Volume 9, Number 1 January, 2000
1009-1963/2000/09(01)/0009-04 CHINESE PHYSICS © 2000 Chin. Phys. Soc.

MICROSTRUCTURE ON COLLECTIVITY IN EVEN $^{116-122}$Xe ISOTOPES

Shi Zhu-yi(石筑一)[a], Liu Yong(刘 庸)[b], and Sang Jian-ping(桑建平)[c]
[a] *Department of Physics, Guizhou Institute for Nationalities, Guiyang 550025, China*
[b] *Institute of Particle Physics, Huazhong Normal University, Wuhan 430070, China*
[c] *Department of Physics, Wuhan University, Wuhan 430072, China*

(Received 17 June 1999; revised manuscript received 7 September 1999)

Using microscopic interacting boson-fermion model formalism, the ground-band, β-band, γ-band and high spins states in even $^{116-122}$Xe isotopes are successfully described. It can explain the recent experimental result that collective structures may coexist with the single-particle states and subshell feature. It predictes the energies of 1^+ states.

PACC: 2100; 2700

I. INTRODUCTION

Experimental investigations of nuclei near $Z = 50$ closed proton shell in the $A \approx 100$ mass region have uncovered exotic collective structures which coexist with the expected single-particle states. In some well-developed rotational band near the $Z = 50-53$ nuclei particle alignment takes place at higher frequencies.[1] An experiment has been designed by Sears *et al.*[1] to find information about the generating mechanisms of collective angular moment in the even ^{116,118}Xe isotopes. As a result of that experiment, level schemes for these nuclei have been extended to high spins and energies, and collective structures which coexist with the single-particle states and subshell feature have been discovered. For bands observed in experiment the assignments of configuration structure are proposed in Ref.[1]. It is significant to use microscopic theory to find explanation.

Reference [2] proposed a microscopic theory to calculate even-even nuclei high-spins states. It assumes that there may be a boson broken into two nucleons in nuclei, and after that these nucleons occupy the intruder orbit, for example $h_{11/2}$, $i_{13/2}$; all the other nucleons form a collective core described approximately by an s, d system. This is the so-called microscopic IBM+2q.p formalism. Subsequently, it successfully describes high-spins phenomenon in three different nuclear regions.[3−6] We use the approach where neutrons and protons are distinguished to describe $^{116-122}$Xe isotopes. The calculated results can explain the data observed in experiment and support the assignments of configuration structure proposed in Ref.[1].

II. THEORETICAL APPROACH[2]

For Xe isotopes, the valence nucleon configurations are $(1g_{7/2}, 2d_{5/2}, 1h_{11/2}, 2d_{3/2}, 3s_{1/2},)^4$ $(2d_{5/2}, 1g_{7/2}, 1h_{11/2}, 3s_{1/2}, 2d_{3/2},)^{N_n}$. In order to study the tendency of variations in some fundamental physical quantities with the increase of the number of neutron, with no loss of generality, we have treated them as particle-like, N_n =12, 14, 16, 18. In general, the valence nucleons Hamiltonian can be written as

$$H_f = H_f^{(n)} + H_f^{(p)} + H_f^{(np)}\,, \tag{1}$$

with

$$H_f^{(\sigma)} = \sum_\alpha E_\alpha a_\alpha^{(\sigma)+} a_\alpha^{(\sigma)} + \sum_{\alpha\beta\gamma\delta} P_{\alpha\beta\gamma\delta}^{(\sigma)} a_\alpha^{(\sigma)+} a_\beta^{(\sigma)+} a_\gamma^{(\sigma)} a_\delta^{(\sigma)} \qquad (\sigma = n, p)\,, \tag{2}$$

$$H_f^{(np)} = \sum_{\alpha\beta\gamma\delta} P_{\alpha\beta\gamma\delta}^{(np)} a_\alpha^{(p)+} a_\beta^{(n)+} a_\gamma^{(p)} a_\delta^{(n)}\,. \tag{3}$$

