Investigation of the ^{128}Ba nucleus with the (p,t) reaction

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The low lying states in ^{128}Ba have been investigated for the first time with the ^{130}Ba$(p,t)^{128}$Ba reaction. The experiment was performed at the Munich Q3D magnetic spectrograph with a 25-MeV proton beam and a high-resolution, 1.5-m-long focal plane detector. As a result of this experiment 27 excited levels with energies below 3.7 MeV have been observed for the first time, significantly increasing (by ~50%) the number of levels observed in ^{128}Ba. Angular distributions of tritons were measured and their comparison with the distorted wave Born approximation calculation allowed in most cases spin and parity assignments for the nuclear levels. The experimental two-neutron transition strengths with transferred angular momentum $L = 0$ and 2 are compared with the predictions of the IBA-1 model with a new set of parameters. The results indicate for the first time from a hadronic probe perspective a transitional structure close to the O(6) symmetry for the ^{128}Ba nucleus, confirming previous conclusions of γ-ray spectroscopy studies.

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I. INTRODUCTION

The nucleus ^{128}Ba is placed in a typical transitional region of the nuclear chart [1]. The entire neutron-deficient Ba region is known as unstable at γ-deformation and was among the first regions proved to have O(6) symmetry in the interacting boson model [2]. The structure of ^{128}Ba has been intensively investigated in the past few decades through γ-ray and electron spectroscopy [3,4]. According to our knowledge this is the first (p,t) experimental study of ^{128}Ba. It is known that (p,t) reactions provide rather complete spectroscopic information for the low spin states in the even-even nuclei. Therefore the ^{130}Ba$(p,t)^{128}$Ba reaction was selected as a tool for exciting the low spin states in ^{128}Ba. Our study revealed excited states with transferred angular momentum $L \leqslant 4$. Comparison between the experimental angular distributions and the distorted wave Born approximation (DWBA) calculation allowed spin and parity assignment for most of these levels. Also, from this comparison relative two-neutron transition strengths for the 0^+ and 2^+ states were extracted. From the 40 states observed in this experiment up to 3.7 MeV excitation energy, 27 are seen for the first time, significantly increasing the number of known states in the ^{128}Ba nucleus. Special attention was given to the observation of the 0^+ states, which are very important in testing nuclear structure models in even-even nuclei and are particularly well revealed in (p,t) transfer [5]. The experimental two-neutron transfer strengths of the low-lying 0^+ and 2^+ states were compared with the predictions of the interacting boson model, by employing a new set of model parameters. These parameters aim to describe simultaneously the existing electromagnetic data and the present hadronic ones. This comparison leads to the conclusion that the structure of the ^{128}Ba nucleus is transitional, close to the O(6) dynamical symmetry. Thus, the present results enhance, from the (p,t) reaction hadronic probe perspective, the previous structure description for ^{128}Ba made on the basis of γ-ray spectroscopic data [2].

II. EXPERIMENTAL CONDITIONS

The experimental data were obtained from the (p,t) reaction, with 25-MeV protons delivered by the MP Tandem accelerator of the Meier-Leibnitz Laboratory of Ludwig Maximilians University and Technical University of Munich. Tritons were analyzed with the Munich Q3D magnetic spectrograph [6] and detected in the focal plane by a 1.5-m-long multidetector system [7] composed of three proportional counters and a plastic scintillator to measure their residual energy. The focal plane detector provides particle identification and background reduction, accepting only events within the correct angle of incidence. The slits placed at the entrance of the Q3D define the acceptance angle in which the particles can enter the spectrograph. This acceptance angle can be changed by modifying the sizes of the slits and ranged from 2.978 to 11.038 msr in this experiment. The energy resolution was 5–10 keV FWHM and was mainly determined by the target. This allowed us to resolve most of the states up to an excitation energy of 3.7 MeV with two magnetic settings of the spectrograph, partially overlapping in energy. The ^{130}Ba targets with thickness of 100 and 50 μg/cm^2, implanted into 30 μg/cm^2 carbon foils, were prepared at the PARIS isotope separator in Orsay, starting from BaF_2 material 37.61% enriched in ^{130}Ba. The high purity of the target (close to 100%) and the good resolution of the spectra rule out that newly observed states belong to other Ba isotopes or other nuclei. Systematic searches of the spectra for triton lines originating from (p,t) reactions in other stable Ba isotopes indicated negligible contributions. Typical beam currents were around 200 nA. The experimental cross sections were obtained by normalizing the area of the peaks from the spectra to the solid angle, target thickness, and the beam charge obtained by integrating the beam current into the Faraday cup placed behind the target.

