NEGATIVE-PARITY STATES OF $N = 88$ ISOTONES IN THE INTERACTING BOSON APPROXIMATION

C.S. HAN, D.S. CHUU
Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan, Republic of China

S.T. HSIEH and H.C CHIANG
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan, Republic of China

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The negative-parity states of $N = 88$ isotones are studied systematically in terms of the interacting boson approximation A mass-independent effective interacting boson hamiltonian reproduced energy levels very well Unified E1 and E3 transition operators are found The effect of p bosons on the energy spectra and electromagnetic transitions is discussed

In the lighter-mass end of the deformed $A = 150$–180 region the shapes of the nuclei change very rapidly. Since the $N = 88$ nuclei lie just outside the permanently deformed region which begins at $N = 90$, they exhibit transitional character and thus attracts great interest in both experimental and theoretical investigations. Recently, in-beam studies [1–6] of the $N = 88$ nuclei had identified some high-spin negative-parity odd-spin bands Various models have been proposed to explain these negative-parity bands (NPB). The NPB seen in ^{152}Gd [1,7] has been interpreted in terms of an octupole vibration coupled either to a deformed or to a spherical core. Zolnowski et al. [3] has investigated the NPB of the $N = 88$ nuclei using a quadrupole–octupole coupled model. The calculated energy levels are in good agreement with the experimental data except for the high-spin states in ^{156}Er. Vogel [8] has pointed out that above a certain critical spin value the NPB can no longer be treated as octupole states but become two-quasiparticle decoupled states. Sunyar et al. [9] interpreted the NPB in ^{156}Er as a rotational band built on a two-quasiparticle state. However, Iachello and Arima [10,11] have shown that this coupling can be treated in a simple way within the framework of the interacting boson approximation (IBA) model. De Voigt et al. [5] investigated the NPB of ^{150}Sm in terms of interacting quadrupole and octupole bosons. Satisfactory results are obtained. Scholten et al. [12] have studied the negative-parity energy levels and E1, E3 transitions of even-mass nuclei of Sm isotopes. They used a mass-dependent interacting hamiltonian with s, d and f bosons. The energy levels can be well explained, but the E1 transitions fail to be reproduced unless the higher order terms in E1 transition operators were taken into account. In this letter, we shall study systematically the NPB of even–even $N = 88$ isotones using the IBA model. It is hoped that the energy levels of the negative-parity states of this series of isotones can be well reproduced by an unified set of parameters

In our model, the inert closed shells are taken at $Z = 50$ and $N = 82$. Extra core nucleons are considered to pair to active bosons. The effective hamiltonian between bosons is taken as the form

$$H = H_{sd} + \varepsilon_f + \left[Q^{(2)}_{sd} \cdot Q^{(2)}_{f} \right],$$

where H_{sd} is the hamiltonian for s and d bosons, ε_f is the single-boson energy of the f boson, $Q^{(2)}_{sd}$

