# Monopole transfer strength to $^{132,134}$Ba in $(p,t)$ reactions and the interacting boson approximation

Gh. Cata-Danil, D. Bucurescu, L. Trache,* and A. M. Oros†
*Institute of Atomic Physics, P.O. Box, MG-6, Bucharest, Romania*

M. Jaskola‡
*INFN, Sezione di Milano, I-20133 Milano, Italy*

A. Gollwitzer, D. Hofer, S. Deylitz, B. D. Valnion, and G. Graw
*Sektion Physik der Universität München, D-85748 Garching, Germany*

(Received 18 December 1995)

The level structure of $^{132,134}$Ba was investigated in $(p,t)$ transfer reactions. High resolution spectra (7–8 keV full width at half maximum) with targets from a mass separator allow us to resolve levels up to 4.0 MeV. New $0^+$ states are identified. The monopole transfer strength shows distributions similar to those observed for $^{194,196}$Pt. This is consistent with the O(6) limit of the interacting boson approximation (IBA-1) model, without ruling out other, more microscopically based interpretations for the low-lying structure of these nuclei. We also compare with the IBA-2 model and geometrical model calculations. [S0556-2813(96)04209-4]

PACS number(s): 21.60.Fw, 21.60.Ev, 25.40.Hs, 27.60.+j

The low-lying excitations of even Pt nuclei of mass 194 and 196 are of interest as a realization of a $\gamma$-soft collective structure (weak restoring force in the $\gamma$ degree of freedom). Similar properties were proposed for the even Ba isotopes near mass 132 [1]. In the interacting boson approximation (IBA-1) model [2] these features are described in the limit of the O(6) dynamical symmetry. The resemblance of these Ba and Pt isotopes is expected due to their location with respect to the closed shells.

The similarity of $^{134}$Ba $(N=5)$ and $^{196}$Pt $(N=6)$, stated by Casten and von Brentano [1], is based on the energy spectra and electromagnetic transition probabilities [3]. For $^{132}$Ba $(N=6)$ knowledge is rather limited. The information on nonyrast bands is incomplete especially on the low-lying excited $0^+$ states. For $^{196}$Pt the two-neutron $L=0$ transfer strength distribution is consistent with the IBA-1 prediction on its O(6) limit. A similar consistency is shown by the present data on $^{132,134}$Ba. The $L=0$ transfer of a neutron pair as $s$ boson has been treated also in an IBA-2 description of these Pt isotopes [4]. It should be noted, however, that the theoretical description of the two-nucleon transition strengths to the excited states remains a challenge [5]. The pairing interaction [6] should concentrate almost all of the $L=0$ strength in the ground-state to ground-state transitions. There are exceptions from this pure pairing expectation as observed in $^{120,122}$Sn [7], $^{166}$Er [8], $^{200}$Hg [9], and $^{150}$Sm [10]. Strong transitions to excited $0^+$ states appear in regions of subshell closure or of a gap in the Nilsson diagram with a magnitude comparable to the neutron pairing strength. This limits the coherent summation of the transition amplitudes to the superconducting ground state and produces large strengths to an excited $0^+$ state. In a macroscopic picture considerable strength to excited $0^+$ states in $(p,t)$ is interpreted as a consequence of a change of shape of the ground states of the nuclei as observed in the Sm isotope chain [10]. However, from the simple analysis of the two-neutron separation energies along the even-$A$ isotopes of Ba such a change of the ground-state shape is not observed.

For the lighter even Ba isotopes the experimental information on two-neutron transfer strength is scarce. According to our knowledge there is only one preceding $(p,t)$ reaction study [11] of these nuclei. Because of momentum matching at the bombarding proton energy of 52 MeV, higher spin states have been excited preferentially . Only in $^{134}$Ba has one weakly excited $0^+$ state been observed. For $^{132}$Ba the most recent compilation [3] reports on one excited $0^+$ state only, tentatively assigned at 1.504 MeV, whereas for $^{134}$Ba five excited $0^+$ states [12] are known.

