Evidence for octupole correlations in ^{124,125}Ba

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The γ decay of the nuclei ^{124,125}Ba has been investigated by means of the EUROBALL spectrometer, coupled to the DIAMANT array of charged-particle detectors, using the reaction ^{64}Ni + ^{64}Ni at $E_{\text{beam}} = 255$ and 261 MeV. In the nucleus ^{125}Ba six new $E1$ transitions have been found to link opposite-parity bands currently interpreted as $\nu d_{5/2}(+g_{7/2})$, $\nu h_{11/2}$ structures. The previously unknown $J^{\pi} = 3^{-}$ level in the nucleus ^{124}Ba has also been identified; its excitation energy is accurately reproduced by a microscopic calculation including octupole correlations. Both issues are bolstered by sizable $B(E1)/B(E2)$ ratios.

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Octupole correlations in atomic nuclei are due to the interaction between orbitals of opposite parity, whose angular momenta differ by $3\hbar$, lying in the proximity of the Fermi surface. In general, this situation occurs when the Fermi level is found between an intruder orbital and the normal-parity subshell, i.e., for particle (proton or neutron) numbers 34 ($g_{9/2} \leftrightarrow p_{3/2}$), 56 ($h_{11/2} \leftrightarrow d_{5/2}$), 88 ($i_{13/2} \leftrightarrow f_{7/2}$), and 134 ($j_{15/2} \leftrightarrow g_{9/2}$) [1]. Experimental fingerprints of octupole correlations, such as alternate-parity bands linked by enhanced $E1$ transitions, very collective $E3$ transitions, and parity doublets in odd nuclei, are in fact long established in the proximity of both the double octupole "shell closures" $Z = 56$, $N = 88$ (corresponding to the nucleus ^{144}Ba, see Ref. [1]) and $Z = 56$, $N = 56$ (corresponding to the so far unidentified-and perhaps unbound-nucleus ^{112}Ba, see for instance [2,3]).

At variance with the symmetry properties of octupole correlations, nevertheless, is the observation of low-lying negative-parity *even*-spin levels in ^{122,124,126}Ba. In these nuclei, in fact, the yrast negative-parity even-spin band can be observed down to as low a spin and an excitation energy as $4\hbar$ and $\sim$2 MeV and provides, basically, the whole feeding of the lowest-observed negative-parity *odd*-spin states, through $M1(+E2)$ transitions [4–6]. The lowest-observed negative-parity levels, however, lie below the energy threshold represented by twice the proton

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pairing gap[1] in all even barium isotopes with $118 \leqslant A \leqslant 126$ [4–9]. This, excluding a simple quasiproton interpretation, hints at a possible role of octupole correlations in the origin of low-lying negative-parity levels. This topic was discussed in Ref. [10], addressing in particular the nuclei ^{124,126}Ba. The excitation energies of $J^\pi \leqslant 9^-$ levels were investigated as a function of the strengths $\chi_{\lambda=3,\mu=0..3}$ in the octupole-octupole term

$$H_{\rm oct} = -\frac{1}{2} \cdot \sum\nolimits_\mu \chi_{3\mu} Q^+_{3\mu} Q_{3\mu}$$

of the assumed Hamiltonian

$$H = H_{\rm sp} + H_{\rm rot} + H_p + H_{\rm oct},$$

where $H_{\rm sp}$ was a Nilsson Hamiltonian, $H_{\rm rot}$ accounted for the rotation of the core and H_p consisted in a pairing force. The conclusion was drawn that octupole correlations (i.e., at least $\mu = 0$ and $\mu = 1$ terms in $H_{\rm oct}$) are indeed necessary to reproduce known experimental data [10]. The excitation energies of the lowest-lying *unknown* levels, stated to provide a stringent test of the model, were also calculated. In particular, the $J^\pi = 1^-$, 2^- and 3^- levels in ^{124}Ba were predicted to have the excitation energies of 1609, 1919, and 1700 keV respectively.

