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AN ALGEBRAIC APPROACH TO GIANT RESONANCES

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ABSTRACT

Collective particle-hole excitations are introduced by means of new bosons in the phenomenological Interacting Boson Model. Schematic results are shown for isovector dipole and isoscalar monopole and quadrupole modes in transitional nuclei.

1. INTRODUCTION

Collective particle-particle (pp), or hole-hole (hh) excitations within the valence shell of non-magic even-even nuclei have been treated as s,d,g,... bosons in the frame of the Interacting Boson Model (IBM)[1] to reproduce low-lying collective states and related electromagnetic transitions.

It is thus natural to add collective particle-hole (ph) excitations across shell closures as a new degree of freedom in IBM to describe high-lying collective states, or giant resonances and related transitions.

2. THE MODEL

A Hamiltonian of interacting pp and ph bosons can be written in the general form :

$$\hat{H} = \hat{H}(a) + \hat{H}(a,A) = \sum_{\lambda\pi}\varepsilon_{\lambda\pi}(-1)^{\lambda}\, a^{+}_{\lambda\pi}\cdot\tilde{a}_{\lambda\pi} + \hat{H}_{int}(a) + \sum_{\eta\pi}E_{\eta\pi}(-1)^{\eta}\, A^{+}_{\eta\pi}\cdot\tilde{A}_{\eta\pi} + \hat{H}_{int}(a,A) \qquad (1)$$

Here, $a^{+}_{\lambda\pi,\mu}$, with $\mu = -\lambda,\ldots,+\lambda$, create pp (hh) bosons of spin-parity $\lambda\pi$ and energy $\varepsilon_{\lambda\pi}$. The set of these $2\lambda+1$ operators forms a spherical tensor of rank λ : $\tilde{a}_{\lambda\pi,\mu} = (-1)^{\lambda-\mu}.a_{\lambda\pi,-\mu}$ so that $\hat{n}_{\lambda\pi} = (-1)^{\lambda}\, a^{+}_{\lambda\pi}\cdot\tilde{a}_{\lambda\pi}$ is the number operator for λ^{π} bosons. $H_{int}(a)$ is the usual IBM-1 Hamiltonian[1]. The total number of pp (hh) bosons, $\hat{N} = \sum_{\lambda\pi}\hat{n}_{\lambda\pi}$, commutes with $\hat{H}$ and is conserved in the model.

On the other hand, $A^{+}_{\eta\pi,M}$, with $M = -\eta,\ldots,+\eta$, create ph bosons of spin-parity $\eta\pi$ and energy $E_{\eta\pi}$, while $\tilde{A}_{\eta\pi,M} = (-1)^{\eta-M}A_{\eta\pi-M}$.

$\hat{H}_{int}(a,A)$ couples a and A bosons and does not commute in general with the number operator for A bosons, since it contains terms proportional to ($A^{+}_{\eta\pi} + A_{\eta\pi}$), when they are not forbidden by parity conservation.

Numerical diagonalization of (1), using the basis states

$$|\psi\rangle = \prod_{\lambda\pi}(a^{+}_{\lambda\pi})^{n_{\lambda\pi}}\prod_{\eta\pi}(A^{+}_{\eta\pi})^{n_{\eta\pi}}|0\rangle, \qquad (2)$$

yields the energies of low-lying discrete states, mainly due to a-type excitations, and those of high-lying states, with large A components, to be identified with giant resonances. When $E_{\eta\pi} \gg \varepsilon_{\lambda\pi}$, the terms of $\hat{H}_{int}(a,A)$ linear in the A degrees of freedom can be neglected in adiabatic approximation : the low-lying states are thus made only of a-type bosons and the parameters of $\hat{H}(a)$ can be found in the standard IBM-1 literature for a large number of nuclei.

The electric multipole ($E\Lambda$) transitions between A-type high-lying and a-type low-lying states are described by operators of the form :

$$\hat{T}(E\Lambda) = \alpha_{\Lambda}(A^{+}_{\Lambda\pi} + A_{\Lambda\pi}), \qquad (3)$$

where α_{Λ} is an effective boson charge.

Finally, let $\zeta(\Lambda^{\pi}_{n})$ be the energy of the n-th high-lying collective state of spin-parity Λ^{π} : the strength of transition to the ground state, $I^{\pi} = 0^{+}_{1}$ for even-even nuclei, can be expressed as a fraction of the corresponding energy-weighted sum rule (EWSR).

The present work is limited to the interaction of the usual pp (hh) bosons with $\lambda^{\pi} = 0^{+}$ and 2^{+}, responsible for low-lying positive-parity states, with a ph boson having $\eta^{\pi} = 1^{-}$, representing the isovector dipole resonance, and $\eta^{\pi} = 0^{+}, 2^{+}$ ph bosons corresponding to the isoscalar monopole and quadrupole resonances, respectively.

