Directional correlations of γ transitions in ^{135}Xe following the decay of ^{135}I

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Directional correlations of coincident gamma transitions have been measured in ^{135}Xe following the β^- decay of fission product ^{135}I ($T_{1/2}=6.7$ h) using a spectrometer consisting of a Ge and a Ge(Li) detector. The measurements were carried out for 14 gamma cascades populated in ^{135}Xe. The present results permitted definite spin assignment to the levels at 1131 keV ($\frac{7}{2}^+$), 1678 keV ($\frac{7}{2}^+$), 1968 keV ($\frac{9}{2}^+$), 2223 keV ($\frac{9}{2}^+$), 2255 keV ($\frac{7}{2}^+$), and 2372 keV ($\frac{9}{2}$). In addition, several previous spin assignments to other levels were confirmed. The multipole mixing ratios $\delta(E2/M1)$ for 12 γ ray transitions were determined from the present results.

INTRODUCTION

The energy levels of ^{135}Xe are of particular interest because this nucleus has only a single neutron hole in the closed shell at $N=82$. Thus, the low-energy levels of ^{135}Xe are expected to be largely single-hole states in the neutron shell. Higher-energy states are likely to result from coupling between excited core and single-hole states or from a three-quasiparticle interaction. Apart from the interest in the nuclear structure of ^{135}Xe, the decay properties of ^{135}I to levels in ^{135}Xe are also of considerable importance for obtaining the precise information on γ rays emitted so as to enable the calculation of independent and cumulative yields from the γ-ray spectra of the fission products. Such data are extremely useful for fission reactor systems since the ^{135}I decay product ^{135}Xe with an enormous thermal neutron capture cross section of 2.7×10^6 *b* constitutes an important reactor poison.

The decay of ^{135}I to the levels of ^{135}Xe has been previously studied by Macias *et al.*[1] through singles and γ-γ coincidence measurements using Ge(Li) and NaI(Tl) detectors. Similar studies were carried out by Saxena[2] and more recently by Walters *et al.*[3] using Ge(Li) detectors. Information on the levels of ^{135}Xe is also available from the ^{136}Xe(d,t) reaction,[4,5] although it is quite limited in scope due to gaseous nature of the target. Earlier angular correlation measurements of γ transitions in ^{135}Xe were reported by Macias and Walters[6] and Begzhanov *et al.*[7] These measurements are, however, restricted to only a few of the strong γ cascades and were performed either with NaI(Tl) detectors or with the combination of a Ge(Li) and a NaI(Tl) detector. Multipole mixing ratios of six γ transitions in ^{135}Xe were calculated from these data by Krane.[8] The conversion coefficients for several γ-ray transitions in ^{135}Xe were measured by Achterberg *et al.*[9] The data were used by the authors to assign multipole character to these transitions. All these previous studies resulted in a level scheme of ^{135}Xe with spin and parity assignments for several levels. The results are summarized in Nuclear Data Sheets.[10] The present investigation was undertaken with a view to enlarge the existing information on the levels and transitions in ^{135}Xe by measuring the angular correlations of as many γ cascades as possible, including those of intermediate intensity, using Ge and Ge(Li) detectors in order to firmly establish the spin assignments to some of the levels determined in the previous studies. At the same time, we desired to obtain the multipole mixing ratios, δ, for a large number of γ transitions to further elucidate the structure of the low-energy levels. The $E2/M1$ mixing ratios may serve to determine the relative importance of collective quadrupole degrees of freedom and admixture of single-particle excitations in nuclear states, in any attempt to describe the level structure of this nucleus. The levels and transitions in ^{135}Xe have been studied by measuring a total of 14 γ-ray cascades populated through the β^- decay of ^{135}I.

EXPERIMENT

The radioactive sources of ^{135}I were produced by chemically separating the iodine activity from the fission products of uranium. Approximately 1 g of $UO_2(NO_3)_2\cdot6H_2O$ was irradiated with thermal neutrons for a period of 5 min at a flux of $\simeq5\times10^{12}$ n/cm^2 s in the IEA-R1 reactor at São Paulo. The iodine activity was chemically separated from fission products and purified a few minutes after the end of irradiation following a procedure described by Kleinberg and Cowan.[11] The source was left to decay for a period of 2–3 h to reduce the activities of ^{134}I (53 min) and ^{132}I (2.2 h). The silver-iodide precipitate was finally dissolved in a drop of 1*M* sodium thiosulphate solution. The dilute solution containing ^{135}I was transferred to a lucite source holder and taken to the γ spectrometer for measurements. The source dimension was 2.5 mm$\times$5 mm.