By generalized Dyson expansion technique, the description of fermion's $H_f(a^+, a)$ is transformed into an ideal boson-fermion description $H_{BF}(A^+, A; \zeta^+, \zeta)$. But, the A-bosons have no collectivity, and a set of Q-bosons are introduced,

$$Q_{r\pi JM}^{(\sigma)} = \sum_{\alpha\le\beta} X_{\alpha\beta}^{(r\pi JM)} A_{\alpha\beta}^{(\sigma)+}\,. \tag{4}$$

With the help of eigenequation

$$H_{BF} Q_{r\pi JM}^{(\sigma)+} |0\rangle = \varepsilon_{\alpha\beta}^{(r\pi JM)} Q_{r\pi JM}^{(\sigma)+} |0\rangle\,, \tag{5}$$

the structure coefficients $X_{\alpha\beta}^{r\pi JM}$ in Eq.(4) are defined. Since the boson with $r = 0$ has the most remarkable collectivity, in the first-order approximation, the s-, d-bosons in the IBM can be defined

$$s^{(\sigma)+} = Q_{0+00}^{(\sigma)+}, \qquad d_v^{(\sigma)+} = Q_{0+2v}^{(\sigma)+}\,. \tag{6}$$

Consequently, we can make the s-d truncation for the part of collective core. Finally, the resulting boson-fermion Hamiltonian, including high-spin states, of

even-even nucleon takes the formas follows:

$$h(N) = h_{\mathrm{IBM-2}}(N-1) + h_{\mathrm{f}} + V_{\mathrm{BF}} + h_{\mathrm{mix}}\,, \qquad (7)$$

where $h_{\mathrm{IBM-2}}$ is the most general IMB-2, h_{f} is the fermion Hamiltonian restricted to a unique parity intruder orbital with spin $h_{11/2}$, V_{BF} is the boson-fermion interaction term, h_{mix} is the term mixing the zero- and two-quasiparticle bands.

The state space of diagonalized Hamiltonian h can be decomposed into three parts: 1) the state α with spin J in IBM–2 space: $|\alpha JM\rangle$; 2) direct product of the state α with spin K in IBM–2 space with the state in neutron two-quasiparticle: $|\alpha K,\, j_{\mathrm{n}}^2 L;\, JM\rangle$; 3) direct product of the state α with spin K in IBM–2 space with the state in proton two-quasiparticle: $|\alpha K,\, j_{\mathrm{p}}^2 L;\, JM\rangle$. The Hamiltonian $h_{\mathrm{IBM-2}}(N)$ is diagonalized in the 1) space, and the spectra of normal state is obtained. The Hamiltonian $h(N)$ is diagonalized in the space of 1) plus 2), the spectra of neutron high-spin states are obtained.

Ⅲ. CALCULATED RESULTS AND DISCUSSION

The single-particle energies for open shells and strengths of the nucleon-nucleon effective interactions are chosen as follows: $g_0^{(\sigma)}$, $G_2^{(\sigma)}$, $K^{(\sigma)}$ (σ=n, p) and $K^{(\mathrm{np})}$, which are the strengths of pairing force, quadrupole pairing force, and quadrupole-quadrupole force for the identical nucleons, and the neutron-proton force of quadrupole-quadrupole type respectively.

Table 1. Single-particle energies of the valence nucleon[7] (MeV).

nlj	$2d_{5/2}$	$1g_{7/2}$	$1h_{11/2}$	$3s_{1/2}$	$2d_{3/2}$	nlj	$1g_{7/2}$	$2d_{5/2}$	$1h_{11/2}$	$2d_{3/2}$	$2d_{1/2}$
α	1	2	3	4	5		1	2	3	4	5
Neutron	4.00	4.28	6.22	6.64	6.74	Proton	4.00	4.54	5.90	7.24	7.47

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

	$g_0^{(\mathrm{n})}$	$G_2^{(\mathrm{n})}$	$K^{(\mathrm{n})}$	$g_0^{(\mathrm{p})}$	$G_2^{(\mathrm{p})}$	$K^{(\mathrm{p})}$	$K^{(\mathrm{np})}$
116	0.0328	0.0257	0.001	0.0284	0.0185	0.080	0.0270
118	0.0324	0.0260	0.001	0.0280	0.0175	0.082	0.0236
120	0.0386	0.0462	0.001	0.0278	0.0170	0.083	0.0178
122	0.0432	0.0555	0.005	0.0276	0.0165	0.084	0.0130