To provide experimental information appropriate to discuss $\gamma$-soft features of the Ba isotopes we have measured the two-neutron transfer. We concentrate here on the $L=0$ transitions and compare their strengths with those observed for Pt and with calculations in the O(6) limit of the IBA model.

In the measurement of $^{134,136}$Ba$(p,t)^{132,134}$Ba reactions at the Q3D spectrograph, with 25 MeV protons of the Munich tandem facility, we proceeded as in Ref. [13]. The focal plane detector [14] provides particle identification, focal plane reconstruction, and background reduction, accepting only events within the correct angle of incidence. The energy resolution obtained is 7–8 keV, determined by the target. This allows us to resolve most of the states populated. Mass-separated targets of the respective Ba isotopes of typically 100 $\mu$g/cm$^2$ on 30 $\mu$g/cm$^2$ carbon foils had been prepared at the PARIS isotope separator in Orsay. The negligible contribution of the other Ba isotopes has been carefully checked by observing with the $^{134}$Ba target in the $\theta_{\rm lab}=6°$ spectrum the ground-state transitions from the nearby stable isotopes $^{132}$Ba, $^{135}$Ba, and $^{136}$Ba with intensities of 0.08%, 0.08%, and 0.01% relative to the transition from $^{134}$Ba, respectively. No other contaminants have been identified in the spectra.

*Present address: Cyclotron Institute, Texas A&M University, College-Station, Texas.

†Present address: Institut für Kernphysik, Universität zu Köln, Germany.

‡Permanent address: Soltan Institute of Nuclear Studies, Swierk, Poland.

 

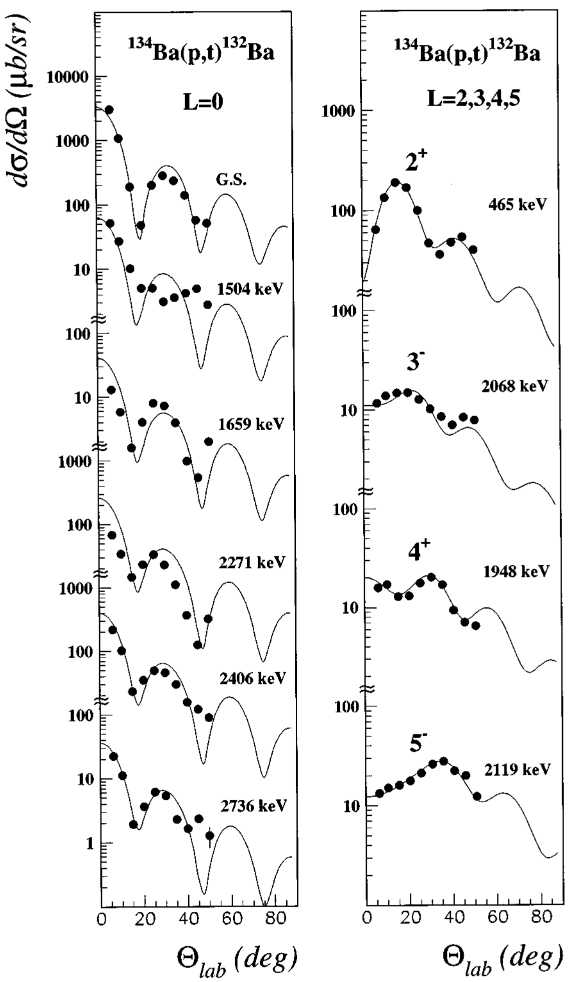


FIG. 1. Angular distributions of the cross sections for $^{134}$Ba$(p,t)^{132}$Ba with DWBA calculations. At the left side $L=0$ transitions for the lowest six $0^+$ states and at the right side selected $L=2,3,4,5$ transitions. Note the changes in the scales. For the DW calculations the code TWOFNR, with standard optical model parameters has been used.

