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Spectral property and its shape transition on $^{72-84}$Kr isotopes in microscopic core plus two-quasiparticle approach*

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By using a microscopic sdIBM-2+2q.p. approach, the levels of the ground-band, γ-band and partial two-quasiparticle bands for $^{72-84}$Kr isotopes are calculated. The data obtained are in good agreement with the recent experimental results, and successfully reproduce the nuclear shape phase transition of $^{72-84}$Kr isotopes at zero temperature. The ground-state band is described successfully up to $J^{\pi}=18^{+}$ and E_x=10.0MeV. Based on this model, the aligned requisite minimum energy has been deduced. The theoretical calculations indicate that no distinct change of nuclear states is caused by the abruptly broken pair of a boson, and predict that the first backbending of Kr isotopes may be the result of aligning of two quasi-neutrons in orbit $g_{9/2}$, which gains the new experimental support of the measurements of g factors in the $^{78-86}$Kr isotopes.

Keywords: microscopic sdIBM-2+2q.p. approach, high-spin states, shape phase transition, $^{72-84}$Kr isotopes

PACC: 2100, 2700

1. Introduction

The phenomenological interacting boson model (IBM) theory has been proved very successful in the description of nuclear collective motion, and it unifies the descriptions of $U(5)$-vibration, $SU(3)$-rotation and $O(6)$-γunstable symmetry under its own frame;[1] its extension, IBM+2q.p. model, has obtained a larger success in the description of nuclear high-spin state.[2] Recently, attention has been drawn to the study of nuclear shape transition and phase coexistence in transitional region by IBM.[3−6] The microscopic sdIBM-2 approach, proposed as a microscopic realization in Ref.[7], has reproduced very successfully the nuclear low-spin phenomenon; its extension, sdIBM-2+2q.p. approach, has described very satisfactorily the high-spin phenomenon in three regions,[8−10] and has reproduced very successfully the high-spin state of nuclei $^{66-70}$Ge[11] and $^{112-130}$Xe.[12,13]

The recent experimental study showed that even Kr isotopes are longer chains; they have complex ground-state bands and two-quasiparticle rotatory bands; the structure of more levels has been identified, while a few rotatory bands have not been well identified.[14−21] They become an ideal object to examine various nuclear models. In fact, applying the phenomenological IBM-2, in 1979, Kaup and Gelberg[22] first studied $^{74-82}$Kr isotopes, but only did it to the 6^{+} state; in 1995, Dejbakhsh *et al*[23] only to the 8^{+} state; in 2000, Giannatiempo *et al*[24] just studied the collective excited spectra of $^{74-82}$Kr isotopes. But, the high-spin states and the backbending phenomenon are not mentioned in their papers.

The main purpose of the present paper is to investigate the spectral property as well as the shape transition of $^{74-84}$Kr isotopes from microscopic viewpoint, and to demonstrate that the ability of the microscopic sdIBM-2+2q.p. approach may well describe the collective states, as well as the shape transition in a nucleus even if the angular momentum of the nucleus is close to a maximum permitted by the valence nucleons, and that the possibility to obtain the microscopic information on nuclear phenomenon extracted from this is helpful in a deeper understanding of the

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shape transition.

2. Outline of the theoretical approach

The phenomenological IBM assumes that nucleons exist as pair-form in a nucleus while a nucleus is in a low-excited and ordinary rotary state, i.e. a superfluid state; once the nucleus is in a high-energy excited or rotating at a high-speed state, a boson at least may be decoupled from the strange-coupled collective state as a non-collective non-coupled fermion-pair, and breaks into two nucleons, which would occupy one of the intruder orbits $g_{9/2}$, $h_{11/2}$, $i_{13/2}$, and pass into an aligning. All the other valence nucleons can form a collective core described approximately by the phenomenological IBM-2. This is the so-called phenomenological IBM-2+2q.p. model.[2] The microscopic theory for the high-spin states is simply obtained by applying the microscopic sdIBFM-2 formalism to the sdIBM-2+2q.p. model. The detailed description of the microscopic high-spin states theory can be found in Refs.[7], [8] and [12].