The angular correlation spectrometer consisted of a fixed Ge detector with a volume of 89 cm^3 and a movable Ge(Li) detector with a volume of 45 cm^3. The electronic setup for the measurements of γ-γ coincidences was the usual low-noise fast-coincidence system along with a 4096-channel pulse-height analyzer. The γ-γ coincidences were measured at angles of 90°, 120°, 150°, and 180°. The angular position of the movable detector was changed every 1 h and the coincidence spectrum observed through the Ge detector was routed to a preassigned 1024-channel subgroup of the multichannel analyzer memory for each angular position. Each radioactive source was counted for a period of 12 h after which it was replaced by a fresh source containing approximately the same initial activity. A total of 60 sources were used for the entire experiment.

The photopeaks at 1131, 1260, and 1458 keV as seen through the Ge(Li) detector were selected by the single-channel analyzer (SCA) and served as gating transitions in the γ-γ coincidence measurements. Additional gates were placed adjacent to the main gates on the higher-energy side in order to determine the effects of Compton scattered radiation of higher-energy γ rays included in the window settings. A careful analysis of the ^{135}Xe level scheme,[10] however, showed that such contributions are not expected for the above-gating transitions. Experimentally, these effects were found to be negligible. The intensities of the coincident γ rays were determined from the Ge detector spectra at various angles and corrected for the source decay during the measurement and chance coincidences. The chance coincidences were determined separately by introducing a delay of 1 μs in the signal pulses from one of the detectors before reaching the coincidence unit and recording the coincidence spectrum. The corrected photopeak areas were normalized at 90° and least-squares fitted to the polynomial

$$W(\theta)=1+A_{22}P_2(\cos\theta)+A_{44}P_4(\cos\theta)$$

to determine the angular correlation coefficients A_{kk}.

RESULTS

The direct γ-ray spectrum in the decay of ^{135}I, obtained with the Ge detector 3 h after the end of the chemical separation, is shown in Fig. 1(a). In addition to the γ rays from ^{135}I, the strongest γ rays from other iodine isotopes $^{131-134}$I are also observed in this spectrum. The presence of small quantities of other iodine isotopes in the sample, however, did not interfere in the γ-γ coincidence measurements. The γ-γ coincidence spectra obtained with the 1131-, 1260-, and 1458-keV gates are shown in Figs. 1(b), 2(a), and 2(b), respectively. The coincidence spectra presented here are the result of only a partial measurement and have not been corrected for the accidentals. The angular correlation coefficients A_{kk} obtained from the present measurements for various γ cascades are given in Table I. The A_{kk} values reported there have already been corrected for the finite solid-angle effects of the detectors. The solid-angle correction factors were determined by the numerical calculations[12] for the Ge detector and taken from the tables of Camp and Van Lehn[13] for the Ge(Li) detector. The A_{kk} values for the γ cascades measured in the previous studies[6,7] are also included in this table for comparison. The multipole mixing ratios $\delta(E2/M1)$ for the γ-ray transitions together with the spin sequence which were found most consistent with the observed correlation data and decay properties are presented in Table II. The value of the