In the first magnetic setting of the spectrograph, which covers an energy range up to 2.7 MeV, spectra were measured

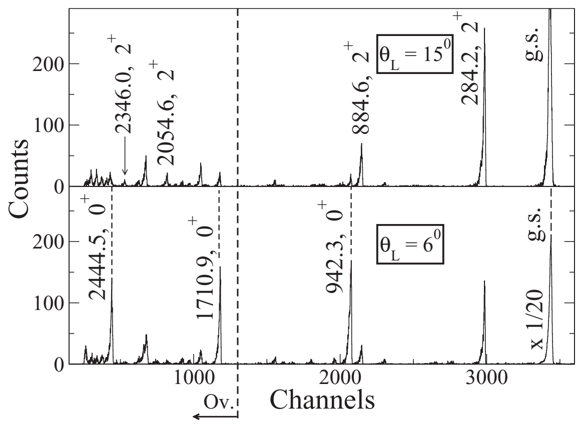

FIG. 1. Triton spectra from the ^{130}Ba$(p,t)^{128}$Ba reaction in the first magnetic setting of the Q3D spectrograph, measured at a laboratory angle of 6° (in the lower panel) and 15° (in the upper panel). The energies of the strong 0^+ and 2^+ excited levels are marked on the figure and are determined following a calibration procedure described in the text. The horizontal arrow placed below the lower panel and labeled "Ov." indicates the region overlapped with the second magnetic setting.

at laboratory angles between 5° and 40° in steps of 5°. In the second magnetic setting of the spectrograph, covering excitation energies up to 3.7 MeV, the spectra were recorded at 6° and 15°, as the primary interest was to identify the 0^+ states. Figure 1 presents examples of the triton spectra measured with the first magnetic setting at 6° (lower panel) and 15° (upper panel), and Fig. 2 shows spectra recorded with the second magnetic setting at 15°.

For the spectra obtained with the first magnetic setting an internal energy calibration was performed for the entire length of the detector with a third-order polynomial by using as calibration peaks the energies of well-known nuclear states obtained in previous γ-ray experiments [4]. The spectra measured with the second magnetic setting cannot be calibrated in energy using the same procedure because prior to our experiment there was no information on states with spin smaller than $4\hbar$ at excitation energies higher than 2.629 MeV (see Ref. [4]). Therefore, for the calibration in the second magnetic setting, we used the ^{144}Sm$(p,t)^{142}$Sm reaction measured under identical magnetic conditions of the Q3D. From the mass table [8] the ground-state Q value of the ^{130}Ba$(p,t)^{128}$Ba reaction is $-9520.9(103)$ keV and that of the reaction ^{144}Sm$(p,t)^{142}$Sm is $-10639.9(56)$ keV. As presented in Fig. 2, these Q values allowed us to record 12 triton lines from the ^{144}Sm$(p,t)^{142}$Sm reaction [9]. These lines correspond to well-known excited states in ^{142}Sm with energies between 768.0(2) and 2582(2) keV. By using kinematical calculations performed with the Q values of Ref. [8] the energy calibration from ^{142}Sm in the excitation range 768.0(2)–2582(2) keV [Fig. 2(a)] was transferred to ^{128}Ba in the corresponding excitation range: 1833–3611 keV [Fig. 2(b)].

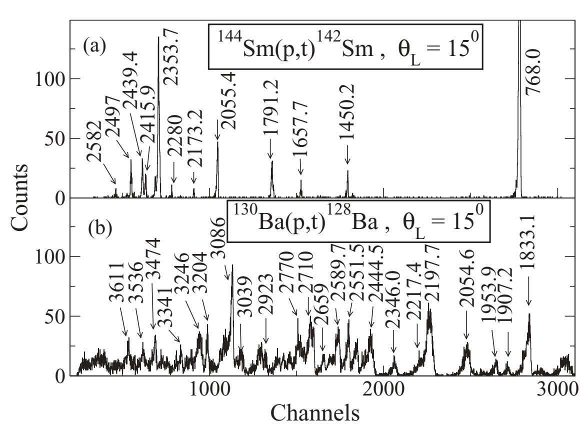

FIG. 2. Illustration of the energy calibration procedure for the second magnetic setting (highest energy) of the Q3D spectrograph. The spectra drawn in panels (a) and (b) are obtained in the same setting of the spectrograph. The peaks from ^{142}Sm (a) are well known and their energies (in keV) are taken from Ref. [8]. The procedure for transferring the calibration from ^{142}Sm to ^{128}Ba (b) revealed a constant shift of 24(1) keV (see text).

The region between channels 1600 and 3000 measured in the second magnetic setting was recorded also in the first magnetic setting (the overlapping region indicated in Fig. 1). Therefore, for the 14 peaks in this overlapping region we obtained energy values in two ways: on the basis of the internal calibration and by transferring the ^{144}Sm$(p,t)^{142}$Sm calibration to the ^{130}Ba$(p,t)^{128}$Ba spectra. By comparing the energies of peaks obtained by these two alternative procedures we observed a systematic shift estimated at an average value of 24(1) keV. This result led to a more precise measurement of the Q value of the ^{130}Ba$(p,t)^{128}$Ba reaction. Taking as reference the ^{144}Sm$(p,t)^{142}$Sm reaction, we adopted for the Q value of the ^{130}Ba$(p,t)^{128}$Ba reaction the value of $-9.544(1)$ MeV. With this value we obtained the energies of all peaks from the spectra measured in the second magnetic setting. The energies of the 14 peaks from the overlapping region are consistent in both magnetic settings. The excitation energies in ^{128}Ba measured in this work are listed in Table I. The uncertainties of the energies up to $E = 2629.7$ keV are given by the uncertainty of the centroid and are determined from the first magnetic setting. Above this energy the uncertainties are larger, being determined from the second magnetic setting by transferring the calibration from ^{142}Sm.

