Projected SD-pair shell model study for even-even Xe isotopes*

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Abstract Projected SD-pair shell model is used to study the collectivity of low-lying state for even-even Xe isotopes. It is found that the collectivity can be reproduced in term of a three-parameter Hamiltonian.

Key words projected SD-pair shell model, spectrum，E2 transition

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1 Introduction

How to describe the nuclear collective motions in terms of the shell model is a central task in nuclear structure theory. In 1993, Prof. Jin-quan Chen proposed the nucleon pair shell model (NPSM)[1]. The tremendous success of the IBM[2] has suggested a possible truncation, the truncation to the SD subspace with S-D collective nucleon-pairs as the building blocks[3, 4]. Therefore, we truncated the full shell-model space for medium and heavy mass nuclei to the collective SD-pair subspace in the NPSM, which is called SD-pair shell model(SDPSM)[5, 6]. Our previous work and Dr. Zhao Yumin's work show that the collectivity of low-lying states can be reproduced very well with the SDPSM[5—15].

But we also found that within the SDPSM, the subspace is not closed under the action of a pair annihilation operator $A^s, s=0,2$. Namely,

$$\hat{H}_{\rm SM}|\psi_{\rm SD}\rangle \Longrightarrow |\psi_{\rm SD}\rangle \oplus |\psi_{\rm other}\rangle, \tag{1}$$

where $\hat{H}_{\rm SM}$ is the shell model Hamiltonian, $|\psi_{\rm SD}\rangle$ stands for the basis vectors in a special SD-pair subspace, and $|\psi_{\rm other}\rangle$ stands for the basis vectors outside the SD-pair subspace.

Since only a special SD-pair subspace is important in the description of nuclear collective motions, we propose the following projected SD-pair shell model(PSDPSM), in which

$$\hat{\mathcal{P}}\hat{H}_{\rm SM}\hat{\mathcal{P}}|\Psi_{\rm SD}\rangle \Longrightarrow |\Psi_{\rm SD}\rangle + |\Psi_{\rm S'D'}\rangle, \tag{2}$$

where $\hat{\mathcal{P}}$ is the projection operator which project the full shell model space onto SD-pair subspace, and $|\psi_{\rm S'D'}\rangle$ is the basis vector in the new collective S′D′ space, the S′D′ space is in the subspace of $|\psi_{\rm other}\rangle$. It is the aim of this paper to see if the low-lying states for Xe isotopes can be described reasonably within this framework.

2 Brief review of the model

In this paper, we choose a rather simple Hamiltonian,

$$H_{\rm SD} = \hat{\mathcal{P}} H_{\rm SM} \hat{\mathcal{P}}, \tag{3}$$

where $\hat{\mathcal{P}}$ is the projection operator, $H_{\rm SM}$ is the shell model Hamiltonian.

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$$
\begin{aligned}
H_{\mathrm{SM}} &= H_0+V(\sigma)+\kappa Q_{\pi}^2\cdot Q_{\nu}^2, \qquad (4)\\
H_0 &= \sum_{a\sigma}\varepsilon_{a\sigma}\hat{n}_{a\sigma},\quad \sigma=\pi,\ \nu\\
V(\sigma) &= V_{\mathrm{SDI}}(\sigma)=4\pi G_{\sigma}\sum_{i>j=1}^{n}\delta(\Omega_{ij}),\\
Q_{\mu}^2 &= \sum_{i=1}^{n} r_i^2 Y_{2\mu}(\theta_i\phi_i),
\end{aligned}
$$

where ϵ_a and $\hat{n}_a$ are the single-particle energy and the number operator, respectively.

The E2 transition operator is

$$E2=e_{\pi}\hat{\mathcal{P}}Q_{\pi}^2\hat{\mathcal{P}}+e_{\nu}\hat{\mathcal{P}}Q_{\nu}^2\hat{\mathcal{P}}, \qquad (5)$$

where e_{ν} and e_{π} are effective charges of a neutron and proton, respectively.