For $^{132}$Ba, in the range of excitation energy up to 4.0 MeV, we observe 57 levels, 27 of them for the first time. Angular distributions have been measured (Fig. 1) showing typical shapes which allow unique assignments of transferred angular momentum $L$ and thus $J^\pi$. A good signature for $L=0$ transitions (see Fig. 1, left panel) is the value of the ratio $R_\sigma=\sigma(6°)/\sigma(15°)$ of the differential cross section at the laboratory angles of 6° and 15°. It is larger than 3.0 for $L=0$ transitions, while for higher $L$ transfers shown in Fig. 1 (right panel) these ratios are *significantly* lower: $R_\sigma\simeq$ 0.3 $(L=2)$ , 0.7 $(L=3,5,7)$, and 1.2 $(L=4)$. The observations are in agreement with distorted-wave Born approximation (DWBA) calculations shown as solid curves in Fig. 1, where the normalization factors are adjusted to account for the respective strength. In Table I the results for $0^+$ states observed in this experiment are listed. The results for transitions with $L\neq 0$ will be presented and discussed elsewhere.

For $^{134}$Ba, to determine the $L=0$ strength distribution we measured at these two angles (6° and 15°) only. Up to 4 MeV we observe 44 levels, 18 of them new. From the ratio $R_\sigma$ we identify the five excited $0^+$ states already known [12] and six additional ones (Table I). The purity of the target and the resolution of the spectra rule out that these newly observed $0^+$ states belong to other Ba isotopes or nuclei.

TABLE I. Excitation energies and *enhancement factors*[a,b] for $L=0$ transitions obtained in the present $^{134,136}$Ba$(p,t)\,^{134,132}$Ba experiments.

| $^{134}$Ba$(p,t)\,^{132}$Ba | | $^{136}$Ba$(p,t)\,^{134}$Ba | |
|---|---|---|---|
| $E_x$ (MeV) | $\epsilon$ (%) | $E_x$ (MeV) | $\epsilon$ (%) |
| 0.000 | 100. | 0.000 | 100. |
| 1.504 | 2.12 | 1.759 | 3.73 |
| 1.659 | 0.55 | 2.161 | 14.85 |
| 2.271 | 3.37 | 2.336 | $\leqslant$1.05 |
| 2.406 | 11.15 | 2.378 | 0.52 |
| 2.736 | 1.29 | 2.485 | 6.67 |
| 2.886 | 0.75 | 2.722 | 1.99 |
| 3.412 | 1.15 | 2.874 | 1.81 |
| 3.445 | 1.98 | 2.996 | 0.63 |
| 3.751 | 1.50 | 3.181 | 1.40 |
| 3.812 | 2.19 | 3.501 | 1.47 |
| 3.882 | 0.92 | 3.618 | 1.22 |

[a]The factors are based on the $\sigma(\theta=6°)$ values. Their uncertainties are less than 15 %.

[b]The DWBA calculations assume a cluster transfer form factor. The involved configuration was $(2d_{3/2})^2$ for $L=0$. Alternative form factors such as $(1h_{11/2})^2$, $(1g_{7/2})^2$, or $(3s_{1/2})^2$ give similar results.

For the energy calibrations of the $^{132,134}$Ba spectra we used as input the gamma-ray spectroscopic information from NDS [3,12]. Up to $E_x$=2.5 MeV the uncertainty of the excitation energy is lower than $\pm 1$ keV. For higher energies, due to the lack of reference transitions, the presence of systematic shifts of up to $\pm 10$ keV, when approaching $E_x=4$ MeV, cannot be excluded.

The strengths of the $L=0$ transitions (see Table I) are described by *enhancement factors* $\epsilon$ which are related to the experimental cross section by [15] $\sigma_{\rm expt}(\theta,E_x^i)=\aleph\epsilon(E_x^i)\sigma_{\rm DWBA}(\theta,E_x^i)$, where $\aleph$ is an overall factor to normalize the ground-state transition $E_x$=0 keV to $\epsilon=100\%$. We use the DWBA as a reference to correct for $Q$-value dependence. Because of the particular shape of $L=0$ transitions, $\epsilon(E_x^i)$ is determined from the differential cross sections at $\theta=6°$. The same procedure has been applied in the analysis of $(p,t)$ reactions from Pt isotopes [15,16].