III. ANGULAR DISTRIBUTIONS AND THEIR DWBA ANALYSIS

The angular distributions of tritons measured in this work are presented in Figure 3. To extract the value of the transferred angular momentum (L value) we compared the experimental angular distributions with calculations done with the DWBA [10]. The numerical calculations were performed with the DWUCK-4 computer code [11,12] in which it was assumed that the (p,t) reaction was a direct single-step process. The optical model parameters employed for protons and tritons were taken from Ref. [13]. For the transfer of the two neutrons the procedure was similar to that of Refs. [14,15] by considering a cluster form factor in the configuration $(1h_{11/2})^2$ for $L =$ even and $(1h_{11/2}, 1g_{7/2})$ for $L =$ odd. Alternative form factors such as $(2d_{3/2})^2$, $(1g_{7/2})^2$, or $(3s_{1/2})^2$ for $L =$ even and

TABLE I. Excitation energy, spin-parity, and relative $2n$-transfer intensity (ϵ) for ^{128}Ba obtained in the present work, compared with the adopted values from Ref. [4]. The normalization for the $2n$-transfer strengths is chosen such that $\epsilon = 100\%$ for transition to the ground state and $\epsilon = 100\%$ to the first 2^+.

ENSDF [4]		Present work		
E_{ex} (keV)	J^π	E_{ex} (keV)	J^π	ϵ (%)
0.0	0^+	0.0	0^+	100
284.00(8)	2^+	284.2(1)	2^+	100
763.31(11)	4^+	762.7(4)	4^+	
884.50(12)	2^+	884.6(2)	2^+	25.5(28)
942.2(6)	0^+	942.3(1)	0^+	2.8(1)
1321.1(5)	2^+	1320.1(10)	$(2)^+$	1.6(5)
1372.32(13)	4^+	1373.3(5)	4^+	
1710.0(10)	0^+	1710.9(1)	0^+	3.3(2)
1833.75(19)	$(3^-,4)$	1833.1(5)	3^-	
1907.5(5)		1907.2(6)	4^+	
		1953.9(5)		
		2054.6(7)	2^+	6.2(13)
		2197.7(3)	$3^-, 4^+$	
2218.8(5)	0^+	2217.4(7)	0^+	0.5(1)
		2250.6(9)	4^+	
2347.2(5)	$(0^+, 1^+)$	2346.0(10)	2^+	2.3(8)
		2444.5(2)	0^+	3.3(2)
		2486.2(10)		
		2511.2(7)		
		2551.5(7)	4^+	
		2589.7(7)	2^+	7.4(2)
2629.0(10)	0^+	2629.7(5)	0^+	0.7(1)
		2659(1)	(3^-)	
		2710(1)	(2^+)	7.8(5)
		2749(1)		
		2770(1)	0^+	2.4(2)
		2804(1)		
		2840(1)	0^+	2.4(3)
		2870(1)		
		2923(1)	0^+	2.5(3)
		2950(1)		
		3039(1)		
		3086(1)	(3^-)	
		3127(1)		
		3204(1)		
		3246(1)		
		3341(3)	(4^+)	
		3474(3)	(3^-)	
		3536(3)		
		3611(3)	(3^-)	