It is well known that the intrinsic structure of $U(5)$-, $O(6)$-, and $SU(3)$-symmetries at zero temperature for the phenomenological IBM results from the variation in levels caused by a stronger spin–orbit coupling. In this approach, by means of adjusting the parameters of nucleon–nucleon effective interaction, the spectra of coupled bosons will reproduce the experimental results, the macroscopic process of phase transition will reappear microscopically, and the microscopic information on the boson structure and the variation in single-particle levels are obtained.

3. Calculated results and discussion

For $^{74-84}$Kr isotopes, the valence nucleon configurations are

$$(1p_{3/2}, 1f_{5/2}, 2p_{1/2}, 1g_{9/2})^{8}$$

$$(1p_{3/2}, 1f_{5/2}, 2p_{1/2}, 1g_{9/2})^{N_n},$$

with N_n=8, 10, 12, 14, 16, 18, 20. To study how the parameters change with increasing neutron number, without loss of generality, the nucleons have been treated as particles. Parameters $g_0^{(\sigma)}$, $G_2^{(\sigma)}$, $K^{(\sigma)}$ (σ=n,p) and $K^{(\mathrm{np})}$ are the strength of the pairing force, quadrupole pairing force, and quadrupole–quadrupole force for the identical nucleons, and the neutron-proton force of quadrupole–quadrupole type respectively. The single-particle energies for open shells are listed in Table 1 and the strengths of the nucleon–nucleon effective interactions are listed in Table 2. Other energy values concerning this paper are given in Table 3.

Table 1. Single-particle energies of the valence nucleon[11] (MeV).

nlj	$2p_{3/2}$	$1f_{5/2}$	$2p_{1/2}$	$1g_{9/2}$
neutron	4.00	5.10	6.00	6.40
proton	4.00	5.10	6.20	7.05

Table 2. The parameters of nucleon–nucleon effective interaction (MeV).

Isotopes	$g_0^{(\mathrm{n})}$	$G_2^{(\mathrm{n})}$	$K^{(\mathrm{n})}$	$g_0^{(\mathrm{p})}$	$G_2^{(\mathrm{p})}$	$K^{(\mathrm{p})}$	$K^{(\mathrm{np})}$
72	0.0640	0.0760	0.0200	0.0645	0.0720	0.0200	0.0170
74	0.0640	0.0920	0.0220	0.0645	0.0720	0.0220	0.0540
76	0.0650	0.0860	0.0250	0.0650	0.0705	0.0250	0.0440
78	0.0670	0.0831	0.0260	0.0650	0.0700	0.0250	0.0290
80	0.0851	0.0677	0.0350	0.0650	0.0700	0.0350	0.0240
82	0.1100	0.0510	0.0370	0.0670	0.0690	0.0370	0.0160
84	0.1320	0.0560	0.0380	0.0700	0.0650	0.0370	0.0160

Table 3. Total energy E, non-perturbation energy E', aligned energy $E_{\rm align}$ of bosons (MeV).