The building blocks of the NPSM in the S-D subspace are "realistic" collective pairs $A_{\mu}^{r\dagger}$ of angular momentum $r=0,2$ with projection μ, built from many non-collective pairs $\left(C_a^{\dagger}\times C_b^{\dagger}\right)_{\mu}^{r}$ in the single-particle levels a and b,

$$
\begin{aligned}
A_{\mu}^{r\dagger} &= \sum_{ab} y(abr)\left(C_a^{\dagger}\times C_b^{\dagger}\right)_{\mu}^{r}, \qquad (6)\\
y(abr) &= -\theta(abr)y(bar),\quad \theta(abr)=(-)^{a+b+r},
\end{aligned}
$$

where $y(abr)$ are the distribution coefficients. As in the SDPSM, SDI-A method is used to determine the S-D pairs, i.e., by diagonalizing the SDI Hamiltonian in the orthonormal basis $|(ab)r\mu)$, and choosing the lowest 0^+ and 2^+ as our S and D pair.

In the PSDPSM, due to the projection operator $\hat{\mathcal{P}}$, the new collective pairs appeared in the one- and two-body matrix elements are restricted to S and D-pairs only. As an example, the expression of the matrix element for pairing interaction is given in the following[16].

$$
\begin{aligned}
&\langle 0|A_{M_N}^{J_N}(s_i,J_i')\hat{\mathcal{P}}A^{s\dagger}\cdot A^{s}\hat{\mathcal{P}}A_{M_N}^{J_N}(r_i,J_i)^{\dagger}|0\rangle=\\
&\widehat{J}_N^{-1}\sum_{k=N}^{1}\sum_{L_{k-1}\cdots L_{N-1}}(-)^{J_N+s-L_{N-1}}\widehat{L}_{N-1}H_N(s)\cdots H_{k+1}(s)\times\\
&\big[\psi_k\delta_{s,r_k}\delta_{L_{k-1},J_{k-1}}\langle s_1s_2...s_N;J_1'...J_{N-1}'J_N|r_1...r_{k-1},r_{k+1}...r_Ns;J_1...J_{k-1}L_k...L_{N-1}J_N\rangle+\\
&\sum_{i=k-1}^{1}\sum_{r_i'=0,2}\sum_{L_i...L_{k-2}}\langle s_1...s_N;J_1'...J_{N-1}'J_N|\,r_1...r_i'...r_{k-1},r_{k+1}...r_Ns;J_1...J_{i-1}L_i...L_{N-1}J_N\rangle\big], \qquad (7)
\end{aligned}
$$

where $r_i'=0,\ 2$ represents the new S and D pair.

3 Results

The Xe isotopes have been studied extensively in the interacting boson model (IBM) and fermion dynamical symmetry model (FDSM). We take $H_0=H_0^{\exp}(\pi)+H_0^{\exp}(\nu)$, where $H_0^{\exp}(\pi)$ and $H_0^{\exp}(\nu)$ are the s. p. energies of the nuclei ${}^{133}_{51}\mathrm{Sb}_{82}$, and ${}^{131}_{50}\mathrm{Sn}_{81}$, respectively, taken from[17, 18] and listed in Table 1. The parameters obtained by fitting the experimental excitation energies in each case are listed in Table 2.

From Fig. 1 one can see that except for ^{134}Xe, a general agreement between the calculation and experiment is achieved for the Xe isotopes. The even–spin yrast sequence is reproduced quite well. The prediction of the quasi-γ band can also be considered nearly satisfactory. One can also see that the larger the N_{ν}, the better the agreement between the calculation and the experiments.

Table 1. The single particle (hole) energies.

ϵ_{π}/MeV	$g_{7/2}$	$d_{5/2}$	$d_{3/2}$	$h_{11/2}$	$s_{1/2}$
	0	0.963	2.69	2.76	2.99
ϵ_{ν}/MeV	$d_{3/2}$	$h_{11/2}$	$s_{1/2}$	$d_{5/2}$	$g_{7/2}$
	0	0.242	0.332	1.655	2.434

Table 2. The parameters we used.