In Fig. 2(a) the experimentally determined monopole strength distributions for $^{132,134}$Ba are compared with those for $^{194,196}$Pt of Cizewski *et al.* [15]. The energy range is restricted to $2\Delta_n$, the value of twice the neutron pairing gap (shown as dotted lines), to avoid the region of noncollective quasiparticle excitations. The $\epsilon$ values are indicated numerically and represented graphically by the length of the horizontal bars at the respective excitation energies.

As a common feature of all four nuclei we observe transition strengths near 10% at excitation energies where in the O(6) limit the second excited $0^+$ state is expected. Below these states the first excited $0^+$ state and, in the case of $^{132}$Ba, $^{194}$Pt, and $^{196}$Pt, one or two additional $0^+$ states have much weaker transition strengths. Obviously we observe in Ba a similar distribution of monopole strength as Cizewski

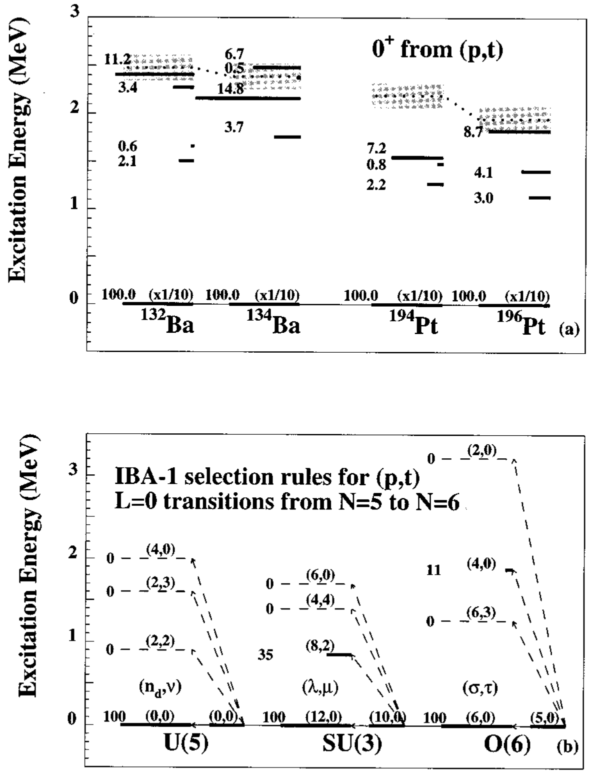


FIG. 2. Comparison of the $L=0$ transfer strength for $^{132,134}$Ba with results for $^{194,196}$Pt from Ref. [15] (upper frame) and with the predictions of the IBA-1 model in the pure dynamical symmetry limits (lower frame). The lengths of the horizontal bars are proportional to the strength. The *dotted* lines are the $2\Delta_n$ values (see text) calculated in the Nilsson prescription and the shaded region represent the average departure from the $12A^{-1/2}$ trend [26]. The quantum numbers given in the lower frame are those of Ref. [2].

*et al.* [17] observed for $^{196}$Pt. In a phenomenological picture these distributions are consistent with the O(6) limit predictions of the IBA-1 model as was previously found from the electromagnetic observables. However, as mentioned before, this pattern is not unique to O(6) and more microscopically based alternative explanations could produce similar results.

In Fig. 2(b) the level schemes, taken from Iachello and Arima [2], are schematic IBA-1 calculations for $0^+$ states in $N=6$ nuclei [as the final states in $^{134}$Ba$(p,t)^{132}$Ba and $^{198}$Pt$(p,t)^{196}$Pt] for the U(5), SU(3), and O(6) limits of the IBA model. For U(5) and SU(3) the energy scales are in arbitrary units and differ from each other, whereas for O(6) the energies are typical values for nuclei near $A=130$ as determined by formula (2) from Ref. [1]. Indicated are also values of the transfer strengths, and their derivation is discussed below.

In $(p,t)$ the typical feature of the O(6) limit is a vanishing cross section of the first excited $0^+$ state and a strength near 11% for the second excited $0^+$ state. The experimental $(p,t)$ $L=0$ cross sections, as discussed above, follow this prediction.