Isotopes	States	$E_{\rm s}^{(\rm n)}$	$E_{\rm d}^{(\rm n)}$	$E_{\rm s}^{(\rm p)}$	$E_{\rm d}^{(\rm p)}$	$E_{\rm s}^{'(\rm n)}$	$E_{\rm d}^{'(\rm n)}$	$E_{\rm s}^{'(\rm p)}$	$E_{\rm d}^{'(\rm p)}$	$E_{\rm dec.s}^{(\rm n)}$	$E_{\rm dec.s}^{(\rm p)}$	$E_{\rm dec.d}^{(\rm n)}$	$E_{\rm dec.d}^{(\rm p)}$	$E_{\rm align}^{(\rm n)}$	$E_{\rm align}^{(\rm p)}$
72	normal	6.835	7.785	6.911	7.811	8.588	8.022	8.518	8.005	1.753	1.607	0.237	0.194	5.015	6.289
74	normal	6.822	7.716	6.892	7.806	8.583	8.080	8.517	8.002	1.761	1.723	0.364	0.196	5.084	6.297
	high-spin	6.822	7.749	6.892	5.819	8.583	8.029	8.517	7.980						
76	normal	6.776	7.729	6.862	7.802	8.595	8.046	8.520	7.992	1.819	1.658	0.317	0.190	5.071	6.298
78	normal	6.715	7.737	6.862	7.803	8.632	8.032	8.520	7.990	1.917	1.658	0.295	0.187	5.063	6.297
	high-spin	6.715	7.762	6.862	7.819	8.632	7.992	8.520	7.968						
80	normal	6.113	7.758	6.803	7.776	8.962	7.954	8.501	7.966	2.849	1.698	0.196	0.190	5.042	6.324
	high-spin	6.113	7.777	6.803	7.792	8.962	7.930	8.501	7.942						
82	normal	5.241	7.799	6.741	7.774	9.365	7.908	8.533	7.958	4.124	1.792	0.109	0.184	5.001	6.326
	high-spin	5.241	7.808	6.741	7.789	9.365	7.896	8.533	7.935						
84	normal	4.406	7.783	6.664	7.785	9.634	7.916	8.589	7.948	5.228	1.925	0.133	0.163	5.017	6.315
	high-spin	4.406	7.794	6.664	7.800	9.634	7.900	8.589	7.929						