The calculated spectrum of Xe isotopes, given in Fig.1, shows that a good description is obtained. Some fundamental physical quantities are listed in the following tables:

Table 3. Structure coefficients $X_{\alpha\beta}^{r\pi JM}$ of bosons Q_{0+jm}^{+} in normal states.

	s-boson					d-boson										
Nucl.	(1,1)	(2,2)	(3,3)	(4,4)	(5,5)	(1,1)	(1,2)	(1,4)	(1,5)	(2,2)	(2,4)	(2,5)	(3,3)	(4,4)	(4,5)	(5,5)
116N	−0.793	−0.567	−0.191	−0.068	−0.093	−0.957	0.145	0.063	−0.033	−0.228	0.000	0.058	−0.051	0.000	0.026	−0.019
P	−0.905	−0.361	−0.189	−0.105	−0.066	0.991	−0.009	−0.066	0.000	−0.089	0.032	−0.038	0.042	0.035	0.020	0.000
118N	−0.796	−0.564	−0.188	−0.067	−0.091	−0.955	0.146	0.064	−0.034	−0.231	0.000	0.059	−0.052	0.000	0.026	0.000
P	−0.906	−0.359	−0.187	−0.105	−0.065	0.992	−0.017	−0.064	0.000	−0.084	0.031	−0.036	0.039	0.035	0.010	0.000
120N	0.763	0.592	0.222	0.079	0.109	0.853	−0.219	0.137	0.073	0.406	0.000	−0.128	0.116	0.000	−0.059	0.042
P	−0.907	−0.358	−0.184	−0.105	−0.065	−0.992	−0.020	−0.063	0.000	0.082	0.032	−0.035	0.038	0.035	0.019	0.000
122N	0.742	0.605	0.245	0.090	0.122	−0.799	0.236	0.175	−0.092	−0.459	0.000	0.1620	−0.148	0.000	0.077	−0.055
P	−0.908	−0.357	−0.184	−0.105	−0.065	0.992	−0.024	−0.062	0.000	−0.079	0.030	−0.034	0.037	0.035	0.018	0.000

Table 4. Structure coefficients $X_{\alpha\beta}^{r\pi JM}$ of bosons Q_{0+jm}^{+} in high spin-states.

	s-boson					d-boson										
Nucl.	(1,1)	(2,2)	(3,3)	(4,4)	(5,5)	(1,1)	(1,2)	(1,4)	(1,5)	(2,2)	(2,4)	(2,5)	(3,3)	(4,4)	(4,5)	(5,5)
116N	−0.793	−0.567	−0.191	−0.068	−0.093	−0.966	0.112	0.047	−0.025	−0.218	0.000	0.049	−0.512	0.000	0.018	−0.057
P	−0.905	−0.361	−0.189	−0.105	−0.066	0.988	0.074	−0.067	0.000	−0.096	0.032	−0.031	0.043	0.033	0.019	0.000
118N	−0.788	−0.571	−0.196	−0.070	−0.095	−0.955	0.126	0.055	−0.029	−0.248	0.000	0.000	−0.057	0.000	0.021	−0.021
P	−0.913	−0.347	−0.177	−0.100	−0.062	0.993	−0.058	−0.057	0.000	−0.071	−0.027	−0.022	0.030	0.030	0.030	0.000
122N	0.742	0.605	0.245	0.090	0.122	−0.830	−0.206	−0.139	−0.073	0.453	0.000	−0.117	0.000	0.000	0.054	0.052
P	−0.908	−0.357	−0.184	−0.105	−0.065	0.989	0.070	−0.065	0.000	0.087	0.038	−0.028	0.038	0.033	0.017	0.000

Table 5. Some Calculated energies (MeV).