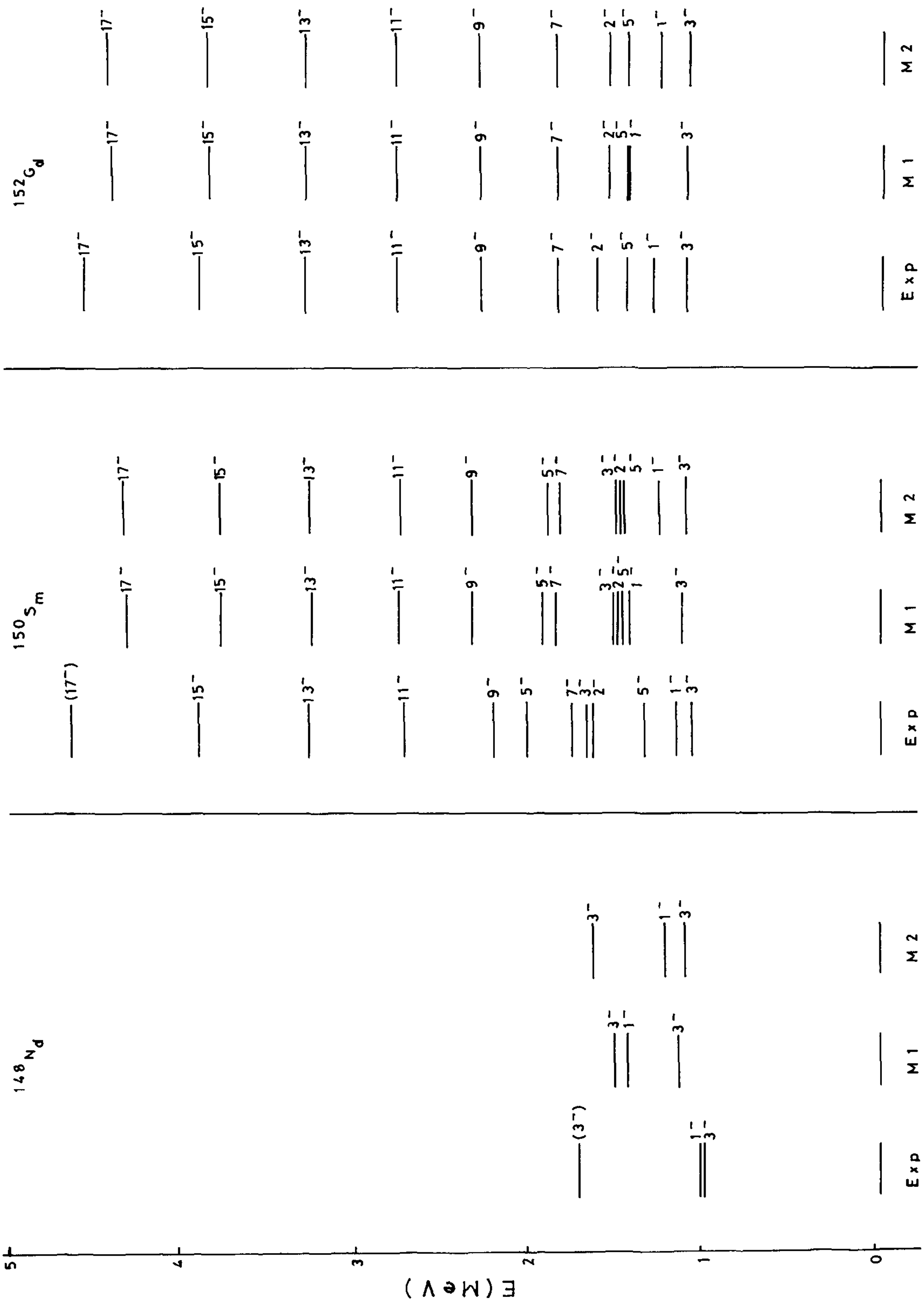
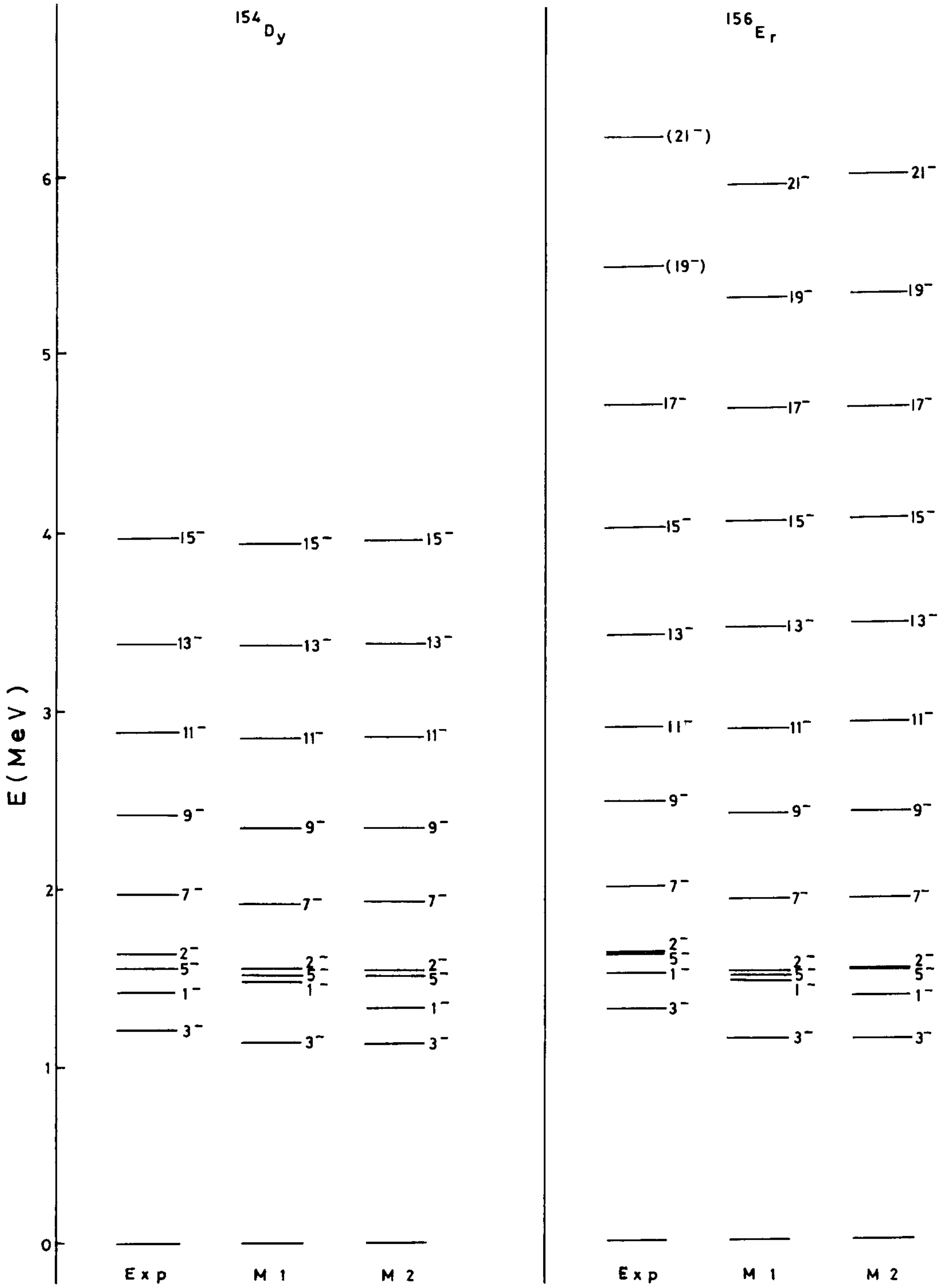