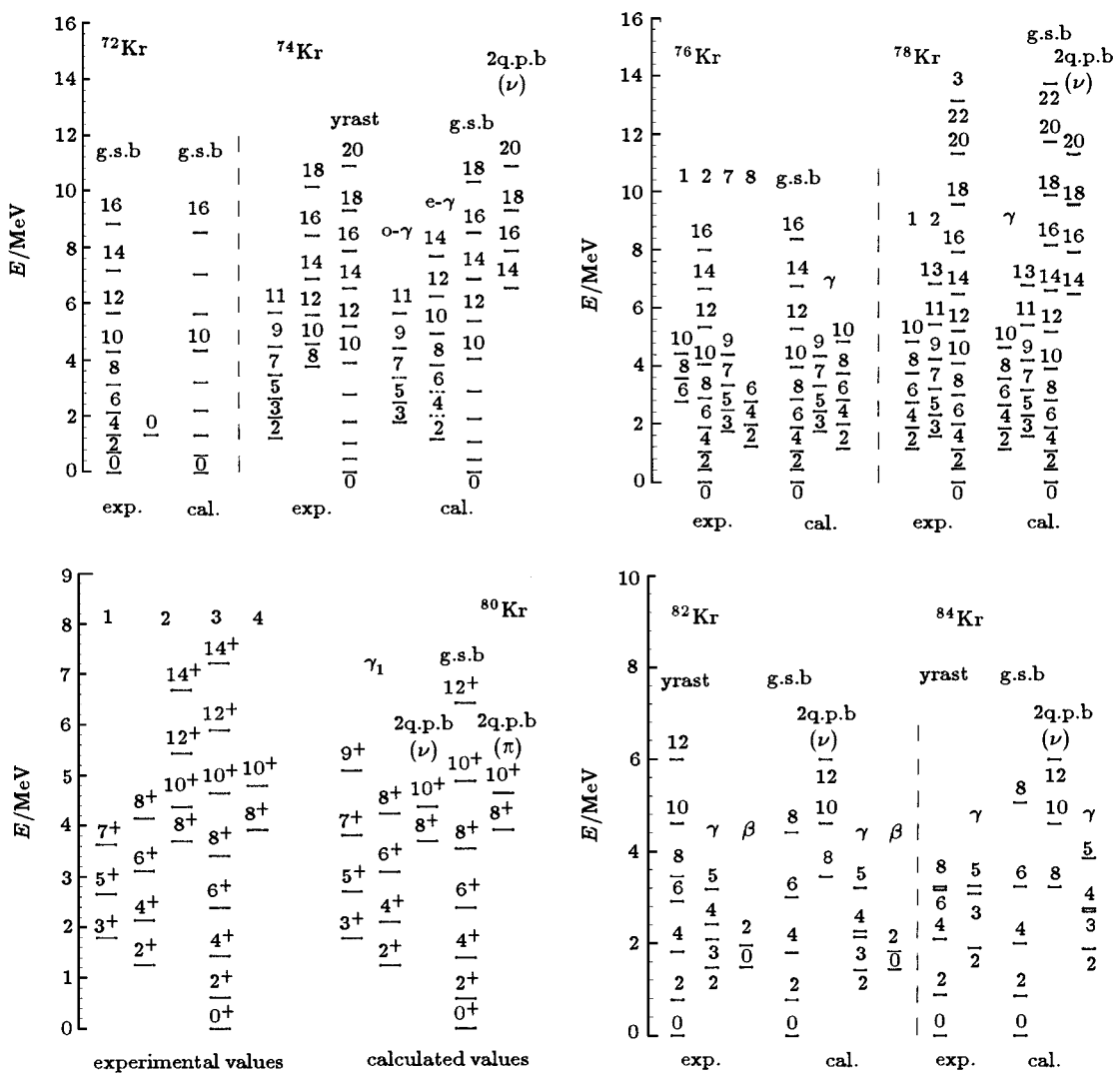


Fig.1. Comparison of the calculated and the experimental spectra in $^{72-84}$Kr. The experimental results and energy bands labelled are taken from Refs.[14–21].