Ragnarsson and Broglia showed that for two-nucleon transfer significant strengths to excited states may result from details in the microscopic structure [18,19]. This could also explain the experimental results obtained in the present work. However, the mean behavior of these microscopic features should be included in a macroscopic model such as IBA in our case.

Because of intruder configurations (states with wave functions beyond the IBA space), additional $0^+$ states may exist in this range. Because of their noncollective (four-quasiparticle, etc.) nature, they will be excited only weakly in $(p,t)$. Thus the observation of additional, weakly excited $0^+$ states in the spectra [Fig. 2(a)] should not affect the comparison of strongly excited states with the IBA predictions [Fig. 2(b)].

In lowest order the monopole transition amplitude for transfer from a $N$ boson to a $N+1$ boson nucleus in $(p,t)$ is proportional to $s^\dagger$, the creation operator of an $s$ boson [2]:

$$P^{(0)}_{+2\nu}=\langle[N+1],0^+_n|\sqrt{(N_\nu+1)/(N+1)}s^\dagger \times\sqrt{\Omega_\nu-N_\nu-(N_\nu/N)\,n_d}|[N],0^+_1\rangle.$$

In the U(5) limit in lowest order the ground state has $n_s=N$ $s$ bosons. The operator $s^\dagger$ connects the ground states of the adjacent U(5) nuclei (with $N$ and $N+1$ bosons), but excludes transitions to excited $0^+$ states due to their $n_d>0$ components in the wave function ($n_d=N-n_s$ is the number of $d$ bosons in the respective component of the wave function). If anharmonicity is allowed, the wave functions, e.g., of the U(5) ground state (the zero phonon state) and the first excited U(5) $0^+$ state (the two-phonon state) may be mixed to some extent and thus provide some transition strength to the first excited $0^+$ state.

In the SU(3) and O(6) limits both the ground states and excited $0^+$ states have configurations in the wave functions with $d$-boson numbers $n_d\neq 0$. The $L=0$ transitions to excited $0^+$ states result from configurations having identical $d$-boson structure in the initial and final state wave functions.

In the SU(3) limit $s^\dagger$ connects $(\lambda,\mu)=(2N,0)$ of the target only with $(\lambda,\mu)=(2N+2,0)$ of the ground state and $(\lambda,\mu)=(2N-2,2)$ of the first excited $0^+$ state in the final nucleus.

The O(6) eigenfunctions have a particular quantum number $\tau$, which is related to the expectation value of the $d$-boson number $\langle n_d\rangle$ . For $L=0$ the $\tau$ selection rule is $\Delta\tau=0$, while the $\sigma$ selection rule is $\Delta\sigma=\pm 1$, since addition or substraction of an $s$ boson changes $N$ by one unit [15]. In the O(6) spectrum the ground states have $\tau=0$ ($\langle n_d\rangle\cong 2$). The first and second excited $0^+$ states have $\tau=3$ ($\langle n_d\rangle\cong 3$) and $\tau=0$ ($\langle n_d\rangle\cong 2$), respectively. Thus in the O(6) limit the strongest $L=0$ transitions are the ones populating the ground state and the *second* excited $0^+$ state.

In the three limiting cases of IBA the transfer intensities are obtained analytically with reasonable accuracy if one replaces the operator $n_d$ by the expectation value in the ground state $\langle n_d\rangle$. Using this approximation (included in relation 2.234 of Ref. [2]) we obtain the $\epsilon_i$ values (relative monopole strength distribution) shown in Fig. 2(b) for transitions from a nucleus with $N=5$ to $N=6$. In agreement with the O(6) expectation for all four nuclei the experiment shows higher excited $0^+$ states that are much stronger populated than the first excited $0^+$ states and with strengths consistent with the model predictions for the second excited $0^+$ states.

Including $g$ bosons in the IBA model [21] the number of dynamical symmetries is much higher than in the IBA1-sd model due to the U(15) group structure of the sdg model. It may cover in an effective way transitional situations between the three symmetries of the IBA1-sd model. For the lowest $0^+$ states one does not expect significant changes using the IBA1-sdg model instead of the IBA1-sd model. This can be seen comparing the $(p,t)$ study of the Sm chain in the sdg model of Ref. [21] with the one of Ref. [22] in the sd model. In order to emphasize the gamma-soft features we keep to the more intuitive frame of the IBA1-sd model.