Fig 1



154Dy
156Er
E (MeV)
0
1
2
3
4
5
6
15⁻
13⁻
11⁻
9⁻
7⁻
2⁻
5⁻
1⁻
3⁻
(21⁻)
21⁻
(19⁻)
19⁻
17⁻
Exp
M 1
M 2

Fig 2

and $Q_f^{(2)}$ are the quadrupole operators for s, d and f bosons defined as follows·

$$Q_{sd}^{(2)} = [d^+ \times \tilde{s} + s^+ \times \tilde{d}]^{(2)} - \tfrac{1}{2}\sqrt{7}\,[d^+ \times \tilde{d}]^{(2)},$$

$$Q_f^{(2)} = C_1[f^+ \times \tilde{f}]^{(2)}$$

The parameters in H_{sd} are taken from a previous calculation for the positive-parity states of the $N = 88$ isotones [13]. The remaining two parameters ε_f and C_1 are determined from a least-squares fitting to forty-three negative-parity states of five $N = 88$ isotones ^{148}Nd, ^{150}Sm, ^{152}Gd, ^{154}Dy and ^{156}Er. We find that accurate fits to the energy spectra can be obtained by using an effective hamiltonian without any explicit boson-number dependence in the parameters The overall root-mean-square deviation is 0.119 MeV with the parameters (in MeV) $\varepsilon_f = 1.123$, $C_1 = 0.028$. The results (referred to as M1) are shown in figs. 1 and 2. In general, the calculated values are in good agreement with the observed ones, except the 1^- states for all nuclei. The calculated 1^- states lie much higher than the observed ones, so that the energy spacings between 1^- and 3^- states are almost doubled as compared to the observed values. From in-beam spectra of the (A, xn) reaction, high-spin negative-parity states have been identified up to 15^- for ^{150}Sm and ^{154}Dy and to 17^- for ^{152}Gd and ^{156}Er. These high-spin levels are all well reproduced in our calculations

To test the wave function, we also calculated the electromagnetic transitions. The one-body E1 and E3 transition operators in the space of s, d and f bosons can be written as

$$T(\mathrm{E1}) = \alpha_1[d^+ \times \tilde{f} + f^+ \times \tilde{d}]^{(1)},$$

$$T(\mathrm{E3}) = \alpha_3[s^+ \times \tilde{f} + f^+ \times \tilde{s}]^{(3)} + \beta_3[d^+ \times \tilde{f} + f^+ \times \tilde{d}]^{(3)}$$

It is found that the unified parameters $\alpha_3 = 0.12$ and $\beta_3 = -0\,70$ can reproduce the B(E3) values quite well. The results are shown in table 1. However, the calculated values for B(E1) cannot fit the observed values with either a mass-independent parameter α_1 or mass-dependent parameter α_1.

