A CALCULATION OF LOW-LYING COLLECTIVE STATES IN ODD-EVEN NUCLEI

C.E. ALONSO, J.M. ARIAS

Departamento de Física Atomica y Nuclear, Universidad de Sevilla, Spain

R. BIJKER

Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen, The Netherlands

and

F. IACHELLO

A.W. Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06520, USA

Received 19 April 1984

Revised manuscript received 4 June 1984

We present results of a calculation of properties of low-lying collective quadrupole states in odd-even nuclei within the framework of the proton-neutron interacting boson-fermion model.

The importance of proton-neutron degrees of freedom in low-lying collective states of nuclei has been emphasized in recent years by the interacting boson model [1]. In addition to introducing specific proton-neutron effects, such as the occurrence of $K^P = 1^+$ bands in deformed nuclei [2], this model has the advantage that, being closely related to the microscopic shell model, it allows one to make extrapolations and predictions for properties of nuclei hitherto unknown. The next logical step in the direction of a detailed understanding of nuclear properties is that of performing similar proton-neutron calculations for *odd-even nuclei*. Because of the large number of low-lying states, these calculations present a major challenge. Previous calculations of odd-even nuclei within the framework of the interacting boson model have been done with the version of the model in which no distinction is made between proton and neutron degrees of freedom [3]. In this letter, we present the results of the first systematic calculations performed using the proton-neutron interacting boson-fermion model. The corresponding computer program was originally written by Otsuka and Yoshida [4], and applied to the study of ^{79}Rb and ^{79}Kr in ref. [5]. The calculations presented

in this article are based on an improved version of this program obtained by one of us (R.B.), together with B. Visscher [6]. The improvement consists of a prediagonalization and truncation of the boson spectrum before coupling the odd fermion.

In the interacting boson-fermion model, spectra of odd-even nuclei are calculated by coupling the collective degrees of freedom, described by bosons, to the single-particle degrees of freedom (fermions). The hamiltonian is written as

$$H = H^{(B)} + H^{(F)} + V^{(BF)}, \quad (1)$$

where $H^{(B)}$ is the proton-neutron interacting boson hamiltonian [1], $H^{(F)}$ is the hamiltonian describing the single-particles degrees of freedom, and $V^{(BF)}$ is their interaction. The structure of the boson-fermion interaction is, in general, rather complex since the bosons are composite rather than fundamental particles and thus one needs to take into account the effects of the Pauli principle. A purely phenomenological treatment of this interaction is not possible, since it contains a large number of parameters. One must therefore rely on a microscopic derivation. Several of these have been given [7-10]. In the calculations pre-

sented here, we have used the following form

$$V^{(BF)} = \Gamma_\nu(Q_\nu \cdot q_\nu) + \Lambda_\nu F_{\nu\pi} + A_\nu(n_{d_\pi} \cdot n_\nu), \quad (2)$$

for odd neutron nuclei, and

$$V^{(BF)} = \Gamma_\pi(Q_\nu \cdot q_\pi) + \Lambda_\pi F_{\nu\pi} + A_\pi(n_{d_\nu} \cdot n_\pi), \quad (3)$$

for odd proton nuclei. The first terms in eqs. (2) and (3) represent a quadrupole-quadrupole interaction between bosons and fermions,

$$Q_\rho = \{(d^\dagger \times \tilde{s} + s^\dagger \times \tilde{d})^{(2)} + \chi(d^\dagger \times \tilde{d})^{(2)}\}_\rho,$$

$$q_\rho = \left\{ \sum_{jj'} Q_{jj'} (u_j u_{j'} - v_j v_{j'}) (a_j^\dagger \times \tilde{a}_{j'})^{(2)} \right\}_\rho, \quad \rho = \pi, \nu, \quad (4)$$

where we have used the usual notation for boson and fermion creation and annihilation operators. The second term, representing the effects of the Pauli principle (exchange interaction), has been taken in this article to be [7]

$$F_{\pi\nu} = -\{(s^\dagger \times \tilde{d})^{(2)}\}_\pi \cdot \left\{ \sum_{jj''} (10/N)^{1/2} (2j+1)^{-1/2} \right. \\ \times Q_{jj''} (u_j v_{j''} + v_j u_{j''}) Q_{j''j'} (u_{j''} v_{j'} + v_{j''} u_{j'}) \\ \times \left. : [(d^\dagger \times \tilde{a}_{j''})^{(j)} \times (\tilde{s} \times a_{j'}^\dagger)^{(j')}]^{(2)} : \right\}_\nu \\ + \text{hermitean conjugate.} \quad (5)$$

while $F_{\nu\pi}$ is obtained from eq. (5) by interchanging the indices π and ν . Other, more complex forms, could be used, if needed. The third term represents a monopole-monopole interaction

$$n_{d_\rho} = \left\{ \sum_m d_m^\dagger d_m \right\}_\rho, \\ n_\rho = \left\{ \sum_{jm} (2j+1)^{1/2} a_{jm}^\dagger a_{jm} \right\}_\rho, \quad \rho = \pi, \nu. \quad (6)$$

