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TOWARDS A SHELL-MODEL DESCRIPTION OF INTRUDER STATES AND THE ONSET OF DEFORMATION

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Abstract

Basing on the nuclear shell-model and concentrating on the monopole,pairing and quadrupole corrections originating from the nucleon-nucleon force,both the appearance of low-lying 0^+ intruder states near major closed shells(Z=50, 82)and sub-shell regions (Z=40,64) can be described.Moreover,a number of new facets related to the study of intruder states are presented.

1.Introduction.

In a nucleus,the major part of the nucleonic motion is determined by the average single-particle field.This field approximation implies the existence of magic numbers i.e. 20,28,50,82,126 ,determining extra stability for the particular nuclei having proton and/or neutron number equal to such a magic number.The energy separation between the last filled single-particle orbitals and the lowest,unfilled orbitals varies from ≈6 MeV(light nuclei) to≈3.5 MeV(Z=82 gap).Besides,a number of subshell closures have by now been established i.e. Z=40,64.In these cases,a much smaller energy gap of 1 and 2.5 MeV,respectively results.It is precisely the existence of particular configurations that makes the study of nuclear structure approximate tractable.Most nucleons can be considered to contribute to the "core" nucleus and thus to the average field leaving only a small number of nucleons,called valence nucleons(particles or holes) outside closed shells(see fig.1).In region I,few valence nucleons are present

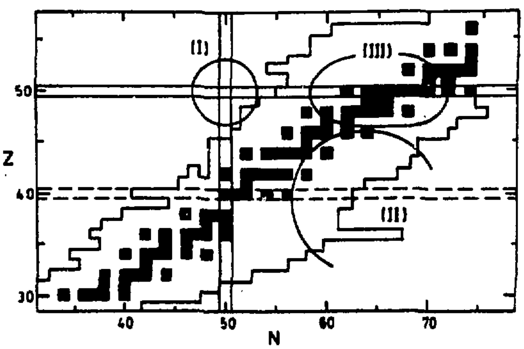

Fig.1 Schematic division of nuclei in three major regions: (I) region near doubly closed shells; (II) region of strongly deformed nuclei; (III) region of intruder states.

and the nuclear shell-model techniques[SHA63] allow for a detailed study of low-lying nuclear excited states. In region I, the pairing properties between identical nucleons are primordial and strongly collective motion does not develop until many valence protons and neutrons (region II [BOH75]) moving in identical single-particle (or spin-orbit partner) orbitals [SHA53,FED79] are present. In this case, the strong proton-neutron interaction is the dominant contribution and leads to permanently deformed nuclei.

The separation in two regions I, II very much relies on the existence of a set of well defined closed shell configurations. Since the value of the shell gaps can be shown to be A dependent (see sect.2 [GUO77,SOR84]), a more detailed analysis of the variation of shell gaps as a function of A will have to be studied.

There now also exists an idealized region III (see fig.1) where one type of nucleons is near a closed shell configuration (very few valence nucleons) and the other has a maximal number of valence nucleons (mid-shell situation). It has been shown that in such nuclei, the closed shell can be excited and low-lying particle-hole (p-h) excitations result (1p-2h or 2p-1h in odd-A nuclei having originally 1h or 1p outside a closed shell). These "intruder" statesfor which one would expect, at first, a larger excitation energy, have been studied in detail for odd-A nuclei in [HEY83], where most closed-shell regions are covered in detail. In the present discussion (specific for even-even nuclei), we present a shell-model approach for describing both the small excitation energy and the particular A-dependence of such intruder states throughout region III nuclei.

2. Shell-model description of intruder states

In a schematic presentation (see fig.2) of a single-closed shell nucleus, we take as the lowest intruder state (0^+ state) a proton (π) 2p-2h configuration

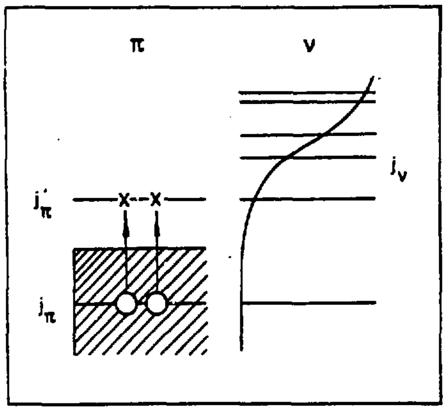

Fig.2 Schematic representation of a proton (π) intruder 2p-2h 0^+ configuration where j_π denotes the regular orbital, j'_π the intruder orbital and j_ν the neutron orbitals filled in a BCS way (ν)

with the valence neutrons distributed over the available single-particle orbitals. The unperturbed energy then becomes

$$E^{unp.}_{intr.}(0^+) = 2(\varepsilon_{j'_\pi} - \varepsilon_{j_\pi}). \quad (1)$$

We now shortly discuss the different energy corrections due to both the strong pairing correlations in the 2p and 2h configurations and the proton-neutron interaction affecting both the proton single-particle energies and the binding energy of these intruder 2p-2h configurations due to core polarization effects of the underlying 0^+ core.