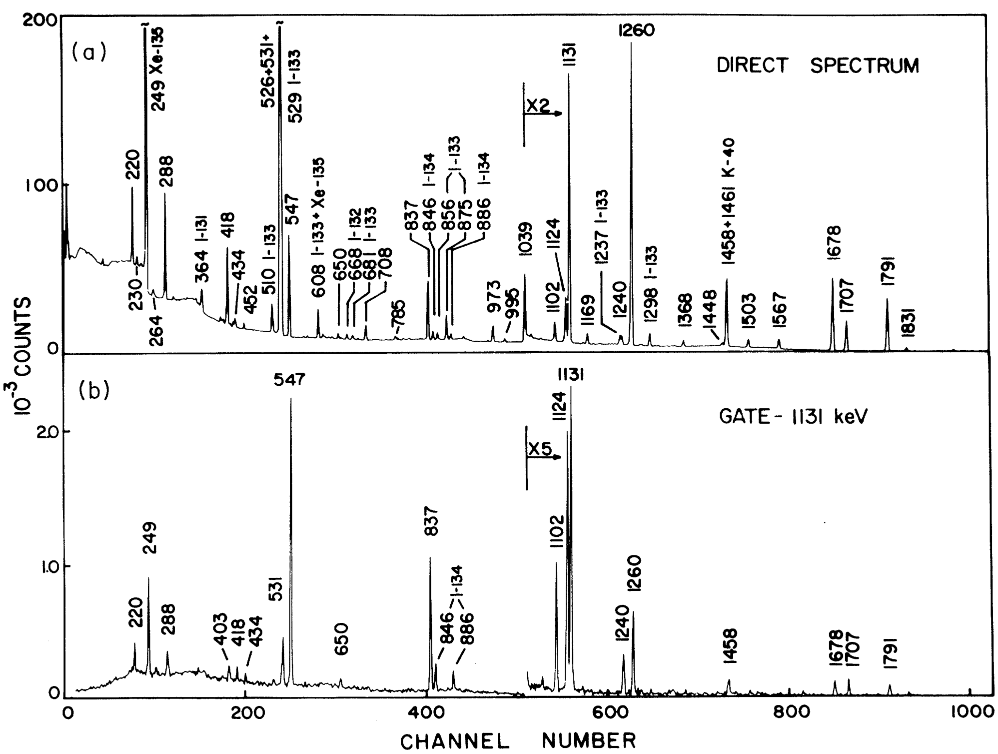

FIG. 1. Direct γ-ray spectrum in the decay of ^{135}I observed with the Ge detector 3 h after the end of the chemical separation (a) and γ-ray spectrum in coincidence with the photopeak 1131 keV (b).

TABLE I. Results of the directional correlation measurements of transitions in ^{135}Xe.

γ cascade (keV)	A_{22}	A_{44}
434–1131	−0.38±0.05	0.04±0.06
547–1131	0.24±0.01	−0.002±0.02
	0.25±0.04[a]	−0.04±0.07[a]
650–1131	0.16±0.07	0.02±0.11
837–1131	0.05±0.02	−0.08±0.03
	0.11±0.06[a]	−0.22±0.09[a]
1102–1131	0.17±0.04	−0.05±0.07
1124–1131	0.21±0.03	0.09±0.04
	0.09±0.08[a]	0.13±0.13[a]
	0.145±0.025[b]	−0.022±0.013[b]
1240–1131	−0.11±0.06	0.03±0.10
	0.155±0.066[b]	0.061±0.045[b]
418–1260	−0.50±0.02	0.02±0.03
	−0.55±0.06[a]	0.04±0.09[a]
531–1260	0.43±0.07	0.03±0.10
708–1260	0.11±0.04	0.00±0.07
785–1260	0.43±0.09	0.01±0.12
973–1260	0.10±0.04	0.02±0.07
	0.094±0.028[b]	0.043±0.028[b]
995–1260	−0.55±0.10	0.00±0.14
220–1458	0.29±0.02	0.07±0.03
	0.31±0.06[a]	0.01±0.10[a]
	0.205±0.020[b]	−0.024±0.009[b]

[a]Values from Ref. 6.
[b]Values from Ref. 7.

mixing ratio in each case was determined from the usual χ^2 analysis as a function of δ for the mixed transition. The convention of Becker and Steffen[14] was adopted for the definition of mixing ratio.

The parametric plots for some of the relevant spin sequences are shown in Fig. 3. The corrected values of A_{kk} with associated errors for some of the γ cascades are displayed as (A_{22}, A_{44}) points in this plot. A partial-level scheme of ^{135}Xe taken from Nuclear Data Sheets[10] is shown in Fig. 4. Only the γ-ray transitions of interest in this study are shown. The spin and parity assignments deduced from the present investigation are included in this figure.

The ground level and the levels at 288 and 526 keV have fairly well established spin and parity assignments of $\frac{3}{2}^+$, $\frac{1}{2}^+$, and $\frac{11}{2}^-$, respectively, from previous studies.[4,5,9] A number of other higher-energy levels relevant to the present study also have known spins and parities as reviewed in Nuclear Data Sheets[10] and these will not be discussed further except by mentioning that the present angular correlation data for γ cascades involving these levels are quite consistent with these assignments. Results for individual cascades and spin assignments to other levels which need additional confirmation[10] are discussed briefly.