2.1 Isovector dipole resonance

Putting $a^+_{0+} = s^+$, $a^+_{2\pm\mu} = d^+_\mu$, with $|\mu| \leq 2$ and $A^+_{1-\nu} = P^+_\nu$, with $|\nu| \leq 1$, the Hamiltonian, $\hat{H}_{int}(s,d,P)$, describing the interaction of a giant dipole resonance (GDR) with low-energy collective modes reduces to the form :

$$\hat{H}(s,d,P) = b_1^{(0)} \left[(P^+ x\tilde{P})^{(0)} (s^+ x\tilde{s})^{(0)} \right]^{(0)} + b_2^{(0)} \left[(P^+ x\tilde{P})^{(0)} \cdot (d^+ x\tilde{d})^{(0)} \right]^{(0)} + b^{(1)} \left[(P^+ x\tilde{P})^{(1)} (d^+ x\tilde{d})^{(1)} \right]^{(0)} + b^{(2)} \left[(P^+ x\tilde{P})^{(2)} \hat{Q}(s,d) \right]^{(0)} , \quad (4)$$

where :

$$\hat{Q}(s,d) = (d^+ x\tilde{s} + s^+ x\tilde{d})^{(2)} + \chi (d^+ x\tilde{d})^{(2)} \quad (5)$$

is the s-d quadrupole operator contained in $\hat{H}(s,d)$. The coupling of angular momenta and the scalar product have their usual definition[1].

A dipole-dipole interaction proportional to $(P^+ + P)$ is here forbidden by parity conservation. The energies of GDR states are obtained through diagonalization of (4) using basis (2), with $n_s + n_d = N$, the usual boson number, and $n_p = 1$. The widths, Γ, of these states cannot be calculated within the framework of the model, but are assumed to depend on excitation energy, E, $\Gamma(E) = kE^\gamma$. The parameters k and γ , those of the P-boson Hamiltonian and the effective charge α_1 in (3) are so chosen as to reproduce total photoabsorption cross sections, where GDR is strongly excited, and allow us to predict elastic and inelastic photon scattering without further adjustment. A number of GDR calculations at the IBM limit symmetries[2-4,7] as well as in transitional regions[5-8] have been published : measurements of 8-20 MeV photons scattered by non-magic even-even nuclei could supply a good test of the model.

2.2 Isoscalar monopole and quadrupole resonances

Giant monopole (GMR) and quadrupole (GQR) resonances are described by two A-bosons, namely $A^+_{0+} = S^+$, and $A^+_{2+,\nu} = D^+_\nu$, with $|\nu| \leq 2$. $\hat{H}_{int}(s,d,S,D)$ can be written as :

$$\hat{H}_{int}(s,d,S,D) = c_1^{(0)} \left[(S^+ + S)(s^+ x\tilde{s}) \right]^{(0)} + c_2^{(0)} \left[(S^+ + S)(d^+ x\tilde{d})^{(0)} \right]^{(0)} + c_3^{(0)} \left[(S^+ x\tilde{S})(s^+ x\tilde{s}) \right]^{(0)} + c_4^{(0)} \left[(S^+ x\tilde{S})(d^+ x\tilde{d})^{(0)} \right]^{(0)} + c_5^{(0)} \left[(D^+ x\tilde{D})^{(0)} (d^+ x\tilde{d})^{(0)} \right]^{(0)} + c^{(1)} \left[(D^+ x\tilde{D})^{(1)} (d^+ x\tilde{d})^{(1)} \right]^{(0)} + c_1^{(2)} \left[(D^+ + D)^{(2)} \hat{Q}(s,d) \right]^{(0)} + c_2^{(2)} \left[((S^+ x\tilde{D} + D^+ x\tilde{S})^{(2)} + \chi' (D^+ x\tilde{D})^{(2)}) x \right.$$

$$\hat{Q}(s,d)\Big]^{(0)} + c^{(3)}\Big[(D^+ x\tilde{D})^{(3)}(d^+ x\tilde{d})^{(3)}\Big]^{(0)} + c^{(4)}\Big[(D^+ x\tilde{D})^{(4)}(d^+ x\tilde{d})^{(4)}\Big]^{(0)} , \qquad (6)$$

where $\hat{Q}(s,d)$ has been defined by formula (5).

The parameters of (6), the GMR and GQR widths and the effective boson charges, α_0 and α_2, from (3), should be adjusted on experimental data of inelastic hadron or electron scattering, where GMR and GQR are better seen. Up to now, only schematic calculations have been carried out, by assigning constant values $\Gamma(E) = k$ close to experimental data, to the GMR and GQR widths and evaluating the effective boson charges from the corresponding EWSR[9].

3. RESULTS AND COMMENTS

Schematic GDR, GMR and GQR calculations are here described for two transitional isotope chains, Pd and Sm, whose low-lying levels are reproduced by the s-d parametrization of refs.[10] and [5], respectively.