The experimental results presented in this work were obtained through the analysis of double and triple γ coincidences collected by the EUROBALL spectrometer [11,12] in a four-week experiment primarily aimed at the search for hyperdeformed bands in the nucleus ^{126}Ba, using the reaction ^{64}Ni + ^{64}Ni at the bombarding energies of 255 MeV in the first half of the experiment and 261 MeV in the second half [13]. The EUROBALL array consisted of 30 single-crystal (TAPERED), 26 four-crystal (CLOVER), and 15 seven-crystal (CLUSTER) germanium detectors, while an INNER BALL of 210 BGO scintillation detectors served as a multiplicity filter. The beam was delivered by the VIVITRON accelerator at IReS Strasbourg (France); thin self-supporting targets, $\sim$500 μg/cm^2 thick, were employed. The choice of projectile, target, and beam energy was made with the purpose of maximizing the angular momentum of the compound nucleus while minimizing its nonrotational excitation energy. The most intense evaporation channels were $2n$, $3n$, $4n$, $\alpha 2n$ and $p2n$, corresponding to ^{126,125,124}Ba, ^{122}Xe and ^{125}Cs respectively. To better select proton and α-particle channels the DIAMANT array of charged-particle detectors [14] was used; the data set on which the present analysis was performed was prepared imposing an off-line veto condition on the detection of any charged particle. Transitions were established in their electromagnetic characters on the basis of their angular distributions and (the sign of their) degrees of linear polarization. Our polarimeter was the ensemble of the CLOVER detectors [15], each made up of four crystals located at spherical coordinates (θ_1, ϕ_1), (θ_1, ϕ_2), (θ_2, ϕ_1) and (θ_2, ϕ_2) respectively, where

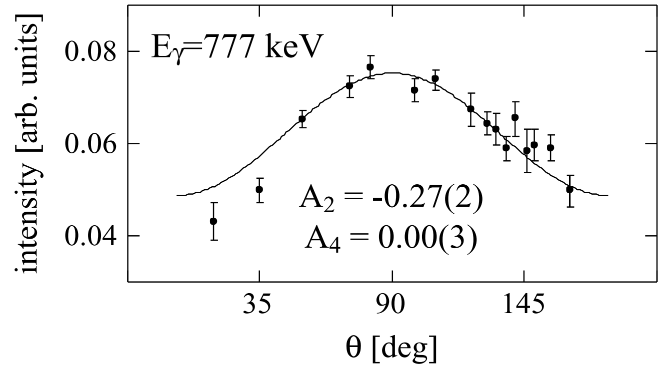

FIG. 1. The angular distribution of the $E_\gamma = 777$ keV transition linking the $23/2^+$ and $21/2^-$ levels in ^{125}Ba. The data fit corresponds, aside from a normalization factor, to the function $1 + A_2 P_2[\cos(\theta)] + A_4 P_4[\cos(\theta)]$, where P_n is the n-th Legendre polynomial. The best-fit values of Legendre polynomial coefficients are reported in the figure.

$\{\theta_1, \theta_2\} = \{72°, 81°\}$ or $\{99°, 108°\}$. These detectors allowed to measure the Compton-scattering asymmetry

$$A_{\rm CS} \equiv \frac{N_\perp - N_{||}}{N_\perp + N_{||}},$$

where $N_\perp$ and $N_{||}$ denote the number of photons scattered in the orthogonal and parallel direction respectively, relative to the beam direction. This was done in practice by comparing peak areas in pairs of spectra obtained from two asymmetric matrices, updated at every occurrence of a couple of coincident photons (γ_1, γ_2) in which γ_1 or γ_2 corresponded to the sum-energy of a *pair* of signals produced by adjacent crystals respectively having a common θ or ϕ coordinate. (Two coincident hits in neighboring CLOVER elements were interpreted as signaling the Compton scattering of a single photon.) The asymmetry $A_{\rm CS}$ has the same sign as the degree of linear polarization of γ rays at $\theta_{\rm CLOVER}$ [16–18]; it is therefore

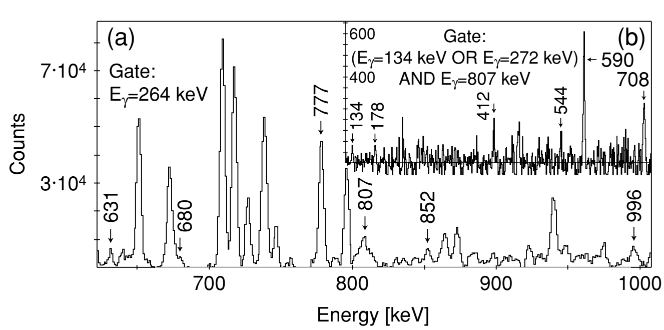

FIG. 2. (a) Section of a single-gate spectrum showing five of the six new $E1$ transitions identified in ^{125}Ba. (b) Section of a double-gate spectrum clinching the location of the new $E_\gamma = 807$ keV transition in the level scheme of ^{125}Ba: The two most prominent peaks correspond to the $E_\gamma = 708$ and 590 keV transitions respectively feeding the $19/2^+$ level and deexciting the $17/2^-$ one whereas, for instance, the peak corresponding to the $19/2^- \rightarrow 15/2^-$, $E_\gamma = 604$ keV transition (see Fig. 3) is not present.

