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SD-pair Shell Model Calculation of Even-even Mo Isotopes*

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Abstract: The SD-pair shell model was applied to study the even-even ^{94}Mo—^{100}Mo. It is found that with the SD pair determined as 0_1^+ and 2_1^+ states of a two-valence-nucleon system with a Hamiltonian, which contains the single particle energy term and the Surface-Delta interaction (SDI) between like nucleons, the collectivity of low-lying states can be described reasonably.

Key words: SD-pair shell model; spectrum; E2 and M1 transitions

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Recently, a nucleon-pair shell model (NPSM) has been proposed[1]. It is found that the computing time increase drastically with the increase of the model space. The success of the interacting boson model[2] indicated that the full shell model space could be truncated to SD pair subspace. Therefore, as an approximation, the NPSM was truncated to SD-pair subspace, which is called SD-pair shell model (SDPSM)[3,4]. Our previous results shows that the SDPSM can reproduce the limiting cases of the IBM very well[5,6]. This model was also used to study the even-even Xe and Ba isotopes, which is in the region of 50—82 shells for both proton and neutron sectors, and the results show the collectivity of low-lying states can be described very well[7,8]. In this paper, we will examine the goodness of the SDPSM for even-even $^{94-100}$Mo, for which the proton sector is in the region of 28—50 shells and it is in 50—82 shells for neutron.

A rather simple Hamiltonian was used

$$H = H_0 - V(\nu) - V(\pi) - kQ^2(\pi)\cdot Q^2(\nu)\ ,$$
$$H_0 = \sum_{a\sigma}\varepsilon_{a\sigma}n_{a\sigma}\ ,\ \sigma=\pi,\nu \qquad (1)$$

$$V(\sigma) = V_{\rm SDI}(\sigma) = 4\pi G\sigma\sum_{i>j=1}^{n}\delta(\Omega_{ij})\ ,\ \sigma=\pi,\nu$$
$$Q^2 = \sum_i r_i^2 Y^2(\theta_i,\ \phi_i)\ , \qquad (2)$$

where, $V_{\rm SDI}(\sigma)$, $\sigma=\pi(\nu)$, is the surface delta interaction between like nucleons. G_σ and k are the strength of the SDI interaction and quadrupole-quadrupole interaction strength between proton and neutron, respectively.

The E2 transition operator is

$$T({\rm E2}) = e_\pi Q_\pi^2 + e_\nu Q_\nu^2\ , \qquad (3)$$

where e_π and e_ν are effective charges of proton-hole and neutron, respectively. The M1 transition operator is

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$$T(\mathrm{M1}) = T(\mathrm{M1})_\pi + T(\mathrm{M1})_\nu \,, \qquad (4)$$

$$T(\mathrm{M1})_\sigma = \sqrt{\frac{3}{4\pi}}\,(g^{\mathrm{eff}}_{l,\rho} l_\rho + g^{\mathrm{eff}}_{s,\rho} s_\rho) \,, \qquad (5)$$

and the M3 transition operator is

$$T(\mathrm{M3}) = \frac{\sqrt{21}}{2} \sum_{\rho=\pi,\nu} (g^{\mathrm{eff}}_{l,\rho} \sum_{i\in\rho} r_i^2 [Y^{(2)}(r_i) l_i]^{(3)} + 2 g^{\mathrm{eff}}_{s,\rho} \sum_{s\in\rho} r_i^2 [Y^{(2)}(r_i) l_i]^{(3)} \,,\ \rho = \pi, \nu \qquad (6)$$

where $g^{\mathrm{eff}}_{l,\rho}$ and $g^{\mathrm{eff}}_{s,\rho}$ are the orbital and spin effective gyro-magnetic ratios, which are fixed as those in Ref. [9], i. e. $g_{l\pi}=1$, $g_{l\nu}=-0.0$, $g_{s\pi}=3.910$, $g_{s\nu}=-2.678$ (all in units of μ_N^2). The building blocks of the SDPSM are "realistic" collective pairs, denoted by A^{r+}_μ, $r=0,2$, taken from the 0_1^+ and 2_1^+ eigenstates of a two-valence system with a single-particle energy term and SDI term

$$A^{r+}_\mu = \sum_{c\text{-}d} y(cd^2 r)(C_c^1 \times C_d^1)^r_\mu \,, \qquad (7)$$

where $y(cdr)$ are structure coefficients for the pair A^{r+}_μ. The single particle energies, taken from Refs. [10] and [11], are listed in Table 1. The parameters obtained by fitting the spectra are presented in Table 2, from which one can see that although the parameters are adjusted for each nucleus, they change with N_ν monotone and very smoothly.