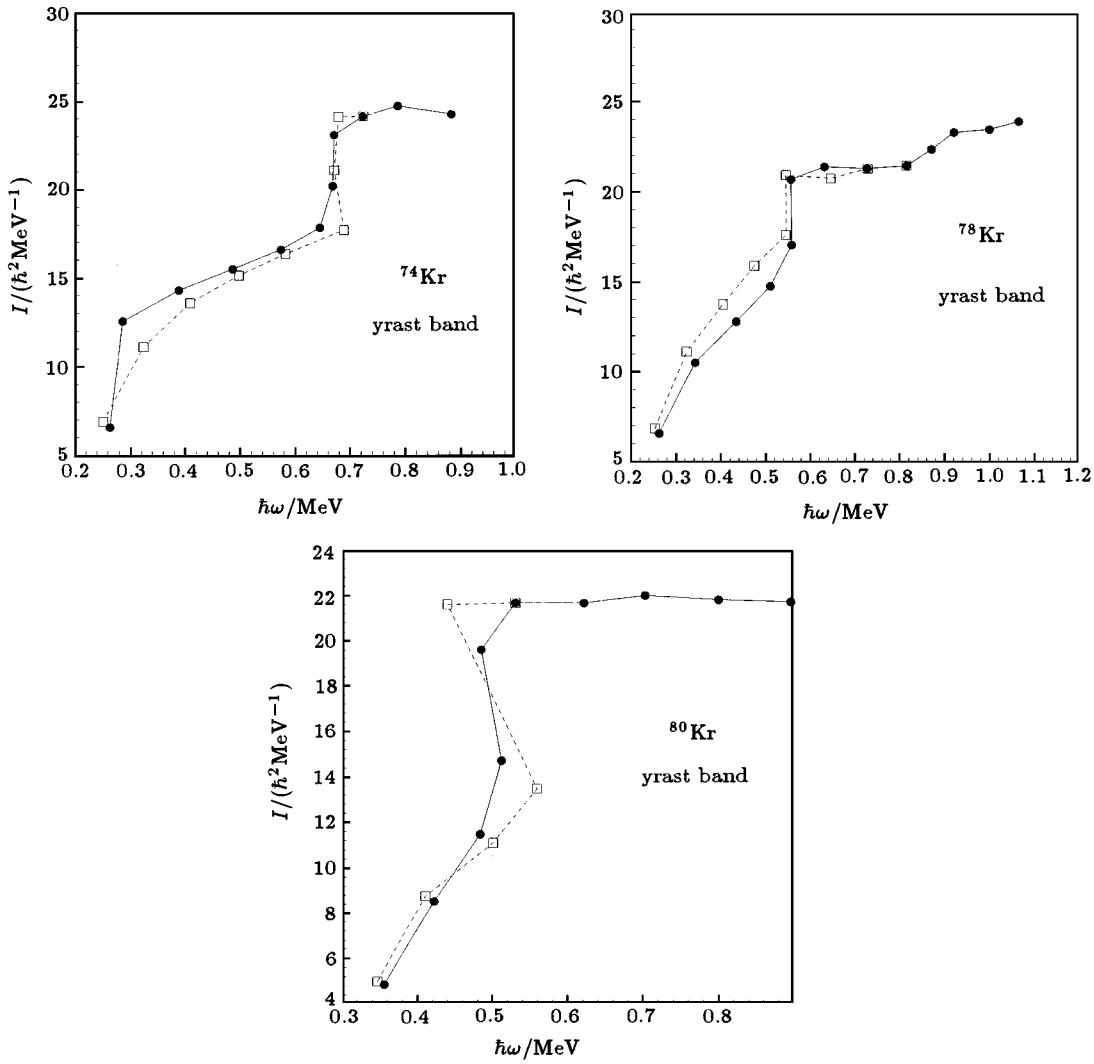


Fig.2. Comparison of the experimental (•) and calculated (□) (I-ω) plots for yrast spectra in ^{74,78,80}Kr.

So far, for even–even nuclei in $A = 70 - 80$ mass region the property of 0^+ excited states in the low-lying region is not clearly, and the information on levels in β-band is very little. In the present paper, the 0_2^+ state is treated as an intruded one, without studying β-band, just as in Ref.[24]. Based on the data or the results in Tables 1–3 and Figs.1 and 2, we may conclude that:

1) The calculated spectra, the ground-band, γ-band and partial two-quasi-particle band, are consistent satisfactorily with the experimental values. Particularly, for ^{72}Kr[15] the maximum angular momentum permitted by the valence bosons is 16^+, and the excited energy is up to 10.0MeV; for ^{74}Kr[16] they are 18^+ and 10.0MeV respectively, these values which have been reproduced satisfactorily are much higher than ordinary $6^+ - 8^+$ and 2–3MeV. And this approach predicts the probable levels of ^{74}Kr, the 4_2^+ (1.99MeV) and 6_2^+ (2.84MeV), they are fitted into the even-γ band together with the experimental levels 2_2^+ (1.203MeV), 8_2^+ (3.761MeV), 10_2^+ (4.556MeV) and 12_2^+ (5.750MeV); while the levels 14_2^+ (6.853MeV), 16_2^+ (8.412MeV) and 18_2^+ (10.135MeV) attach to the ground-state band (see Fig.1., the predicted levels are indicated by a broken line).

2) When the parameters of nucleon–nucleon effective interactions in the proton are nearly constant, by means of adjusting parameters in the neutron, the whole process of the transition of the spectral property has been realized. To be exact, while the neutron-boson number increases from 4 to 10, the spectral property transits from near $U(5)$-limited nuclei (in ^{72,74}Kr nuclei) to well $O(6)$-limited nuclei (in ^{76,78}Kr nuclei), then to transient nuclei between $U(5)$-and $O(6)$-limited nuclei (in $^{80-84}$Kr nuclei). The nuclear

shape transition at zero temperature has been described successfully. Table 2 shows that the strengths of effective interactions in neutrons vary slowly in the same limited region, and change suddenly in different limited regions.