[1]Calculated from the odd-even mass difference as $\Delta \approx M_{A={\rm odd}}$-$(M_{A-1} + M_{A+1})/2$.

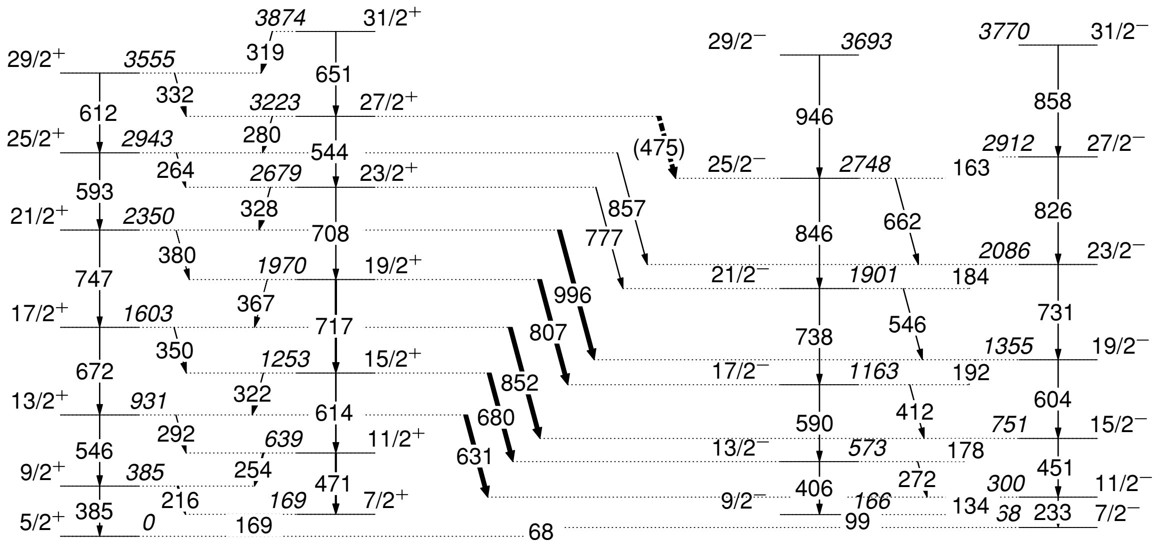

FIG. 3. Partial level scheme for ^{125}Ba, including all the $E1$ transitions that are now known to connect the positive-parity yrast structure (i.e., the coupled bands on the left-hand side) with the negative-parity one (right-hand side). The newfound transitions are shown with thicker arrows. Previously known levels and transitions are taken from Ref. [19].

positive for stretched $E1$ and $E2$ transitions and negative for stretched $M1$ ones.[2]

The first experimental results we report in this work concern the nucleus ^{125}Ba. This nuclide, when populated by means of heavy-ion fusion-evaporation reactions, is long known to display two major structures (i.e., couples of bands of common parity linked by $M1 + E2$ transitions) having opposite parities, interpreted as quasineutron bands respectively based on the $d_{5/2} + g_{7/2}$ and $h_{11/2}$ orbitals [19,20]. This interpretation is suggestive of octupole correlations, in that the observation of enhanced $E1$ transitions linking the two structures would then signify an enhanced interaction between the $d_{5/2}$ (although to some extent mixed with the $g_{7/2}$) and the $h_{11/2}$ orbitals, i.e., an octupole interaction. But only few $E1$ transitions were known to connect opposite-parity levels in ^{125}Ba prior to our work, namely a low-lying $E_\gamma = 68$ keV transition (moreover having a rather small $B(E1)$ value, i.e., $\sim 2 \cdot 10^{-7}$ W.u. [20]) and two higher-lying transitions having $E_\gamma = 777$ and 857 keV respectively [19] whose electric dipole character, as far as we know, had been assigned only on the basis of the decay scheme, and whose strengths had never been measured.