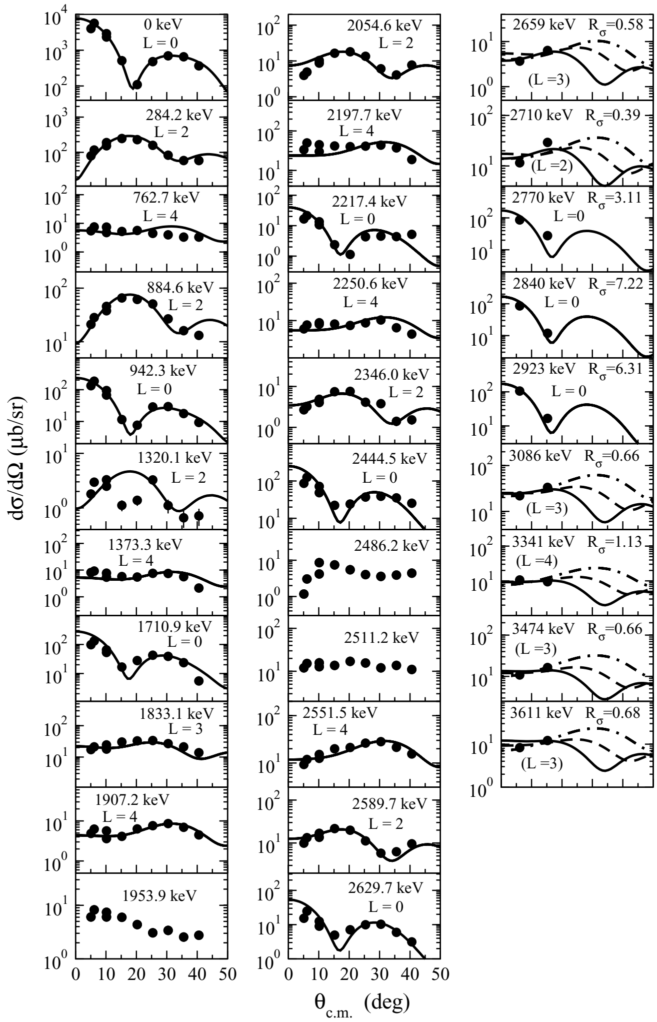

FIG. 3. Experimental angular distributions (points) and DWBA calculations (curves) for the transferred angular momentum $L = 0$, 2, 3, and 4, in the ^{130}Ba$(p,t)^{128}$Ba reaction at 25 MeV. The shape for $L = 0$ transfer is unambiguously identified in both magnetic settings. The angular distributions with only two angles, measured for the second magnetic setting ($E_x > 2600$ keV) cannot discriminate among $L = 2$, 3, and 4 shapes. (The $L = 2$ shapes are represented with full lines, $L = 3$ with dashed lines, and $L = 4$ with dash-dotted lines.) For these angular distributions the L assignment is based on the R_σ ratio used for L-transfer estimation (see text).

$(1h_{11/2},2d_{5/2})$ for $L =$ odd give similar shapes and relative normalization factors.

As can be observed from Fig. 3 most of the experimental angular distributions exhibit a clear pattern, allowing unambiguous spin assignments. For some of the levels with experimental cross sections smaller than 5 μb/sr the angular distributions shape does not allow a unique spin assignment. The spin-parity of the 1320.1 keV level is known from Ref. [4] to be 2^+ and in Fig. 3 we compare our data for this level with an $L = 2$ shape. The agreement is good except for the values measured at $\theta_L = 15^\circ$ and 20°. For the excited states at 1953.9, 2486.2, and 2511.2 keV the cross sections are of the order of 5 μb/sr or below and their angular distributions are structureless. This may indicate a multistep excitation process not considered in the DWBA calculations. For these states it was not possible to assign an L value.

For the levels higher than 2650 keV (appearing only in the spectra of the second magnetic setting) only two angles were measured, as our interest was mainly concentrated in identifying the 0^+ states. For these levels the tentative spin assignments were based on the values of the ratio $R_\sigma = \sigma(6^\circ)/\sigma(15^\circ)$ of the differential cross section at laboratory angles of 6° and 15°, which is a good spin signature especially for 0^+ states. It is larger than 3.0 for $L = 0$ transitions, whereas for higher L transfer the ratios are significantly lower: $R_\sigma \simeq 0.3$ for $L = 2$, $R_\sigma \simeq 0.7$ for $L = 3$, and $R_\sigma \simeq 1.2$ for $L = 4$. For each state the corresponding tentative L-value assignments are given in Fig. 3. The tentative J^π values reported in Table I are based on these R_σ values.

IV. DISCUSSION

Table I summarizes the experimental information obtained in the present study for ^{128}Ba, in comparison with previous knowledge. The relative $2n$-transfer strengths, ϵ, of the $L = 0$ and $L = 2$ transitions are given for the 0^+ and 2^+ states. These strengths are defined as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp} = \epsilon \cdot \left(\frac{d\sigma}{d\Omega}\right)_{\rm DWBA}, \quad (1)$$

where $(d\sigma/d\Omega)_{\rm exp}$ is the experimental angular distribution and $(d\sigma/d\Omega)_{\rm DWBA}$ the corresponding DWBA one. Their normalization is chosen separately for $L = 0$ and $L = 2$ transfers such that $\epsilon = 100\%$ for the ground state and the first excited 2^+ state, respectively.