The spin and parity of the 1131-keV level is strongly suggested as $\frac{7}{2}^+$ from most of the previous studies. With the known spin and parity of $\frac{9}{2}^+$ for the 1565-keV level,[3,10] the presently measured angular correlation of the

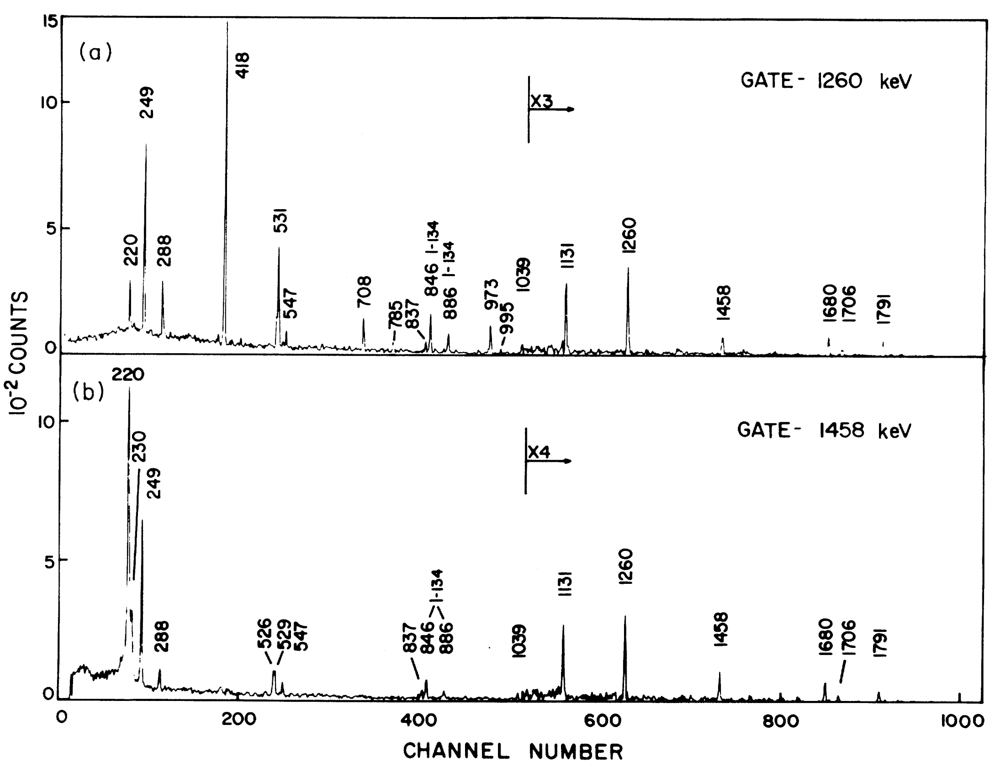

FIG. 2. γ-ray spectra observed in coincidence with the photopeaks at (a) 1260 and (b) 1458 keV.

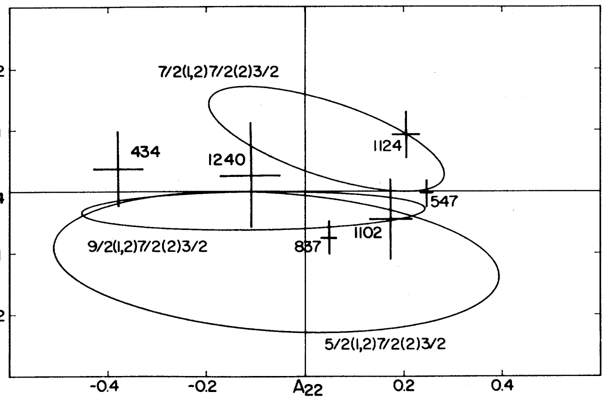

FIG. 3. Parametric plots for some of the relevant spin sequences for γ cascades involving the 1131-keV transition. The experimental (A_{22}, A_{44}) points are shown with error bars.

434–1131-keV γ-ray cascade ($A_{22}=-0.38\pm0.05$) rules out a spin of $\frac{5}{2}$, the only other possible assignment for the 1131-keV level, since a $\frac{9}{2}$-$\frac{5}{2}$-$\frac{3}{2}$ spin sequence would require $0.170\geq A_{22}\geq-0.206$ for any possible value of $\delta(1131)$. The spin and parity of the 1131-keV level is thus firmly established as $\frac{7}{2}^+$.