2.1 Monopole field correction

The proton single-particle energies become modified due to the proton-neutron interaction in the following way

$$\tilde{\varepsilon}_{j_\pi} = \varepsilon_{j_\pi} + \sum_{j_\nu} v^2_{j_\nu} (2j_\nu + 1) E(j_\pi, j_\nu) , \quad (2)$$

with $E(j_\pi, j_\nu)$ the average proton-neutron interaction energy [TAL63] and $v^2_{j_\nu}$ the BCS occupation probabilities of the j_ν neutron orbitals. Because of these single-particle energy variations, a <u>first</u> correction to the unperturbed proton intruder configurations results as

$$\Delta E_M = 2(\tilde{\varepsilon}_{j'_\pi} - \tilde{\varepsilon}_{j_\pi}) - 2(\varepsilon_{j'_\pi} - \varepsilon_{j_\pi})$$

$$= 2\sum_{j} v^2_{j_\nu} (2j_\nu + 1) [E(j'_\pi, j_\nu) - E(j_\pi, j_\nu)] . \quad (3)$$

This monopole correction has been studied in some detail for both the large shell Z=50,82 and the subshell Z=40,64 regions [HEY85]. It thereby becomes clear that for the large spherical single-particle shell gaps (50,82) only a small modification of the original gap results. On the contrary, for the subshell regions, when N increases, an almost complete eradication of the subshell gaps (for Z=40 near N=58,60; for Z=64 near N=88,90) results and thus, in the latter cases, we end up with nuclei similar to the region II type of fig.1, thus giving rise to strongly deformed nuclei which is also experimentally the case.

2.2 Pairing field correction

When exciting a 2p-2h configuration, we form 0^+ coupled configurations as the lowest-lying states therby obtaining a large pairing binding energy gain. This latter value can be calculated using the residual nucleon-nucleon force or estimated, starting from proton separation energies as

$$\Delta E_P = \Delta E_{pairing}(part.) + \Delta E_{pairing}(holes), \quad (4)$$

$$\Delta E_{pairing}(holes) = 2S_p(Z,N) - S_{2p}(Z,N) , \quad (5)$$

(similar expression for $\Delta E_{pairing}(part.)$), where $\Delta E_{pairing}$ is determined at (if experimentally known) or near the doubly-closed shell configurations i.e.

^{208}Pb, ^{146}Gd, ^{132}Sn, ^{90}Zr,..).This pairing correction results in an important lowering of the intruder state energy,which is of the order of $E_p \simeq 4-5$ MeV at Z=50,N=82;$E_p \simeq 2.5$ MeV at Z=82,N=126 region,but largely independent of the mass number A.

2.3 Quadrupole proton-neutron energy correction

Up to now,we always assumed a 0^+ coupled pair distribution to give a good description of both the proton 2p-2h excitation and of the neutron distribution over the valence model space.The quadrupole component of the proton-neutron force will induce $0^+ \rightarrow 2^+$ pair breaking for both protons and neutrons which we call the core polarization effect.Thus,0^+ ground state and intruder wave functions are changed into

$$|0^+_\pi \otimes 0^+_\nu> \;\rightarrow\; |0^+_\pi \otimes 0^+_\nu> + \alpha|2^+_\pi \otimes 2^+_\nu> + \ldots . \qquad (6)$$

Using perturbation theory and the lowest seniority shell-model description of the 0^+ pair distribution,one calculates a quadrupole polarization energy gain

$$\Delta E_Q = \kappa^2_{sm} N_\nu (\Omega_\nu - N_\nu).F \quad , \qquad (7)$$

where κ_{sm} is the strength of the quadrupole proton-neutron force component ($\kappa_{sm} Q_\pi \cdot Q_\nu$ with $Q_\rho \equiv (r\sqrt{\frac{m\omega}{\hbar}})^2 Y_2(\bar{r}_\rho)$) and N_ν the number of neutron pairs (F contains the particular j'_π ,j_π and j_ν orbital information).If many valence nucleons are present,many 2^+ proton-neutron pairs can become admixed and perturbation theory breaks down.In the latter case,using an SU(3) wave function for describing the repartition of 0^+ and 2^+ coupled proton and neutron pairs, one obtains the expression