The present experiment almost doubled the number of observed 0^+ states in ^{128}Ba. It is interesting to compare their distribution in energy and transfer strength with the corresponding values from other neutron-deficient Ba isotopes. As discussed in Ref. [14], the systematics of excited 0^+ states below the pairing gap (calculated from the odd-even mass difference) revealed five states in ^{130}Ba and four states in ^{132}Ba and ^{134}Ba nuclei. A similar counting in ^{128}Ba indicates seven excited 0^+ states in the excitation range up to the pairing gap (2.923 MeV). In Table I are shown energies and transfer strengths for all 0^+ states observed in the present experiment. The excitation energies and $2n$-transfer strengths of the 0^+ states from ^{128}Ba (present work) are qualitatively similar with those from ^{130}Ba (Ref. [14]). Up to 2 MeV there is only one excited 0^+ state populated in ^{130}Ba and two states in ^{128}Ba. Also, there is a group of states close to the pairing gap spread across 1000 keV in ^{128}Ba and 500 keV in ^{130}Ba. The first excited 0^+ state has a small intensity in both nuclei: 2.8(1)% from that of the ground state in ^{128}Ba and 1.1% in ^{130}Ba. Also, its excitation energy is near 1 MeV in both cases: 942.2 keV in ^{128}Ba and 1179.5 keV in ^{130}Ba. The second excited 0^+ state behaves differently in the two nuclei. In ^{128}Ba it is located at 1710.0 keV and has a $2n$-transfer intensity of 3.3(2)% from that of the ground state. In ^{130}Ba it appears at 2230.1 keV with 0.1% intensity. As discussed in Ref. [15], in the O(6) limit, the interacting boson approximation (IBA-1) predicts a vanishing (p,t) transfer to the first excited 0^+ state and a strong one ($\sim$11%) from that to the ground state to the second excited 0^+. In the SU(3) limit of the model there is a strong transfer ($\sim$35%) to the first excited 0^+ state and a vanishing excitation to the second excited 0^+. In this picture, the experimental data obtained in the present work qualitatively place the ^{128}Ba structure between these two limiting cases, but closer to O(6).

To obtain a numerical estimation of the relative (p,t) transfer strengths the wave functions of the low-lying states in ^{128}Ba and ^{130}Ba were calculated in the IBA-1 model. The IBA-1 Hamiltonian was diagonalized with the computer code PHINT and the electromagnetic matrix elements were calculated with the FBEM package [16]. The calculations were performed with a new set of parameters determined to reproduce all available experimental spectroscopic data in these nuclei. The only existing data previous to the present work [3,4] were obtained from the γ-ray spectroscopy experiments in ^{128}Ba and from γ-ray and hadronic probe spectroscopy in ^{130}Ba [14]. The electromagnetic data refer to excitation energies, branching ratios, transition probabilities, and mixing ratios of the γ transitions. By using definitions of bosonic operators from Ref. [17], the IBA-1 Hamiltonian employed in the present calculation is

$$\hat{H}_{sd} = \mathrm{EPS} \cdot \hat{n}_d + 1/2 \cdot \mathrm{QQ} \cdot (\hat{Q} \times \hat{Q})^{(0)} - 5\sqrt{7}\mathrm{OCT} \cdot [(\hat{d}^\dagger \tilde{d})^{(3)} \times [(\hat{d}^\dagger \tilde{d})^{(3)}]^{(0)}, \quad (2)$$

where $\hat{Q}$ is the quadrupole operator given by

$$\hat{Q} = \sqrt{5}[(\hat{s}^\dagger \tilde{d} + \hat{d}^\dagger \hat{s})^{(2)} + \mathrm{CHQ}/\sqrt{5}(\hat{d}^\dagger \tilde{d})^{(2)}] \quad (3)$$

and EPS, QQ, CHQ, and OCT are the model parameters.

The electromagnetic transition operators are

$$\hat{T}(E2) = e_2 \hat{Q} \quad (4)$$

and

$$\hat{T}(M1) = \alpha_1 [\hat{Q} \times \hat{L}]^{(1)} + \gamma_1 [\hat{n}_d \times \hat{L}]^{(1)}, \quad (5)$$

where e_2 represents the boson effective charge and α_1 and γ_1 are other parameters [17].

The search for the model parameters started from the global values given in Ref. [18], where we employed the extended consistent Q-formalism (ECQF) Hamiltonian [the first two terms in Eq. (2)]. To describe simultaneously both electromagnetic and (p,t) data with the ECQF Hamiltonian, it is essential to consider also the octupole term, whose strength is defined by the parameter OCT in Eq. (2). The properties of the 2^+_2 and 0^+_3 states are rather sensitive to this term. The effect of considering a nonvanishing value for the OCT parameter on the observables related to the 2^+_2 and 0^+_3 states from ^{128}Ba can be observed in Table II. The numerical values for the new parameters obtained in the present work are given in Table III for ^{128}Ba and ^{130}Ba. The quality of the present calculation in describing the experimental data can be observed from Fig. 4 for electromagnetic data and from Figs. 5 and 6 for the hadronic ones. The properties of the ground-state band [energies and $B(E2)$] and those of the quasi-γ band are well described. Also the calculated decay patterns of the excited 0^+ states are in good agreement with the measured values.

In Ref. [19] a simple procedure was introduced to obtain a pictorial view of the position of a nucleus in the symmetry triangle based on its ECQF parameters. To reveal this positioning for ^{128}Ba and ^{130}Ba with the present values of the parameters, the octupole term from $\hat{H}_{sd}$ was neglected (since it is considered as a perturbation to the ECQF Hamiltonian), then the procedure from Ref. [19] was applied. The location of the two nuclei based on the parameters from Table III is shown in Fig. 7. The locations of the two nuclei support the idea discussed in Ref. [2] and reiterated in Ref. [14] that Ba isotopes in the $N < 82$ region pass through a transitional

TABLE II. Comparison between the experimental values (Exp.) of the sensitive observables of ^{128}Ba for the 2_2^+ and 0_3^+ states and the corresponding IBA-1 values with two sets of parameters. Set 1 comprises the parameters given for ^{128}Ba in Table III. Set 2 takes the same values of the parameters as those used in Set 1 except for the OCT parameter, which was set to zero. $\epsilon_{2_2^+}$ and $\epsilon_{0_3^+}$ are the $2n$-transfer intensities given in Table I.