The level at 1678 keV has been assigned[10] a spin and parity of $\frac{7}{2}^+$. The present result for the 547–1131-keV cascade is quite unambiguous indicating a $\frac{7}{2}$-$\frac{7}{2}$-$\frac{3}{2}$ spin sequence (Fig. 3). The result for the 418–1260-keV cascade provides additional support for this assignment.

The angular correlation of the 650–1131-keV cascade is in excellent agreement with the theoretically expected values ($A_{22}=0.127$, $A_{44}=0.003$) for the $\frac{11}{2}$-$\frac{7}{2}$-$\frac{3}{2}$ spin sequence thus confirming the $\frac{11}{2}^+$ assignment for the 1781-keV level.

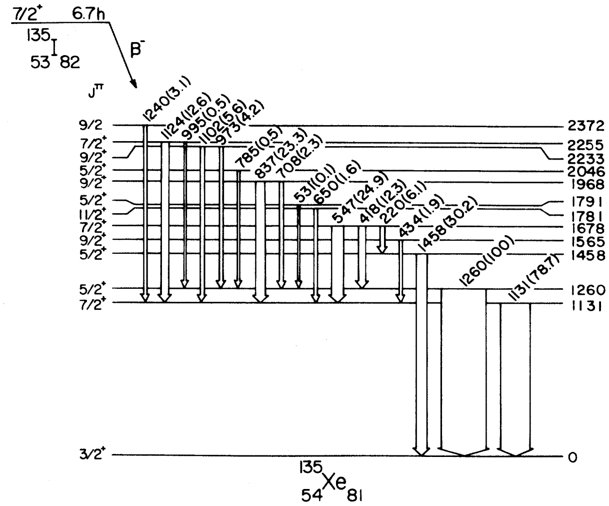

FIG. 4. A partial-decay scheme of ^{135}I to the levels in ^{135}Xe.

The measured angular correlation of the 837–1131-keV cascade is in very good agreement with the earlier $\frac{9}{2}^+$ assignment[9,10] for the 1968-keV level. Analysis of the result of another γ cascade at 708–1260 keV from this level gave

$$\delta(1260)=0.56\pm0.05$$

in fair agreement with the value reported in Ref. 8. This value has been used in the analysis of other γ cascades involving the 1260-keV transition.

Spins and parities for the 2233-keV and 2255-keV levels are most likely to be $\frac{9}{2}^+$ and $\frac{7}{2}^+$, respectively.[10] The angular correlation results of the 1102–1131- and 1124–1131-keV γ cascades, as can be seen in Fig. 3, are

TABLE II. Multipole mixing ratios of γ transitions in ^{135}Xe.

Level (keV)	Transition (keV)	I_i^π-I_f^π	Mixing ratio δ (this work)	Mixing ratio δ (previous work)[a]
1131	1131	$\frac{7}{2}^+$-$\frac{3}{2}^+$	$E2$	
1260	1260	$\frac{5}{2}^+$-$\frac{3}{2}^+$	0.56 ± 0.05	0.50 ± 0.11
1565	434	$\frac{9}{2}^+$-$\frac{7}{2}^+$	-0.52 ± 0.10	
1678	418	$\frac{7}{2}^+$-$\frac{5}{2}^+$	-1.86 ± 0.20	$-1.2\pm^{1.2}_{0.6}$
	547	$\frac{7}{2}^+$-$\frac{7}{2}^+$	-0.14 ± 0.05	$-0.45\pm^{0.62}_{0.43}$
1791	531	$\frac{5}{2}^+$-$\frac{5}{2}^+$	-0.55 ± 0.20	
1968	708	$\frac{9}{2}^+$-$\frac{5}{2}^+$	$E2$	
	837	$\frac{9}{2}^+$-$\frac{7}{2}^+$	3.58 ± 0.10	
		$\frac{5}{2}^+$-$\frac{7}{2}^+$		$-12\pm^{50}_{6}$
2046	785	$\frac{5}{2}^+$-$\frac{5}{2}^+$	-0.56 ± 0.10	
2233	973	$\frac{9}{2}^+$-$\frac{5}{2}^+$	-0.01 ± 0.05[b]	
	1102	$\frac{9}{2}^+$-$\frac{7}{2}^+$	1.82 ± 0.20	
2255	995	$\frac{7}{2}^+$-$\frac{5}{2}^+$	-1.14 ± 0.30	
	1124	$\frac{7}{2}^+$-$\frac{7}{2}^+$	-1.08 ± 0.2	0.160 ± 0.06
2372	1240	$\frac{9}{2}$-$\frac{7}{2}^+$	-0.06 ± 0.10	$0.39\pm^{2.3}_{1.4}$

[a]Values from Ref. 8.
[b]Values for $\delta(M3/E2)$.

in agreement with these assignments.