3) The parameters $K^{(\mathrm{np})}$ of Kr isotopes are larger than those of Xe isotopes (most of Xe are 0.010–0.020[12,13]). The reason lies in that the valence neutrons and valence protons occupy the same major shell, and they interact strongly with each other. In accordance with the phenomenological theory, the description of a light mass nucleus demands the introduction of the neutron-proton δ-boson. Although the microscopic Hamiltonian in this paper does not include the δ-boson term explicitly, the neutron-proton interaction has been covered by the term of a quadrupole–quadrupole type neutron-proton force. The contribution of δ-bosons has been converted into the term of the neutron-proton interaction, so that the parameter $K^{(\mathrm{np})}$ increases. Naturally, this approach can describe the light mass nuclei, as successfully as the nuclei of $^{66-70}$Ge,[11] ^{24}Mg[25] and ^{48,52,56}Cr.[26]

4) Table 3 shows that when a boson suddenly breaks up and two neutrons pass into the aligning, the physical quantities, for example, various energies, structure coefficients (they are not listed here because of the space) obviously do not alter before and after the change of states, so we can neglect the change of these states.[12,13]

5) In this paper the total energy of d-boson is defined as $E_{\mathrm{d}}^{(\sigma)} = E_{\mathrm{d}}^{'(\sigma)} + E_{\mathrm{d}}^{''(\sigma)}$, where $E_{\mathrm{d}}^{'(\sigma)}$ and $E_{\mathrm{d}}^{''(\sigma)}$ are the boson non-perturbation energy and inherent energy respectively.[7,25] According to the above model theory, when the boson is produced from the decoupling, breaking up, occupying the intruder orbit, and passing into the aligning, the requisite energy should be:

$$E_{\mathrm{align}}^{(\sigma)} = -(E_{\mathrm{d}}^{'(\sigma)} + E_{\mathrm{d}}^{''(\sigma)}) + 2E_{\mathrm{int}}^{(\sigma)} = 2E_{\mathrm{int}}^{(\sigma)} - E_{\mathrm{d}}^{(\sigma)}. \quad (1)$$

Obviously, the boson that requires less energy may first of all break up, and pass into the aligning. Table 3 shows that based on the relationship (1), the first backbending of Kr isotopes may be the result of crossing of the ground-state band and the band with two quasi-neutrons occupying the intruder orbit $g_{9/2}$. This gains the new experimental support of the measurements of g factors in the $^{78-86}$Kr isotopes at present;[27] and the neutron aligning becomes even easier with increasing neutrons. The relationship (1) may also identify the classes in angular momentum multiple-states, for example, as the ^{80}Kr nucleus is concerned, this model identifies that the 8_1^+, 8_2^+, and 8_3^+ states may belong to the ground-state band, quasi-neutron and quasi-proton bands respectively; while the 8_4^+ state is a member of γ-band (see the levels scheme of the ^{80}Kr nucleus in Fig.1).[29] In the past, the upbending in the (I-ω)-curve of the yrast band of ^{74,78}Kr isotopes in Fig.2 was interpreted as the combined result of the aligning of 2q.p.(ν) and 2q.p.(π) in the orbit $g_{9/2}$,[17,28] while the upbending of the ^{80}Kr nucleus was the result of the aligning of 2q.p.(ν).[19] Now our explanation on the aligning of the whole Kr isotopes is consistent with the experiment.

4. Conclusion

In summary, the microscopic sdIBM-2+2q.p. approach may reproduce the ground-band, γ-band, and partial two-quasiparticle band, and demonstrate the whole process of the nuclear shape transition in Kr isotopes. Based on this model, the aligned requisite energy condition (1) has been deduced. It identifies that the first backbending of Kr isotopes may be the result of the crossing of the ground-state band and the band with two-quasi-neutrons occupying the intruder orbit $g_{9/2}$. Also the probable levels of these isotopes are predicted, and they have been fitted into this approach together with the experimental levels, like ^{74}Kr. Although the microscopic Hamiltonian does not explicitly include the δ-boson term, in fact, because the neutron-proton interaction has been included in the Hamiltonian, the light mass nucleus can be described successfully.

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