The microscopic structure of the bosons enters in eqs. (4)–(5) through the coefficients [11]

$$v_j^2 = \alpha_j^2 N / \sum_j \alpha_j^2 (j + \frac{1}{2}), \quad u_j = (1 - v_j^2)^{1/2}, \\ Q_{jj'} = \langle l \frac{1}{2} j \| Y^{(2)} \| l' \frac{1}{2} j' \rangle, \quad (7)$$

where the α_j are the structure coefficients of the S-

pairs and N is the number of pairs.

Finally, one needs the fermion hamiltonian, $H^{(F)}$. When only one odd particle is present, it is sufficient to consider the single-particle part of $H^{(F)}$,

$$H^{(F)} = \sum_{jm} E_j a_{jm}^\dagger a_{jm}, \quad (8)$$

where the E_j are the single particle energies in the presence of N pairs. In the calculations performed so far, the coefficients u_j , v_j and the energies E_j have been obtained using the BCS approximation

$$E_j = [(\epsilon_j - \lambda)^2 + \Delta^2]^{1/2}, \\ v_j^2 = \frac{1}{2} [1 - (\epsilon_j - \lambda)/E_j], \quad (9)$$

rather than the full generalized seniority scheme.

In conclusion, according to the model described here, spectra of odd-even nuclei can be calculated in terms of three parameters Γ_ν , Λ_ν , A_ν (or Γ_π , Λ_π , A_π). In order to study specifically proton-neutron effects, we have applied this model to odd-neutron Xe nuclei and odd-proton Cs nuclei in the 50–82 major shell. Both isotopic chains have the same even-even core. Thus, differences in the spectra can arise only from the boson-fermion interaction $V^{(BF)}$ and the single-particle hamiltonian, $H^{(F)}$. The boson hamiltonian, $H^{(B)}$ was taken from a previous calculation [12]. The unperturbed single-particle energies, ϵ_j , were taken as in table 1. The values shown in this table were extracted from ref. [13] for proton levels and from the experimental spectrum of $^{131}_{50}\text{Sn}_{81}$ for neutron levels. In the major shell 50–82 there are 5 single-particle levels, 4 with positive parity (1 $g_{7/2}$, 2 $d_{5/2}$, 3 $s_{1/2}$ and 2 $d_{3/2}$) and 1 with negative parity (1 $h_{11/2}$). Since they do not mix, calculations can be done independently for each parity. In this letter, we report only results for negative parity states. Those for positive parity states will

Table 1
Unperturbed single particle energies (MeV) used in the present calculation.

	Level				
	1 $g_{7/2}$	2 $d_{5/2}$	1 $h_{11/2}$	3 $s_{1/2}$	2 $d_{3/2}$
proton levels	0	0.60	1.50	3.35	3.00
neutron levels	0	0.80	2.00	2.10	2.50

Table 2
Boson-fermion interaction parameters for negative parity states (MeV).

	Γ	Λ	A
protons	0.6	1.3	-0.3
neutrons	0.6	1.3	0

be presented in a longer publication [14]. The values of the parameters used in the calculation are given in table 2. Fig. 1 shows the results for the Xe isotopes, while fig. 2 shows the results for the Cs isotopes. The proton-neutron effects are clearly displayed in these figures. In cesium, the $\pi h_{11/2}$ level is almost completely empty ($v_{11/2}^2 \approx 0$). As a result, the exchange inter-

Fig. 1. Calculated negative parity spectra in the odd- A Xe isotopes. The state $J^P = 11/2^-$ is taken as zero of the energy. The experimental values (circles, squares, ...) are from ref. [15].

Fig. 2. Calculated negative parity spectra in the odd- A Cs isotopes. The state $J^P = 11/2^-$ is taken as zero of the energy. The experimental values (circles, squares, ...) are from ref. [16].

action vanishes, and the spectra are dominated by the quadrupole interaction. On the contrary, in Xenon, the $\nu h_{11/2}$ level is empty for smaller neutron numbers (≈ 54) but becomes increasingly populated for larger neutron numbers (≈ 76). A consequence of this is that the state with $J^P = 9/2^-$ becomes lower and lower in excitation energy and it crosses the state with $J^P = 11/2^-$ at neutron numbers ≈ 66 .