It may be interested to study whether the 1^- states and the E1 transitions can be improved by including the p boson. To check this point, we modify our hamiltonian to the following form to incorporate the effects of p bosons:

Table 1

Nucleus	$J_i \to J_f$	B(E3) [e^2b^3] experiment	theory
^{150}Sm	$0^+ \to 3_1^-$	0 36[a]	0 39
	$0^+ \to 3_2^-$	0 15[a]	0 11
^{152}Gd	$0^+ \to 3_1^-$	0 32[b]	0 42
	$0^+ \to 3_2^-$	0 07[b]	0 12

[a] Ref [14] [b] Ref [15]

$$H = H_{sd} + \varepsilon_f + \varepsilon_p + \left[Q_{sd}^{(2)}\;Q_{fp}^{(2)}\right],$$

where ε_p is the single boson energy for p bosons and

$$Q_{fp}^{(2)} = C_1[f^+ \times \tilde{f}]^{(2)} + C_2[p^+ \times \tilde{p}]^{(2)} + C_3[f^+ \times \tilde{p} + p^+ \times \tilde{f}]^{(2)},$$

The energy spectra fitting with an RMS deviation of 0.102 MeV can be obtained with the following unified interaction parameters (in MeV) $\varepsilon_f = 1.106$, $\varepsilon_p = 1.260$, $C_1 = 0.019$, $C_2 = -0.002$, $C_3 = 0.003$. The results (referred to as M2) are also presented in figs. 1 and 2. It can be seen that the 1^- states are all lowered down and thus the 1^-–3^- energy spacings become very close to the experimental data. In order to test the effects of the p boson on E1 and E3 transition rates we also include two terms, $\beta_1[s^+ \times \tilde{p} + p^+ \times \tilde{s}]^{(1)}$ and $\gamma_1[d^+ \times \tilde{p} + p^+ \times \tilde{d}]^{(1)}$, in the T(El) operator and a term $\gamma_3[d^+ \times \tilde{p} + p^+ \times \tilde{d}]^{(3)}$ in the T(E3) operator. The calculated B(E1) transition rates agree reasonably well with the experimental data with a unified set of parameters $\alpha_1 = -0.28$, $\beta_1 = -0\,50$, $\gamma_1 = 1.80$ for all isotones. The calculated and experimental values for some $N = 88$ isotones are shown in table 2. The inclusion of the $\gamma_3[d^+ \times \tilde{p} + p^+ \times \tilde{d}]^{(3)}$ term does not change the values of B(E3) appreciably for a wide range of values of γ_3, thus we put $\gamma_3 = 0$. In shell-model language, it is intended to interpret the p-boson as a two-particle pair within the valence shell having J^- values as 1^-. It is well known that this state contains a large

Table 2

Nucleus	$J_i \to J_f$	B(E1) ratios	
		experiment	theory
^{148}Nd	$3_1^- \to 4_1^+/2_1^+$	$1\ 5 \pm 0\ 2$[a]	3 7
	$1_1^- \to 2_1^+/0_1^+$	$2\ 6 \pm 0\ 3$[a]	2 1
^{150}Sm	$3_1^- \to 4_1^+/2_1^+$	0 78[b]	0 74
	$1_1^- \to 2_1^+/0_1^+$	2 07[b]	1 98
	$1_1^- \to 0_2^+/0_1^+$	0 63[b]	0 05
	$5_1^- \to 4_1^+/6_1^+$	1 0[c]	5 1
^{152}Gd	$3_1^- \to 4_1^+/2_1^+$	0 59[b]	0 35
	$1_1^- \to 2_1^+/0_1^+$	1 62[b]	1 84
	$1_1^- \to 0_2^+/0_1^+$	0 48[b]	0 04

[a] Ref [16] [b] Ref [17] [c] Ref [18]

amount of spurious center-of-mass motion, which is, however, not treated in our calculation. Therefore, we would like to emphasize that the success in fittings of 1^- energy levels and B(E1) transition rates should be interpreted in a phenomenological sense.

In conclusion, the NPB of $N = 88$ isotones can be explained in terms of the interacting boson approximation model. A mass-independent hamiltonian can be used for describing the whole series of isotones. The EM transitions can be reproduced quite satisfactory by a unified set of parameters. It is also found that the inclusion of the p boson improves the fittings in 1^- states and the E1 transition rates although the spurious center-of-mass motion of p boson pairs are not treated in any way.

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