We clinched the $\Delta J = 1 E1$ character of the $E_\gamma = 777$ keV transition through the measurement of its angular distribution (see Fig. 1) and its Compton-scattering asymmetry, which was found to be $A_{\mathrm{CS}} = +0.03(0.03)$. In addition, and most importantly, we found evidence for five new $E1$ transitions linking the positive-parity and negative-parity structures, as shown in Figs. 2 and 3. (A further tentative transition, linking the $27/2^+$ and $25/2^-$ states, was observed). To check the enhancement of $E1$ strengths that octupole correlations are expected to produce we finally measured branching ratios, which in turn yielded $B(E1)/B(E2)$ values. Our results are reported in Table I, in which $B(E1)$ estimates based on the assumption that the nucleus ^{125}Ba has a prolate shape with a somewhat "cautious" deformation of $\beta = 0.2$ are also shown. $B(E1)/B(E2)$ ratios are very similar to those measured in ^{117}Xe [3]; the $E_\gamma =$ 777 keV, $23/2^+ \rightarrow 21/2^-$ transition is particularly enhanced. The $B(E1, 23/2^+ \rightarrow 21/2^-)/B(E2, 23/2^+ \rightarrow 19/2^+)$ ratio is comparable to $B(E1)/B(E2)$ values measured in ^{143,145}Ba [21], and the corresponding $B(E1)$ estimate is larger than any $B(E1)$ value measured in ^{114}Xe [2]. A definite enhancement of $E1$ strengths, then, is observed in ^{125}Ba, pointing to a sizable contribution of octupole correlations to the structure of this nuclide's $\nu d_{5/2}(+g_{7/2})$, $\nu h_{11/2}$ bands.

Our experimental results regarding the nucleus ^{124}Ba are just as indicative of octupole correlations. The first of them is the identification of the previously unknown $J^\pi = 3^-$ state. As shown in Fig. 4, two new coincident

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[2] It should be remarked that, given the finite overall solid-angle coverage of EUROBALL detectors, our angular distribution and polarization measurements from γ-γ or γ-γ-γ data were, in principle, correlation analyses. We experimentally verified, however, that no significant changes in a transition's angular distribution or degree of linear polarization were observed using singles spectra, single-gate spectra or double-gate spectra.

TABLE I. $B(E1)/B(E2)$ ratios for some levels belonging to the positive-parity structure in ^{125}Ba. $B(E1)$ estimates based on the assumption of an axial $\beta = 0.2$ deformation of the nucleus ^{125}Ba are also shown.

J^π	$B(E1)/B(E2)$ (fm^{-2})	$B(E1)$ (W.u.)
$25/2^+$	$5(1) \times 10^{-8}$	8×10^{-5}
$23/2^+$	$1.8(3) \times 10^{-7}$	3×10^{-4}
$19/2^+$	$7(2) \times 10^{-8}$	1×10^{-4}
$15/2^+$	$1.5(7) \times 10^{-8}$	1.5×10^{-5}
$13/2^+$	$2.7(8) \times 10^{-8}$	2×10^{-5}

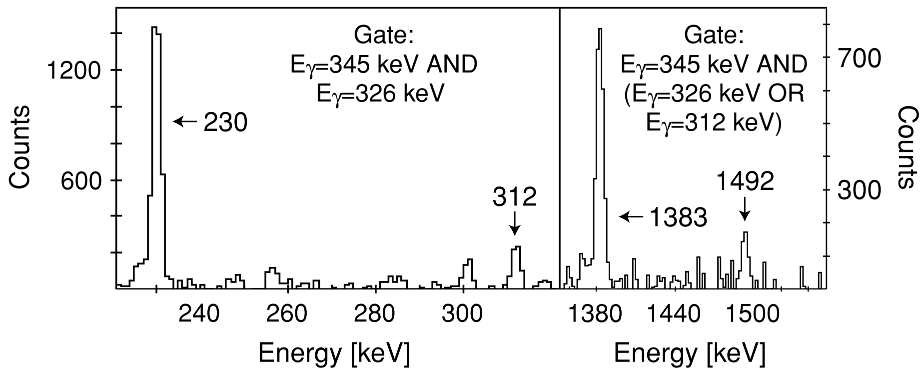

FIG. 4. Intervals of double-gate spectra showing the new $E_\gamma = 312$ keV and $E_\gamma = 1492$ keV transitions in ^{124}Ba.