Nucl.	Normal states								High-spin states							
	$E_s^{(n)}$	$E_d^{(n)}$	$E_s^{(p)}$	$E_d^{(p)}$	$E_s'^{(n)}$	$E_d'^{(n)}$	$E_s'^{(p)}$	$E_d'^{(p)}$	$E_s^{(n)}$	$E_d^{(n)}$	$E_s^{(p)}$	$E_d^{(p)}$	$E_s'^{(n)}$	$E_d'^{(n)}$	$E_s'^{(p)}$	$E_d'^{(p)}$
116	7.082	7.852	6.565	7.376	8.407	8.070	7.970	7.654	7.082	7.865	6.565	7.376	8.407	8.050	7.970	7.656
118	7.098	7.849	6.563	7.370	8.400	8.072	7.955	7.641	7.045	7.840	6.634	7.412	8.422	8.070	7.935	7.380
120	6.840	7.614	6.561	7.367	8.507	8.301	7.947	7.634	----	----	----	----	----	----	----	----
122	6.598	7.431	6.560	7.365	8.568	8.434	7.939	7.628	6.598	7.517	6.560	7.364	8.568	8.322	7.939	7.631

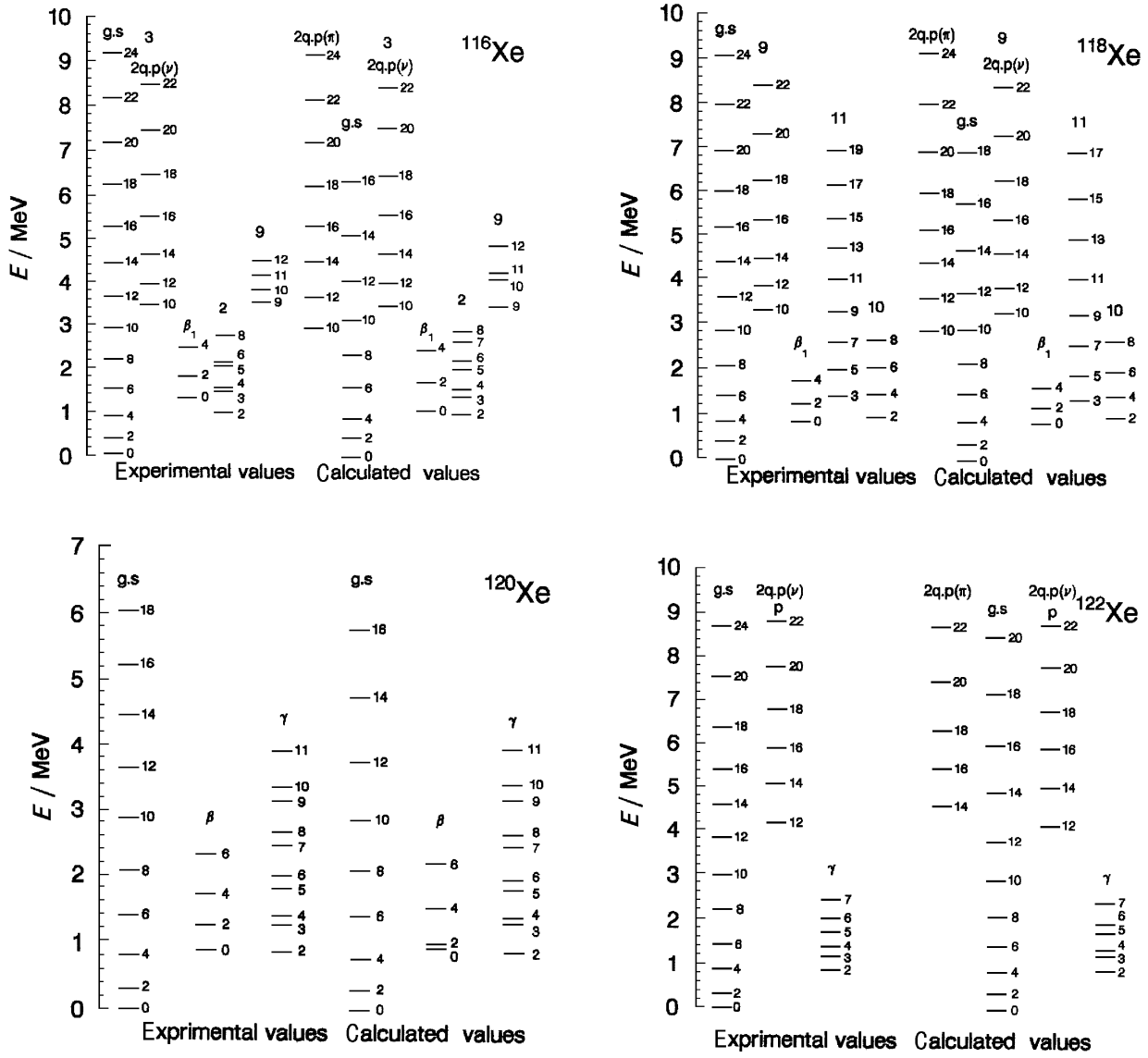


Fig.1. Comparison of experimental and calculated levels in $^{116-122}$Xe isotopes, the experimental values and energy band labeled being taken from Refs.[1,8,–10].

IV. CONCLUSION

From the above calculated results, we may draw following conclusions:

1) Using the same valence nucleon configurations, single-particle energies and strengths of the nucleon-nucleon effective interactions (see Tables 1 and 2), the spectra of Xe isotopes in normal states and high-spin states are calculated at the same time. The calculated results are consistent satisfactorily with the experimental values,[1,8−10], see Fig.1. We believe that the Fermi surface of neutrons is closer to the $h_{11/2}$ Nilsson orbital than that of protons, because the neutron excess energy in neutron-aligned state is higher than that

in proton-aligned state, and the proton-aligned state is favorable to ground states.[6] It shows that there are collective structures coexisting with the two proton-aligned states in ground state band. As for still greater angular momentum states in ground state band and high spin-states, it is presumed that they should be reproduced by breaking more than one boson.[5] The calculated results also show that in order to reproduce high-spin states in ground state band in ^{120}Xe proton-aligned states are needed, which is awaiting future experimental verificatin.