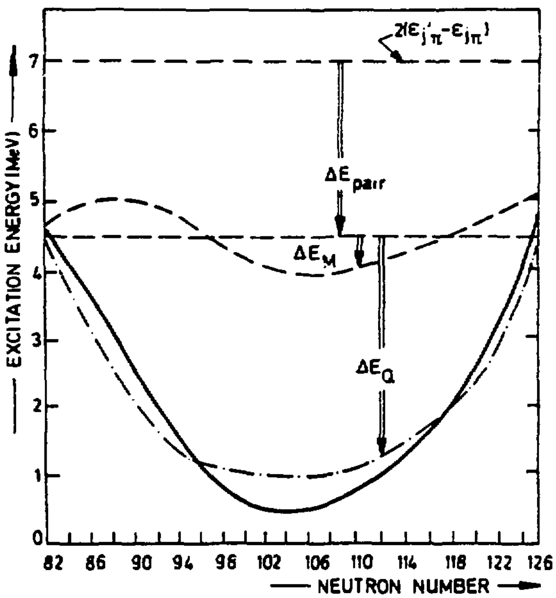

Fig.3 The total energy correction(full thick line)due to both the monopole (ΔE_M;dashed line),the pairing (ΔE_p; straight dashed line)and the quadrupole correlations(ΔE_Q;dot-dashed line) ,for the Pb(Z=82)region.The unperturbed energy(upper straight dashed line) is also shown.

$$\Delta E_Q = 2\kappa_0 N_\pi N_\nu (\Omega_\pi - N_\pi)^{1/2} . (\Omega_\nu - N_\nu)^{1/2} \quad , \qquad (8)$$

(κ is the strength of the quadrupole force in IBM-2 calculations [ARI84] in a sd-boson model space with $\kappa = \kappa_0 (\Omega_\pi - N_\pi)^{1/2} (\Omega_\nu - N_\nu)^{1/2}$ [SCH80]). In the quadrupole energy gain, for given N_π near closed shells ($N_\pi << \Omega_\pi$), a very particular N_ν dependence results, beiing maximal at mid-shell configurations, conform with the known experimental facts on intruder states in even-even nuclei near or at closed-shells (Sn, Pb,..).

Collecting all parts, one obtains the final expression,

$$E_{intr.}(0^+) = 2(\varepsilon_{j_\pi'} - \varepsilon_{j_\pi}) + \Delta E_M + \Delta E_P + \Delta E_Q \quad , \qquad (9)$$

(relation which is illustrated in fig.3 for the Pb region). The expression (9) for $E_{intr.}(0^+)$, is obtained in a separable form pointing out clearly the different contributions from the nucleon-nucleon interaction. This is of course an approximation to the more general result one would obtain when carrying out a full HFB calculation in determining

- the proton (neutron) single-particle energies and orbitals in a self-consistent way for each Z, N, A
- diagonalizing in the appropriate basis, for describing the lowest excited states, the residual nucleon-nucleon interaction [FED79]

We also point out that, when the spherical shell-gap, giving rise to the possibility of defining 2p-2h excitations, disappears due to the monopole correction ΔE_M, the above procedure of separating the different parts of the nucleon-nucleon interaction (single-particle field, pairing correlations and quadrupole correlations) will break down. This is signaled by the intruder 0^+ state crossing the regular 0^+ ground state of the nuclei we are discussing. This is, for instance, the case in the Zr nuclei (near N≈60) and the Gd nuclei (N≈ 90).

3. New facets of intruder states

Here, we shortly mention the possibilities of other intruder state properties:

- "Scaling " property for the intruder excitation energy [VAN85] . Recently, scaling properties have been discussed at length by R.F. Casten [CAS85,85a] when studying low-lying regular collective excitations (2^+, 4^+ energies, B(E2) values)
- intruder states in odd-odd nuclei [MAL82, VAJ83, HUY85, NES82]
- one-broken pair intruder states: these are situations where we consider the $(j_{p_1} j_{p_2}) J_{max.} (j_h^{-2}) 0^+ ; J_{max.}$ configurations. These should occur at an energy, roughly $\Delta E_{pairing}$(part.) above the lowest 0^+ intruder state. Possibilities for such states can exist in the Pb region [NES83, HES85]

-intruder states near neutron closed shells[HEY83]

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