	^{134}Xe	^{132}Xe	^{130}Xe	^{128}Xe
G_{π}	0.185	0.178	0.173	0.170
G_{ν}	0.096	0.098	0.092	0.086
κ	0.172	0.110	0.086	0.071

Table 3. B(E2) (in units of $(ab)^2$). The experimental data taken from Ref. [20].

	$J_i\rightarrow J_f$	^{134}Xe	^{132}Xe	^{130}Xe	^{128}Xe
Expt.	$B(\mathrm{E2};2_1^+\rightarrow 0_1^+)$	0.068(12)	0.092(6)	0.13(1)	0.150(8)
Theo.	$B(\mathrm{E2};2_1^+\rightarrow 0_1^+)$	0.06408	0.08847	0.09967	0.10035
	$B(\mathrm{E2};4_1^+\rightarrow 2_1^+)$	0.05998	0.11876	0.16554	0.18820
	$B(\mathrm{E2};2_2^+\rightarrow 2_1^+)$	0.00512	0.08858	0.11644	0.10070

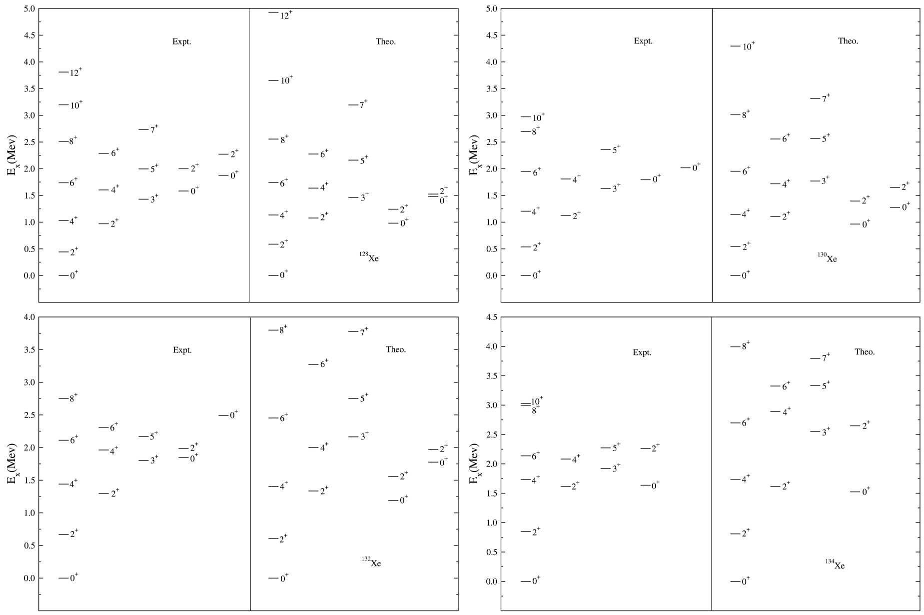

Fig. 1. The spectrum for Xe isotopes. The experimental data are taken from Ref. [19].

Except for the spectra, B(E2) values are also studied. By fitting ^{138}Ba with the SDI-A truncation, the effective charges are fixed as 1.5e for both proton and neutron. Part of the B(E2) absolute values are listed in Table 3. From Table 3 one can see that the calculated results are close to the experiments. The B(E2) values are all strong between yrast states, and they increase with N_ν, For the nuclei with $N_\nu \geqslant 2$, the E2 transition for $2_2^+ \rightarrow 2_1^+$ is about the same magnitude as for $2_1^+ \rightarrow 0_1^+$, which is what one might expects for a $O(6)$ symmetry nuclei, but it is too small for ^{134}Xe.

4 A brief summary

In summary, from above analysis one can see that the property of low-lying states can be reproduced very well with the projected SD-pair shell model. But we also notice that there are still some shortcoming in this model, for example, most of the calculated B(E2) are smaller than the experiments, and although $B(\text{E2}; 2_1^+ \rightarrow 0_1^+)$ increase with N_ν for Xe isotopes, they do not increase as quickly as the experimental case.

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