transitions of energy $E_\gamma = 312$ and 1492 keV respectively are observed following the $8^- \rightarrow 6^-$, $E_\gamma = 345$ keV and $6^- \rightarrow 4^-$, $E_\gamma = 326$ keV transitions. The new transitions are included in the level scheme in Fig. 5, along with two other tentative transitions of $E_\gamma = 191$ and 1071 keV respectively. The $\Delta J = 1$, $\delta \approx 0$ character of the new $E_\gamma = 312$ keV transition was determined on the basis of its angular-distribution asymmetry A_{AD} [22], defined as the efficiency-corrected ratio of the counts recorded by the four innermost detector rings ($\theta = 72°, 81°, 99°, 108°$) to the counts recorded by the three outermost rings ($\theta = 149°, 156°, 163°$). This ratio, which approximately measures the anisotropy $W(76°)/W(156°)$, where $W(\theta)$ is the angular distribution of the transition of interest, was in fact found to be $\mathrm{A_{AD}} = 1.5(3)$ for the newfound $E_\gamma = 312$ keV line, exactly as expected in the case of a $J_i = 4 \rightarrow J_f = 3$ dipole transition ($\mathrm{A_{AD}} \approx 0.6$ would be expected, instead, for a $J_i = 4 \rightarrow J_f = 2$ stretched quadrupole transition). The $M1$ character of the new transition was finally pinned down through a polarization measurement. Because of the limited statistics, a simple integration of the orthogonal- and parallel-scattering spectra corresponding to a gate on the $6^- \rightarrow 4^-$ transition, in the interval containing the $E_\gamma = 312$ keV peak and in two peak-free intervals close to it, was preferred to the straightforward measurement of the $E_\gamma = 312$ keV peak areas. A value $A_{\mathrm{CS}} = -0.015(28)$ was found to correspond to the first interval, whereas the scattering asymmetry of the background surrounding the peak turned out to be $A_{\mathrm{CS}} = +0.06(3)$, meaning that the degree of linear polarization of the $E_\gamma = 312$ keV transition is definitely negative, exactly as expected in the case of a $\Delta J = 1$ $M1(+E2)$ character with $\delta \approx 0$. The level fed by this transition, therefore, has by necessity $\mathrm{J}^\pi = 3^-$; its excitation energy, namely $E_{ex}(3^-) = 1722$ keV, is in very good agreement with the prediction $E_{\mathrm{th}}(3^-) = 1700$ keV given in Ref. [10] (see Fig. 6).

$B(E1, J^- \rightarrow (J-1)^+)/B(E2, J^- \rightarrow (J-2)^-)$ ratios were also determined for three levels in this nucleus, namely the $J^\pi = 11^-$, 9^- and 7^- ones; values are reported in Table II, along with $B(E1)$ estimates corresponding to the nucleus ^{124}Ba having an electric quadrupole moment $Q_0 = 385\, e\,\mathrm{fm}^2$ (this value is derived from the half-life of the $J^\pi = 2^+$ state [23]). The observed enhancement of $E1$ strengths (and, of course, the existence of levels lower in energy than twice the proton pairing gap) would not be expected if the negative-parity odd-spin band, yet interpreted in Ref. [5] as a $\pi(d_{5/2} + g_{7/2}) \otimes \pi h_{11/2}$ structure, had a purely rotational (i.e., quadrupole) origin. Our experimental findings, therefore, indicate that octupole correlations must be included in a proper description of negative-parity states in ^{124}Ba at least up to $J \approx 11$, in agreement with the conclusion of Ref. [10].