With respect to the understanding of the location of the second excited IBA $0^+$ states, we refer to a detailed study of the Pt isotopes within the IBA-2 model of Ref. [4]. They discuss how in $^{194}$Pt the third excited $0^+$ state should correspond to the ''second'' collective state of the model, the second $0^+$ being outside the IBA-2 space $U_\pi(6)\otimes U_\nu(6)$. The same observation is made in the experimental work of Ref. [16] where a quasiparticle structure is suggested for the second excited $0^+$ state. For $^{196}$Pt due to an observed upper limit for the $B(E2)$ transition strength to the $2_1^+$ state the O(6) quantum number $\sigma=N-2$ has been assigned to the $0^+$ state at $E_x=1402.7$ keV [23]. This state is seen in $(p,t)$ with 4.1% of the strength of the ground state. For the next excited $0^+$ state carrying in $(p,t)$ 8.7% of the ground-state strength the electromagnetic transition rates are not known. To our understanding from the knowledge about $B(E2)$ values there is no restriction to assign predominance of $\sigma=N-2$ to the wave function of the latter state.

For $^{132}$Ba, the ''standard'' IBA-2 numerical study of Ref. [24] predicts two $0^+$ states below 2.5 MeV, at 1.521 MeV and 1.925 MeV. This is in reasonable agreement with a geometrical-model study of $^{132}$Ba in the general collective model (GCM) of Gneuss and Greiner, where two excited $0^+$ states at 1.569 MeV and 2.485 MeV are predicted [25]. We observe two weakly excited states near 1.6 MeV and two strongly excited states at 2.271 MeV and 2.406 MeV. The next higher state, not shown in Fig. 1, is at 2.736 MeV and is only weakly excited as all the other, higher-lying states (see Table I). We understand the two weakly excited states near 1.6 MeV as resulting from the first excited $0^+$ state of IBA space and an intruder state, and the two strongly excited states at 2.271 MeV and 2.406 MeV again as a further intruder state and the second excited $0^+$ state of IBA, respectively. This latter state with the large transfer strength, predicted by the model, apparently is mixed to some extent with the nearby intruder state.

We would like to emphasize that our experimental new data concerning the isotopes $^{132,134}$Ba do not support uniquely the O(6) structures. They are just rather consistent with this phenomenological explanation that we have adopted, as are also all the previous electromagnetic data.

To summarize, we observe in $(p,t)$ reactions $0^+$ states in $^{132}$Ba and $^{134}$Ba in the region of the IBA collective excitations which resemble those in $^{194,196}$Pt in respect to the excitation energies and strengths. These are consistent with the O(6) dynamical symmetry limit of the IBA-1 model, but cannot make a definitive distinction among various structure models as long as similar patterns of strengths are observed in nuclei known to have different structure. The results agree with the existing information from the electromagnetic data. Our results do not rule out alternative interpretations based on models considering explicitly the fermionic degrees of freedom as have been done for other mass regions. However, for the observed strength at lower excitation energy a nearly quantitative description is provided by the IBA model if some mixing with the intruder states is considered. Still the role of intruder states in this region is not yet clarified, and a systematic study extending to the lighter barium isotopes might provide information in this respect.

We are very grateful to Ch. Briancon, R. Meunier, and D. Le Du for the preparation of the targets at the Orsay mass separator. Schematic shell model calculations of R.F. Casten were very helpful to understand the noncollective aspects of nuclear structure. Continuous support of L. Zetta and P. Guazzoni from INFN Sezione di Milano is gratefully acknowledged. Two of us (Gh.C.-D. and M.J.) wish to express their gratitude to the Sektion Physik of the LMU and acknowledge financial support of the International Office in Karlsruhe and Istituto Nazionale di Fisica Nucleare. One of us (A.M.O.) acknowledges the support of DAAD, Bonn. This work was supported in part by grants of the DFG under II C4-Gr 894/2 and IFA contract-150B/A4.

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