The spin and parity of the 2372-keV level is believed[10] to be $\frac{9}{2}^+$ or $\frac{7}{2}^-$. The measured angular correlation of the 1240–1131-keV cascade is consistent with either of these spin assignments. A spin of $\frac{7}{2}$ with negative parity for this level, however, may be ruled out from the fact that, with this assignment, the present data would imply an unusually large $M2$ admixture in the 1240-keV transition:

$$\delta(1240)=0.89\pm0.10 \; .$$

This leaves $\frac{9}{2}$ as the only possible assignment for the 2372-keV level. The present data do not permit a definite parity assignment in this case.

DISCUSSION

The low-energy levels of ^{135}Xe seem to fit the expected pattern for a single-hole state in the 82 neutron shell. As expected, the ground state and the two lowest-energy states are strongly excited in the (d,t) reaction representing a single hole in either the $2d_{3/2}$, $3s_{1/2}$, or $1h_{11/2}$ orbitals. A group of six levels $\frac{7}{2}^+$, $\frac{5}{2}^+(2)$, $\frac{3}{2}^+(2)$, and $\frac{1}{2}^+$, which can arise due to coupling of the excited core with the $\frac{3}{2}^+$ or $\frac{1}{2}^+$ single-hole states, are expected around 1–1.5 MeV. The levels at 1131 keV ($\frac{7}{2}^+$), 1260 keV ($\frac{5}{2}^+$), 1448 ($\frac{3}{2}^+$), 1457 keV ($\frac{5}{2}^+$), and 1544 keV ($\frac{1}{2}^+$) (see detailed level scheme Ref. 10) are most likely due to these excitations. The levels above 1600 keV seem to have more complex configurations, probably involving $\frac{5}{2}^+$ and $\frac{7}{2}^+$ hole states, multiple phonon-core excitations, and three-quasiparticle excitations in which a proton pair is broken.

An initial attempt to calculate the properties of odd-A xenon isotopes was made by Kisslinger and Sorensen[15] using a simple two-body force represented by a short-range pairing force and a long-range quadrupole force. The low-energy states of spherical odd-A nuclei are treated in terms of quasiparticle excitation and phonon excitation in addition to the interaction between these two modes. Using this model, Kisslinger and Sorensen were able to successfully reproduce many of the nuclear properties including energies, nuclear moments, transition probabilities, $B(E2)$, etc., in $^{127-135}$Xe.

More recent theoretical discriptions of $N=81$ nuclides range from a simple model in which the single neutron hole is coupled to the $N=82$ core vibrations[16] to detailed shell-model calculations[3] for nuclei near the doubly closed-shell nucleus ^{132}Sn. Heyde and Brussaard[16] have used an intermediate-coupling model where neutron single-hole states are coupled to the collective quadrupole excitations of even-even $N=82$ nuclei, to calculate the energy spectra, ground-state moments, as well as $M1$ and $E2$ transition probabilities. With the exception of the 1260-keV transition the multipole mixing ratios $\delta(E2/M1)$ calculated from these results are, in general, much smaller when compared to the experimentally determined values. A detailed comparison with the calculations is, however, of limited value since the spin assignments to many of the levels in ^{135}Xe were not firmly established.

Recently, Walters *et al.*[3] have carried out a large-scale (four particles and a hole beyond ^{132}Sn) shell-model calculations for ^{135}Xe. The authors had reasonably good success in reproducing the energies, spins, and parities of most of the observed levels up to 2.5 MeV. Detailed calculations of electromagnetic transition probabilities are, however, not reported.

In the present work, angular correlations of 14 γ cascades were measured and multipole mixing ratios of 12 γ-ray transitions were determined. Although the spin and parity assignments to a number of levels in ^{135}Xe are known from previous studies, the present results more conclusively confirm and establish these assignments. The presently measured values of the multipole mixing ratios $\delta(E2/M1)$ for a number of γ-ray transitions in ^{135}Xe, we believe, should stimulate new attempts for theoretical calculation of these quantities to further elucidate the structure of this nucleus.

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