2) When neutron number increases, the strengths of effective interactions in neutron are growing slowly, but those for proton are nearly constant. The strength of the neutron-proton effective interactions decrease all the way (see Table 2). The calculated parameters on each nuclide, for example, boson energy $E_l^{(\sigma)}$, boson no-perturbation energy $E_l^{\prime(\sigma)}$, structure coefficients $X_{\alpha\beta}^{r\pi JM}$ of bosons, etc., change slowly (see Tables 3, 4 and 5). Even when states transform suddenly from normal states to high-spin state, the calculated parameters of the two states alter only slightly (see Tables 3 and 4), so that nothing is worried about due to the serious change of the states. This shows that this approach is a good first-order approximation for calculating high-spin states.

3) The configurations of Xe isotopes are mostly [(1,2), 3] (see Table 3 and 4), for all cases. It shows the subshell feature. Even in ^{122}Xe where neutrons are in the second half of the shell, the sum of square of structure coefficients $X_{\alpha\beta}^{r\pi JM}$ of bosons in neutron normal states is 0.93, all the others are greater (0.96). They agree satisfactorily with the experimental values.

4) The calculated 1_1^+ state energies are: 1.369, 1.294, 1.251 and 1.208 MeV, which attract considerable attention, because the spectra in normal states agree very satisfactorily with the experimental values. These results are a prediction of the present approach. We follow with interest the future report on the experimental results. But why were these states not observed? This problem is quite attracting. If our prediction is not further supported experimentally, then the 1_1^+ state shall does not belong to the present model configuration. It is of particular importance to introduce isospin degrees of freedom in the theory, in order to fully take into account such configuratin. This is the IBM where δ-boson formed by a proton neutron (pn) pair is also included. Since the valence neutrons and the valence protons occupy the same orbits, one has to take into consideration the isospin effect, in a more elaborate study. This additional np interaction can change the number and isospin dependence of the boson parameters.[11,12] This will also provide us information on the importance of the δ-boson.

In conclusion, the present approach explains some results observed in experiment (Ref.[1]) successfully, it supports the assignments of configuration structure proposed in Ref.[1], and predicts energy value in the 1_1^+ state on that isotopes.

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*The authors wish to thank the referee for pointing this to us.