picture in ^{135}Xe and the other $N = 81$ isotones to a more collective behavior expected in the lighter odd-A isotopes [for instance, ^{129}Xe in Fig. 7(b)] as one moves away from the $N = 82$ shell. The first excited states in the ^{136}Xe core are shown in Fig. 8 together with the ^{135}Xe states observed in the present work and those predicted in a shell-model calculation from Ref. [2]. This shell-model calculation predicts the same ordering of levels proposed in the present work while slightly underpredicting the excitation energies of the levels. However, the results of the shell-model calculation in Fig. 8 come from a global fit for the $^{131-136}$Xe isotopes and are not "tweaked" to improve the agreement for ^{135}Xe separately.

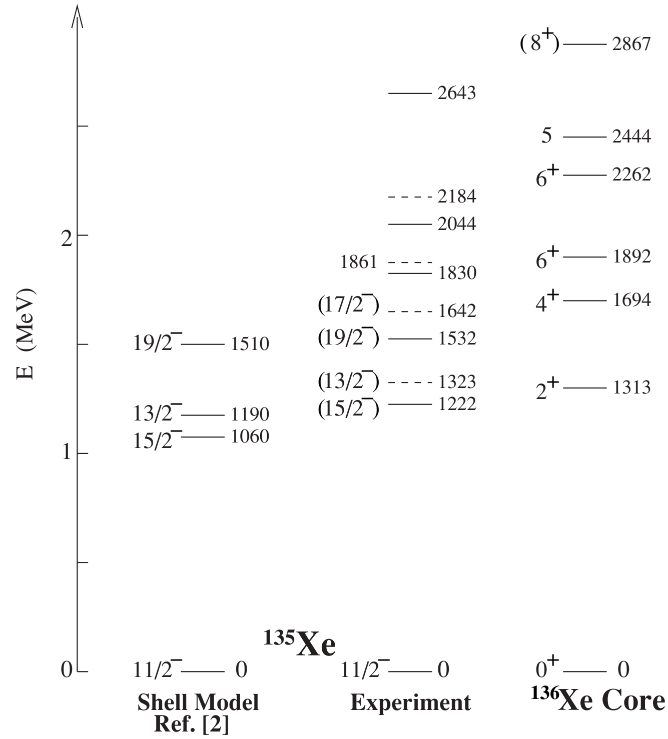

FIG. 8. Comparison of high-spin states assigned to ^{135}Xe in the present work with the predictions of the shell-model calculations described in Ref. [2] and with the excited states in the $N = 82$ core of ^{136}Xe [13]. Excitation energy of $11/2^-$ isomer in ^{135}Xe (527 keV experimentally, 390 keV in the shell-model calculation) has been normalized to zero. Assignment of dashed-line experimental levels to ^{135}Xe is tentative (see text).

V. SUMMARY

The level scheme above the previously known $11/2^-$ isomer of ^{135}Xe was established up to 3170-keV excitation energy. The assignment of new transitions to ^{135}Xe was deduced independently in two different experiments populating this isotope as (i) a fission fragment following the fission of a much heavier compound nucleus formed in a fusion-fission reaction, and (ii) an evaporation residue in the $(n, 2n)$ reaction channel in neutron-induced reactions on ^{136}Xe. Based on a comparison with similar states in the neighboring $N = 81$ Te, Ba, Ce, and Nd isotones and in the lighter odd-A Xe isotopes, the first high-spin states above the $11/2^-$ isomer in ^{135}Xe can be understood as originating from neutron configurations involving the coupling of the $h_{11/2}$ hole to the first excited states in the ^{136}Xe core. Generally, good agreement is observed between measured level energies and those predicted by shell-model calculations reported previously in the literature.

ACKNOWLEDGMENTS

This work has been supported in part by the U.S. Department of Energy under Contract Nos. DE-*A*C52-06NA25396 (LANL), W-7405-ENG-48 (LLNL), and AC03-76SF00098 (LBNL) and by the National Science Foundation (Rutgers University).

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