The P, S and D boson parameters of (4) and (6), the coefficients k and γ for the resonance widths, the boson charges α_0, α_1 and α_2 of (9) are kept constant within each chain and are listed in Table I, with the exception of the P, S and D boson energies, assumed to follow a semiempirical $A^{-1/3}$ law : E_P=77.5 $A^{-1/3}$ MeV ; E_S=76.0 $A^{-1/3}$ MeV ; E_D= 63.0 $A^{-1/3}$ MeV. The resulting giant resonance energies and strengths, expressed as EWSR fractions, are given in Tables II and III for Pd and Sm, respectively.

Commenting first on Pd results, it is to be pointed out that neither P nor S-D boson parameters have been optimized since,in the GDR case, only photoabsorption data on natural Pd[11] have been found in literature : as for GMR and GQR, only the data on the main GR component

Table I

IBM parameters*

GDR:	$b^{(1)}$(MeV)	$b^{(2)}$(MeV)	α_1(efm)	$k(MeV^{1-\gamma})$	γ	
Pd	0.00	0.50	6.4	0.08	1.5	
Sm	1.00	0.48	8.0	0.06	1.6	
GMR+GQR:	$c_3^{(0)}$(MeV)	$c_2^{(2)}$(MeV)	χ'	$\alpha_0(efm^2)$	$\alpha_2(efm^2)$	k(MeV)
Pd	−0.20	0.19	−0.40	47.0	22.0	4.0
Sm	0.	0.15	−0.15	60.0	30.0	3.0

*) Parameters put equal to zero in formulae (4,6) are not listed.

Table II

Giant resonance energies E(MeV) and strengths S(%EWSR) for Pd isotopes

Resonance	^{104}Pd		^{106}Pd		^{108}Pd		^{110}Pd	
	E	S	E	S	E	S	E	S
GDR :	15.67	49	15.32	41	14.93	36	14.54	33
	17.05	35	16.78	30	16.49	20	16.22	12
	17.73	10	17.41	17	17.12	23	16.90	22
	18.14	5	17.84	8	17.51	11	17.22	19
					18.28	7	18.19	9
GMR :	13.14	27	12.75	29	12.37	31	12.01	33
	15.21	7	14.76	5	15.83	56	15.86	41
	15.91	63	15.84	60	17.23	6	16.08	15
							17.16	7
GQR :	13.17	82	12.94	62	12.66	49	12.30	30
	14.20	14	13.90	24	13.00	7	12.67	15
			14.35	11	13.66	35	13.40	34
							13.74	13

Table III

Giant resonance energies E(MeV) and strengths S(%EWSR) for Sm isotopes

Resonance	^{148}Sm		^{150}Sm		^{152}Sm		^{154}Sm	
	E	S	E	S	E	S	E	S
GDR :	13.88	52	13.31	33	12.57	30	12.06	31
	15.22	25	14.38	21	13.76	7	15.86	40
	16.04	12	15.42	22	15.61	37	15.94	21
	16.29	8	15.95	17	15.90	12		
GMR :	11.88	15	11.50	15	10.93	17	10.55	21
	14.93	84	14.93	78	15.18	62	15.59	74
					15.29	5	16.26	4
					15.75	14		
GQR :	11.78	91	11.59	58	11.03	19	10.63	16
	12.72	7	11.89	26	11.67	49	11.59	48
			12.34	12	12.02	12	11.96	17
					12.12	13	12.02	12
							15.67	7

in $^{108-110}Pd$[12] have been considered. Both in the isovector and isoscalar excitation, the quadrupole-quadrupole interaction between high- and low-energy bosons is the leading term responsible for the giant resonance splitting. The monopole-monopole coupling of S and s bosons, which renormalizes the S-boson energy, makes it possible to reduce from 80% to 50% the fraction of EWSR exhausted by the main GMR component, though the experimental values seem to be as low as 30%.

Coming now to the Sm results, the P-boson parameters here adopted allow us to evaluate photoabsorption cross sections which fit the experimental data[13] with good accuracy. The fragmentation of dipole strengths nicely shows the U(5)→SU(3) transition[1] from spherical (^{148}Sm) to prolate shapes (^{154}Sm). As for GMR and GQR, the S-D boson parameters give resonance coupling and splitting for deformed nuclei in reasonable agreement with data on inelastic α scattering[14], but the distribution of monopole strengths in the spherical case (^{148}Sm) could be made closer to experiment[15] by switching on a monopole-monopole interaction as in the Pd case. The boson charges, α_0 and α_2, have been estimated from EWSR's[9]. A better choice, however, will be possible only on the basis of a detailed comparison between experimental angular distributions of emitted particles and coupled-channel calculations incorporating E0 and E2 matrix elements from (3).

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