The results shown in figs. 1 and 2 indicate that it is possible to provide a unified description of long odd-A isotopic chains in terms of few parameters, although a closer inspection reveals that discrepancies between calculations and experiment still remain. Particularly notable is that concerning the location of the lowest $J^P = 7/2^-$ state in Xe. This discrepancy was also present in the calculations performed within the framework of the interacting boson-fermion model without distinction between proton and neutron degrees of freedom [17], and is due to the restriction of the single-particle negative parity space to $1h_{11/2}$. Introduction of the $2f_{7/2}$ and $1h_{9/2}$ levels eliminates the difference between calculated and experimental states [17].

The same conclusions can be drawn by analyzing the results of the calculations of the positive parity states and of electromagnetic transition rates. It appears thus that we have now at our disposal a tool capable of analyzing properties of odd-even nuclei that include isospin effects. The scope and limitations of this tool remain to be seen and will be determined by a comparison between calculations and experiment in other isotopic chains.

We thank A.E.L. Dieperink for discussions. One of us (F.I.) thanks R. Leonardi for his hospitality at the University of Trento where this article was completed. This work was in part supported by the Stichting FOM which receives financial support from the "Stichting Voor Zuiver-Wetenschappelijk Onderzoek" and in part by the Department of Energy Contract No. DE-AC02-76ER 03074.

References

- [1] A. Arima, T. Otsuka, F. Iachello and I. Talmi, Phys. Lett. 66B (1977) 205;
T. Otsuka, A. Arima, F. Iachello and I. Talmi, Phys. Lett. 76B (1978) 139.
- [2] F. Iachello, Nucl. Phys. A358 (1981) 89;
A.E.L. Dieperink, Prog. Part. Nucl. Phys. 9 (1983) 121;
A. Richter, Proc. Intern. Conf. on Nuclear physics (Florence, Italy, 1983).
- [3] F. Iachello and O. Scholten, Phys. Rev. Lett. 43 (1979) 679.
- [4] T. Otsuka and N. Yoshida, Computer Program TWC, University of Tokyo, Japan;
Yoshida, A. Arima and T. Otsuka, Phys. Lett. 114B (1982) 86.
- [5] J. Panqueva, H.P. Hellmeister, L. Lühmann, F.J. Bergmeister and K.P. Lieb, Nucl. Phys. A389 (1982) 424.
- [6] B. Visscher and R. Bijker, Computer Program BOSON and ODD PAR, University of Groningen, The Netherlands.
- [7] I. Talmi, in: Interacting Bose-Fermi systems in nuclei, ed. F. Iachello (Plenum, New York, 1981) p. 329.
- [8] O. Scholten and A.E.L. Dieperink, in: Interacting Bose-Fermi systems in nuclei, ed. F. Iachello (Plenum, New York, 1981) p. 343.
- [9] A. Gelberg, Z. Phys. A310 (1983) 117.
- [10] U. Kaup, Prog. Part. Nuclear Phys. 9 (1983) 561.
- [11] T. Otsuka and A. Arima, Phys. Lett. 77B (1978) 1.
- [12] G. Puddu, O. Scholten and T. Otsuka, Nucl. Phys. A348 (1980) 109.
- [13] P. Mukherjee, R. Bhattacharya and I. Mukherjee, Phys. Rev. C24 (1981) 1810.
- [14] C.E. Alonso, J.M. Arias and R. Bijker, to be published.
- [15] A. Kerek, A. Luukko, M. Grecescu and J. Sztarkier, Nucl. Phys. A172 (1971) 603;
I. Rezanka, A. Kerek, A. Luukko and C.J. Herrlander, Nucl. Phys. A141 (1970) 130;
H. Helppi, J. Hattula and A. Luukko, Nucl. Phys. A332 (1979) 183;
V. Bacri, A. Gizon, J. Crawford, J. Genevy, J. Gizon and A. Plochocki, Proc. Intern. Conf. on Nuclei far from stability (Helsingør, Denmark, 1981) pp. 479, 480;
P. Chowdhury, U. Garg, T.P. Sjoreen and D.B. Fossan, Phys. Rev. C23 (1981) 733;
A. Luukko, J. Hattula, H. Helppi, O. Knuuttila and F. Döna, Nucl. Phys. A357 (1981) 319;
H. Helppi, J. Hattula, A. Luukko, M. Jaaskelainen and F. Döna, Nucl. Phys. A357 (1981) 333.
- [16] U. Garg, T.P. Sjoreen and D.B. Fossan, Phys. Rev. C19 (1979) 207, 217;
Ch. Droste, D. Chlebowska, J. Dobaczewski, F. Döna, A. Kerek, G. Leander, J. Srebrny and W. Walus, Nucl. Phys. A341 (1980) 98.
- [17] M.A. Cunningham, Nucl. Phys. A385 (1982) 204, 221.