State	Observable	Exp.	Set 1	Set 2
2_2^+	$E/E_{2_1^+}$	1	0.9	1.3
	$B(E2; 2_2^+ \to 2_1^+)$ (W.u.)	103	49	76
	$B(E2; 2_2^+ \to 0_1^+)$ (W.u.)	12	5	2
	$\epsilon_{2_2^+}$	25	24	15
0_3^+	$E/E_{0_3^+}$	1	1.01	1.2
	$B(E2; 0_3^+ \to 2_1^+)$ (W.u.)	1	10	0.4
	$B(E2; 0_3^+ \to 2_2^+)$ (W.u.)	<1	18	78
	$B(E2; 0_3^+ \to 2_3^+)$ (W.u.)	<33	1	5
	$\epsilon_{0_3^+}$	3	5	1

TABLE III. The IBA-1 parameters for ^{128}Ba and ^{130}Ba. (See text for details.)

Parameters	Nucleus	
	^{130}Ba	^{128}Ba
EPS	0.777	0.727
QQ	−0.08	−0.08
CHQ	−0.777	−0.777
OCT	−0.0194	−0.0194
e_2	0.135	0.135
α_1	0.002	0.002
γ_1	0.5	0.5

structure situated between vibrational [U(5)] nuclei and γ-soft nuclei [O(6)].

With the wave functions obtained by diagonalizing the Hamiltonian from Eq. (2) with the parameters from Table III $2n$-transfer intensities between the ground state of ^{130}Ba and the first four 0^+ states from ^{128}Ba were calculated. These