Table 1　The single-particle (hole) energies for neutron (proton)

ε_π/MeV	$p_{3/2}$	$p_{1/2}$	$g_{9/2}$		
	0	1.272	1.927		
ε_ν/MeV	$d_{5/2}$	$s_{1/2}$	$d_{3/2}$	$g_{7/2}$	$h_{11/2}$
	0	1.03	2.16	2.67	4.00

Table 2　The parameters used in the calculation

Nucleus	G_π	G_ν	k
^{94}Mo	0.161	0.2972	−0.1601
^{96}Mo	0.156	0.1326	−0.3038
^{98}Mo	0.086	0.0423	−0.3206
^{100}Mo	0.043	0.0266	−0.2942

The spectra for ^{94}Mo—^{100}Mo are given in Fig. 1, from which one can see that the general agreement between the calculation and experiment is achieved.

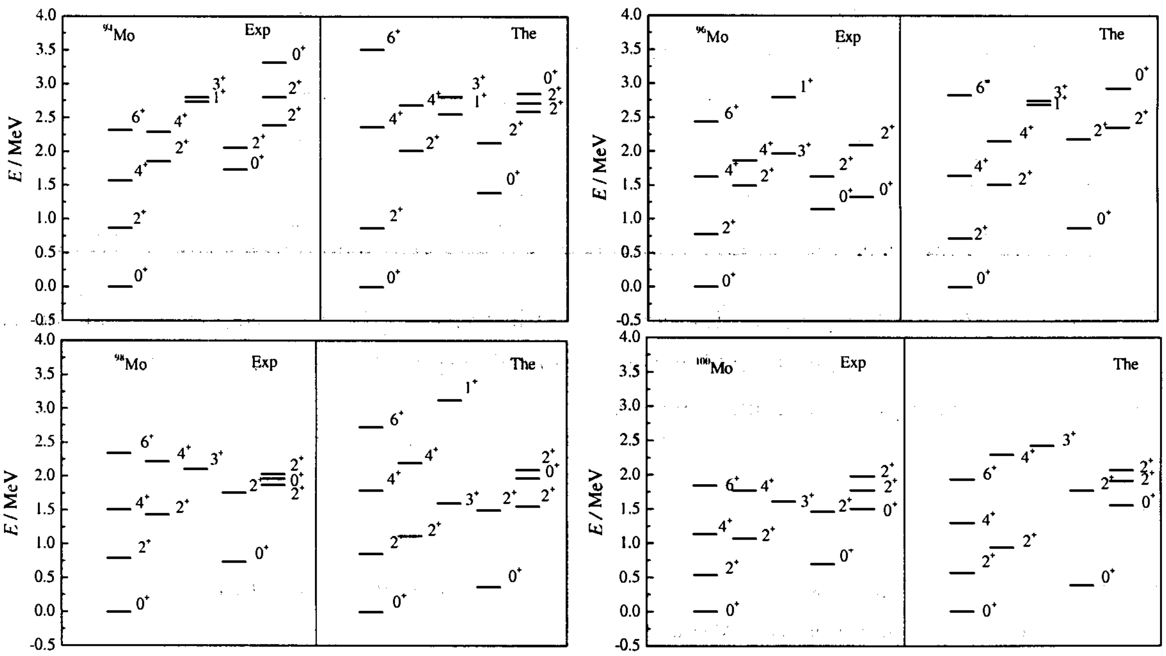

Fig. 1　The spectra for Mo isotopes. The experimental results are taken from Ref. [12].

As shown in Table 3, the $B(\mathrm{E2})$ values are given with the effective charges fixed at 1.7 and 1.9 e for neutron and proton, respectively, which are determined by fitting the $B(\mathrm{E2};\ 0_1^+ \rightarrow 2_1^+)$ for

^{94}Mo—^{100}Mo. It can be seen that the B(E2) for the $4_1^+ \to 2_1^+$ and $2_1^+ \to 0_1^+$ can be reproduced very well, and they all increase with N_ν.