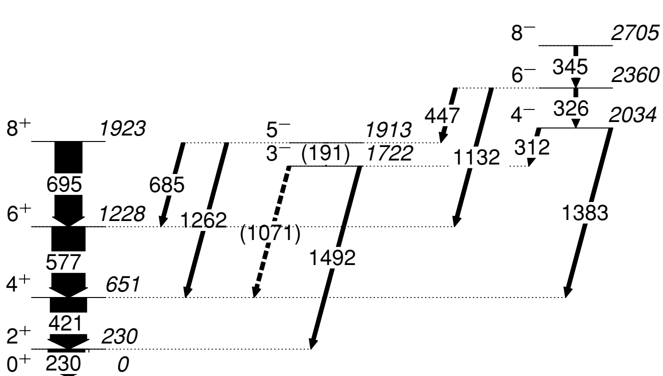

FIG. 5. Partial level scheme for ^{124}Ba. Newly identified $E_\gamma = 312$ and 1492 keV transitions and tentative $E_\gamma = 191$ and 1071 keV ones are included. Previously known levels and transitions are taken from Ref. [5]. Arrow widths are proportional to transition intensities.

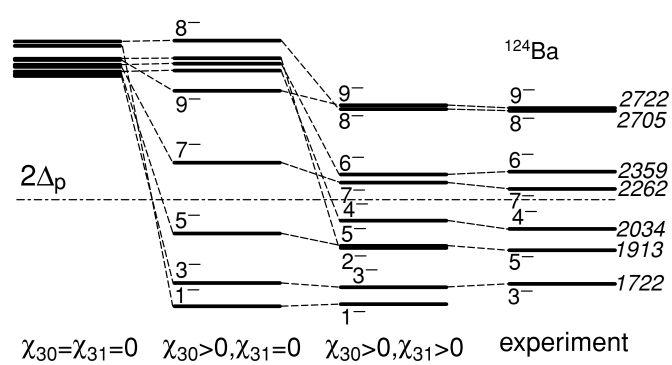

FIG. 6. Partial representation of the calculations described in Ref. [10]. Experimental excitation energies in kiloelectron volts are reported on the right-hand side of the picture (the newly identified 3^- level is included). See text for details. The energy threshold represented by twice the proton pairing gap is also sketched.

TABLE II. $B(E1)/B(E2)$ ratios for three levels belonging to the yrast negative-parity odd-spin band in ^{124}Ba. $B(E1)$ estimates based on the assumption of an electric quadrupole moment $Q_0 = 385\ e\,\text{fm}^2$ are also shown.

J^π	$B(E1)$/B($E2$) (fm^{-2})	$B(E1)$ (W.u.)
11^-	$3.0(4) \times 10^{-8}$	8×10^{-5}
9^-	$4.3(2) \times 10^{-8}$	1×10^{-4}
7^-	$4.3(1) \times 10^{-8}$	8×10^{-5}

It should be noted that this point is not undermined by our nonobservation of the $5^- \rightarrow 2^+$ and $3^- \rightarrow 0^+$ $E3$ transitions. In fact, even assuming rather "extreme" values of $\sim 10^{-5}$ and $\sim 10^2$ W.u. respectively for the quantities $B(E1, J^- \rightarrow (J-1)^+)$ and $B(E3, J^- \rightarrow (J-3)^+)$ with $J = 5$ or $J = 3$, still the intensities of the $E3$ transitions would be $\sim$1/30 of the $E1$ intensities. This implies that the peaks corresponding to the octupole transitions would anyway be just indiscernible from the background even in the spectra in which the $5^- \rightarrow 4^+$, $E_\gamma = 1262$ keV and $3^- \rightarrow 2^+$, $E_\gamma = 1492$ keV transitions are most evident (see for instance the right-hand panel in Fig. 4).

In conclusion, evidence for the existence of octupole correlations in the nuclei ^{124,125}Ba has been presented. The identification of several new $E1$ transitions and the measurement of $B(E1)/B(E2)$ ratios indicate that the $\nu(d_{5/2} + g_{7/2})$, $\nu h_{11/2}$ interpretation of the two major structures in ^{125}Ba [19,20] must be integrated with the inclusion of octupole correlations. This also applies to the $\pi(d_{5/2} + g_{7/2}) \otimes \pi h_{11/2}$ interpretation of the yrast negative-parity bands in the nucleus ^{124}Ba [5], at least for levels with $J^\pi \leqslant 11^-$. The excitation energy of the $J^\pi = 3^-$ level, which has been identified in the present work, had been accurately predicted in Ref. [10] with the addition of an octupole-octupole term to the nuclear Hamiltonian. This issue is corroborated by the measurement of the branching ratios of the $J^\pi = 11^-$, $9,^-$ and 7^- levels, from which large $B(E1)$ estimates can be deduced.

ACKNOWLEDGMENTS

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