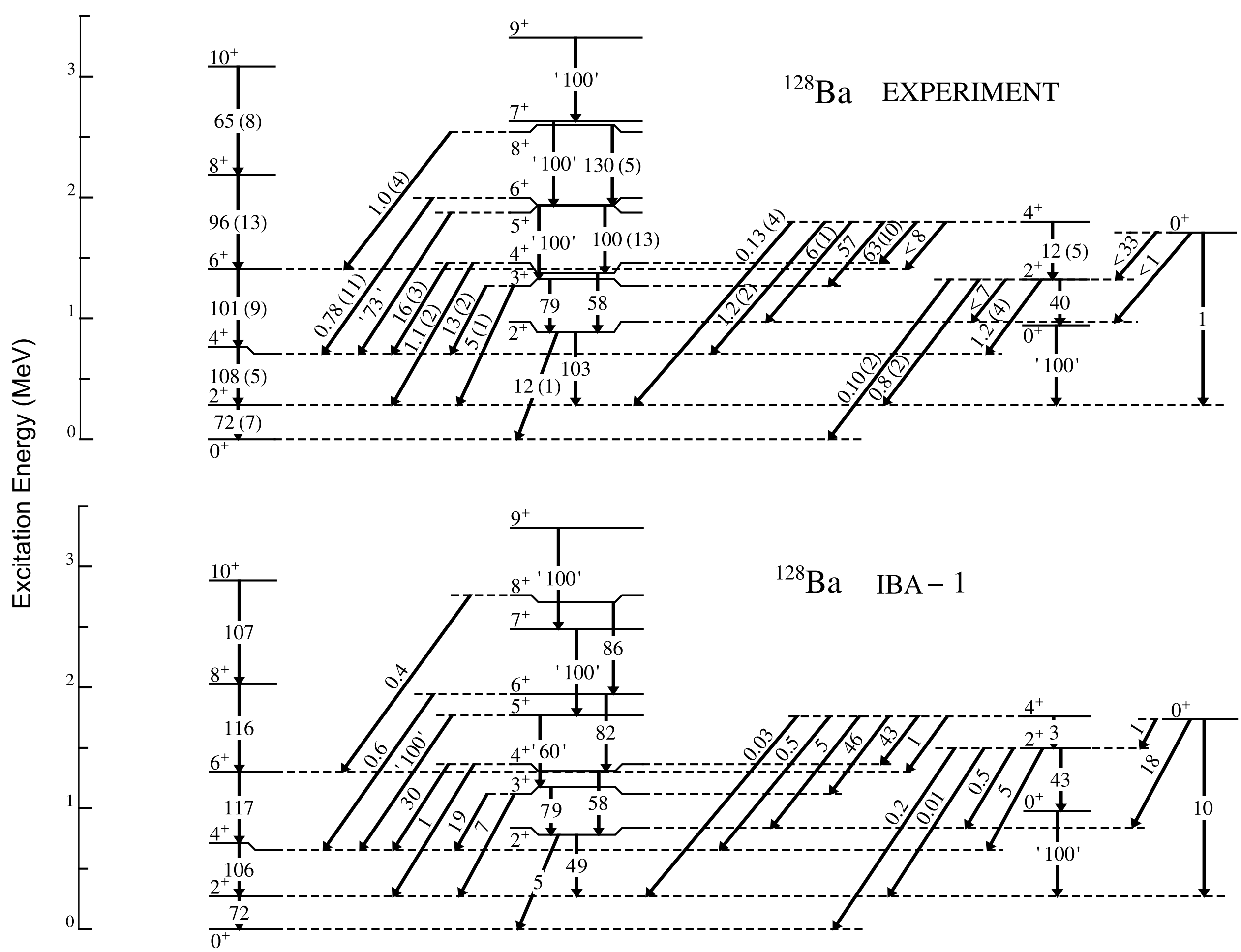

FIG. 4. Experimental excitation energies and transition probabilities or relative intensities of the γ-ray transitions for the low-lying levels of ^{128}Ba compared with the present IBA-1 model calculation. $B(E2)$ values are indicated for some transitions. The numbers within quotation marks are the relative values (branching ratios) for decays where the absolute values are not known. The parameters used for calculations are those from Table III. The γ-ray experimental data are taken from Refs. [3,4].

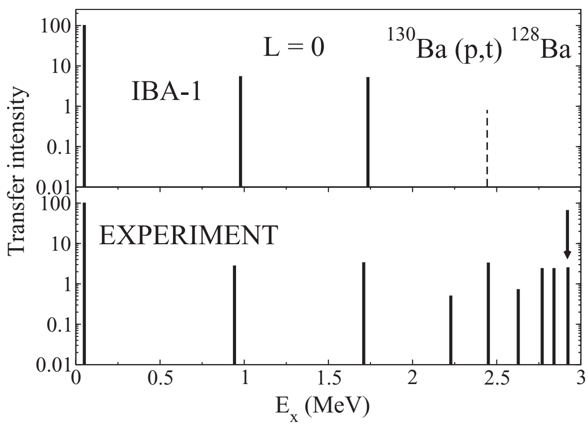

FIG. 5. Comparison of the measured $L = 0$ transfer intensities for the 0^+ states in ^{128}Ba with the IBA-1 predictions. Values are normalized to 100 corresponding to the $0_1^+(^{130}\mathrm{Ba}) \rightarrow 0_1^+(^{128}\mathrm{Ba})$ transition. The vertical arrow indicates the pairing gap, calculated from the odd-even mass difference. The vertical dashed line indicates only the energy of the next excited 0^+ state predicted by the IBA-1. It is located at 2307 keV and has a vanishingly small (p,t) intensity.

calculations were performed with the computer code FTNT, which uses for the $L = 0$ transfer operator the leading order term proportional with the bosonic $\hat{s}$ operator [16]:

$$\hat{P}_\nu^{(0)} = \alpha_\nu \left(\Omega_\nu - N_\nu - \frac{N_\nu}{N}\hat{n}_d\right)^{\frac{1}{2}} \left(\frac{N_\nu + 1}{N+1}\right)^{\frac{1}{2}} \hat{s}, \qquad (6)$$

where Ω_ν is the pair degeneracy of neutron shell, N_ν is the number of neutron pairs, N is the total number of bosons, and α_ν is a constant.

In the excitation range below 3 MeV, the calculation produced two excited 0^+ states with significant (p,t) strengths. The first one at 978.0 keV has 5.4% that of the ground state strength and the second one at 1735.6 keV has 5.1% that of the ground state. Their comparison with the experimental results is shown in Fig. 5. Our calculations provide a good description of the excitation energy and (p,t) strength for the first two excited 0^+ states. In the excitation range up to the pairing gap the model produces only another 0^+ state at 2443.9 keV. This state has a transfer intensity much smaller than the experimental ones in the same excitation range.

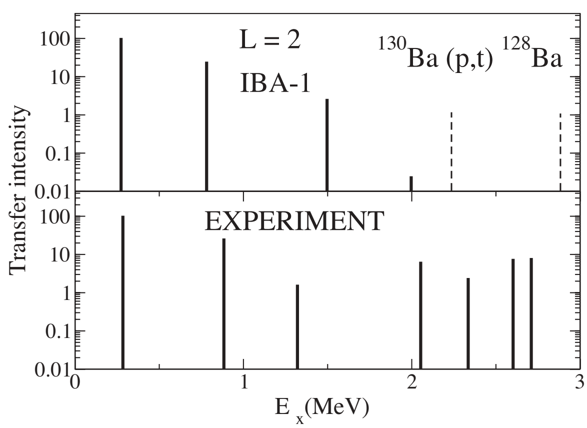

FIG. 6. Comparison of the experimental $2n$-transfer intensity for the 2^+ states and IBA-1 predictions. The intensities are normalized to the $0_1^+(^{130}\mathrm{Ba}) \rightarrow 2_1^+(^{128}\mathrm{Ba})$ transition. The vertical dashed line indicates the position of the next two excited 2^+ states produced by the IBA-1 model. The FTNT code prohibits calculation of the $2n$-transfer matrix elements to more than four states.