Except for the B(E2) values, the M1 transition is also given in Table 3. One can see that for ^{94}Mo, the M1 transition between 2^+ states were dominated by the $2_3^+ \to 2_1^+$, and experimental result can be fitted very well. For example, $B(\mathrm{M1};\ 2_3^+ \to 2_1^+)_{\mathrm{Exp}}$ is $0.48\mu_N^2$, and it is $0.482\mu_N^2$ in the SDPSM. But for the ^{96}Mo, it is seen that although the dominant one is between 2_4^+ and 2_1^+ states as that of the experiment, the M1 transition are fragmented over several 2^+ states. One can also notice that the SDPSM result is much larger than that of the experiment. For $^{98-100}$Mo, the largest M1 transition occurs between $2_4^+ \to 2_1^+$ and $2_3^+ \to 2_1^+$, respectively. In the IBM[16], the 1_1^+ states are predicted as a mixed symmetry state, characterized by large values of B(M1) and small B(E2) values, as shown in Table 3, the $B(\mathrm{M1};\ 1_1^+ \to 0_1^+)$ for ^{94}Mo can be reproduced very well.

Except for the M1 transitions, the M3 transition was also studied within the SDPSM. As shown in Table 3, for ^{94}Mo $B(\mathrm{M3};\ 3_1^+ \to 0_1^+)$ is $4.946\mu_N^2 b^2$, which is much larger than that of the experiment, $0.033\mu_N^2 b^2$. Table 3 also shows that the M3 transition increase with N_ν and it is also fragmented over several 3^+ states.

Table 3　B(E2) (in units of $(eb)^2$, B(M1) (in units of μ_N^2) and B(M3) (in units of $\mu_N^2 b^2$) transition values. The experimental results for B(E2), B(M1) and B(M3) are taken from Refs. [13], [14] and [15], respectively

	$J_i^+ \to J_f^+$	^{94}Mo		^{96}Mo		^{98}Mo		^{100}Mo	
		Exp	Theo	Exp	Theo	Exp	Theo	Exp	Theo
B(E2)	$0_1^+ \to 2_1^+$	0.203 0(40)	0.232 6	0.270 4	0.287	0.268 5	0.270 2	0.510 8	0.421 9
	$4_1^+ \to 2_1^+$	0.067 0(100)	0.024 7		0.064 8		0.013 5		0.093 0
B(M1)	$2_2^+ \to 2_1^+$	0.06(2)	0.148		0.191 8		0.017 6		0.003 2
	$2_3^+ \to 2_1^+$	0.48(6)	0.482		0.371 4		0.025 2		0.147 1
	$2_4^+ \to 2_1^+$	0.07(2)	0.001 5	0.178(10)	0.457 6		0.125 2		0.006 3
	$2_5^+ \to 2_1^+$	0.03(1)	0.006 26		0.053 1		0.008 3		0.014 5
	$1_1^+ \to 0_1^+$	0.16(1)	0.192 56		0.466 1		0.149 5		0.182 3
B(M3)	$3_1^+ \to 0_1^+$	0.03	4.946		12.947		8.862		0.000 7
	$3_2^+ \to 0_1^+$		0.079		1.404 4		0.339 4		28.490

In summary, the low-lying states for even-even ^{94}Mo—^{100}Mo have been investigated within the framework of the SDPSM. It is found that the collectivity of the low-lying states can be reproduced very well.

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利用 SD 对壳模型讨论偶偶 Mo 核的集体性质*

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摘　要：利用 SD 对壳模型讨论了偶偶 Mo 核低激发谱的集体性质。发现当 SD 对按照如下方法来确定，即对于两核子体系，通过对角化表面 δ 相互作用哈氏量，将 SD 对取为 0_1^+ 态和 2_1^+ 态，该模型可以合理的描述偶偶 Mo 核低激发态的集体性质。

关 键 词：SD 对壳模型；能谱；E2 和 M1 跃迁

重要更正：

第 3 期李成波的文章(第 248 页)中，图 1a 处的圆圈应在 a，x，b 交叉点的位置；图 2 和图 3 的图互调(图题注不变)。

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