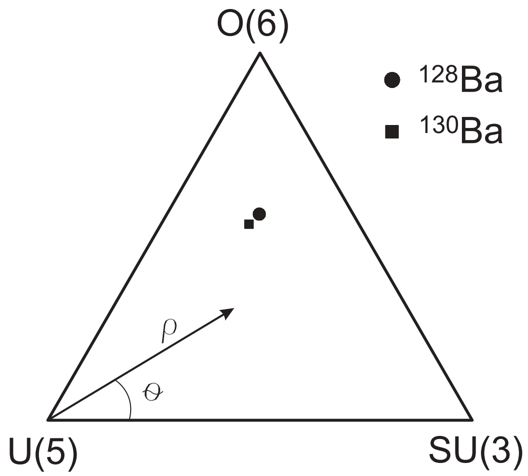

FIG. 7. The positioning of the ^{128}Ba and ^{130}Ba nuclei in the IBA symmetry triangle based on the values of the IBA-1 parameters (Table III) and the procedure from Ref. [19] (see text for details). Also included in the figure are the polar coordinates ρ and θ as defined in Ref. [19].

The two-neutron transfer intensity to the 2^+ states also offers important clues about the nuclear structure. For the $0^+_{\mathrm{g.s}} \rightarrow 2^+$ transitions, the $L = 2$ transfer operator used in the FTNT program contains three different terms, proportional to the $\hat{d}^\dagger$, $\hat{s}^\dagger(\hat{d}^\dagger\tilde{d})^2$, and $(\hat{s}^\dagger\hat{s}^\dagger\tilde{d})$ operators:

$$\hat{P}_{\nu,\mu}^{(2)} = \frac{N_\nu + 1}{N+1}\left[\alpha\left(\Omega_\nu - N_\nu - \frac{N_\nu}{N}\hat{n}_d\right)^{\frac{1}{2}}\left(\frac{N_\nu+1}{N+1}\right)^{\frac{1}{2}}\hat{d}_\mu^\dagger + \beta\frac{(\Omega_\nu - N_\nu)^{1/2}}{\sqrt{5}}\hat{s}^\dagger(\hat{d}^\dagger\tilde{d})^{(2)} + \gamma(\hat{s}^\dagger\hat{s}^\dagger\tilde{d})\right], \qquad (7)$$

where α, β, and γ are constant coefficients.

The intensity of these transitions is computed as a coherent sum of the matrix elements of these three operators. The upper panel of Fig. 6 presents the model predictions for $L = 2$ two-neutron transfer intensity by considering equal values for the parameters α, β, and γ. Up to 2 MeV there are three 2^+ states observed in the present experiment with excitation energies of 284.0, 884.5, and 1321.1 keV, respectively. Their transfer strengths, normalized to that of the first excited 2^+ state are, respectively, 100%, 25.5%, and 1.5%. As can be observed from Fig. 6 for these states the calculated (p,t) transfer intensities are in good agreement with experiment. Namely, the model places the first three 2^+ states at energies of 273.4, 781.3, and 1496.7 keV, with calculated intensities of 100%, 24%, and 2.5%, respectively. Also the simple picture of the O(6) limit predicts the second excited 2^+ state with a (p,t) intensity of ∼20% from the first excited 2^+ state and a vanishing one for the third excited 2^+ state, which is in good agreement with our experimental data. Up to 3 MeV, the model predicts three other 2^+ states, without a clear correspondence with the experimental ones.

Both the $L = 0$ and $L = 2$ two-neutron transfer intensity pattern for the low-lying states are consistent with the IBA-1 model predictions for a transitional region close to the O(6) dynamical symmetry. The role of mixing of the collective states with the intruder (quasiparticle) ones may be of major importance in understanding the structure of ^{128}Ba and ^{130}Ba near the pairing gap, as discussed for other even-even Ba isotopes (Ref. [14] and references therein).

V. SUMMARY

In summary, the ^{128}Ba nucleus was experimentally investigated for the first time using a (p,t) reaction at an incident energy of 25 MeV. The tritons were recorded with a high-resolution focal plane detector. The analysis of the triton spectra allowed us to observe 27 new levels below 3.7 MeV. For some of these states a spin-parity assignment was made. Both the energy and the spin-parity were confirmed for most of the previously known states. The experimental two-neutron transfer strengths of the low-lying 0^+ and 2^+ states were compared with predictions of the IBA-1 model. The calculations were carried out by employing a new set of model parameters determined to describe simultaneously both electromagnetic and (p,t) data. The calculations confirmed previous conclusions of γ-ray spectroscopy studies that the structure of ^{128}Ba nucleus is close to the O(6) dynamical symmetry.

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