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CORRELATIONS IN ODD-MASS NUCLEI

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Résumé: Les corrélations dans les noyaux de masse impaire sont étudiées par expansion des fonctions d'ondes dans un espace de configurations à une et trois quasiparticules. L'opérateur de self-énergie produit un mélange des couches principales de sorte que les facteurs des formes radiales sont différents pour chaque état. La théorie est appliquée au cas de $^{41}$Ca.

Abstract: Correlations in odd-mass nuclei are described by expanding the wave functions into one and three quasiparticle configurations. The self-energy operator induces mixing of radial wave functions from different major shells. This allows to study the state-dependence of correlated single particle wave functions entering e.g. into transfer and knock-out processes. Applications to $^{41}$Ca are discussed.

1. INTRODUCTION

In spectra of odd-mass nuclei the importance of final state interactions is evident from the fragmentation of single particle or hole strengths over many eigenstates. The fragmentation pattern is a finger print of the many body correlations due to the interaction of hole or particle states with the core nucleons. Studies of transfer and knock-out reactions have been concentrating in the past on strength distributions. Typically, form factors obtained from empirical potential i.e. mean field models are being used (see e.g. /1,2/). Such approaches describe data quite successfully at least close to the ground state. However, for accurate spectroscopic studies over a wide range of excitation energies the empirical models are likely to become insufficient because by construction they include form factor correlations only on the level of binding energies. Thus consistency of spectroscopic factors and form factors is not assured.

2. THE QUASIPARTICLE CORE COUPLING MODEL

In the quasiparticle-core coupling (QPC) model /3,4,5/ states $|j\lambda\rangle$ of total angular momentum $j$ (and parity $\pi$) in odd-mass nuclei are described as superpositions of one and three quasiparticle configurations with respect to the BCS-ground state of the even-mass parent system:

$$|j\lambda\rangle = \sum_n z_n|\lambda\rangle |n\rangle + \sum_{j'j'} z_{j'j'}|\lambda\rangle |(j'j')\rangle$$

(1)

By the quasiparticle (QP) method long range pairing correlations in the ground state are included. The 1-QP components have been denoted by $|n\rangle$. The 3-QP configurations $|(j'j')\rangle$ are chosen as QRPA-core excitations $j'$ coupled to 1-QP-states $j$. A special feature of the present approach is the expansion of the 1-QP component into radial wave func-

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tions with different radial nodes \(n/4,5/\). This "major shell" mixing is an important extension over other approaches of similar kind \(5,6/\) because in this way correlations in strength distributions and wave functions are described consistently. In particular wave function correlations are introduced on safe theoretical grounds avoiding the arbitrariness of phenomenological approaches. The Hamiltonian is \(H = H_0 + V_{13}\) where \(H_0\) is diagonal in the 1- and 3-QP subspaces which are coupled by the residual interaction \(V_{13}\). Projection onto the 1-QP subspace leads to an effective eigenvalue equation for the 1-QP states \(|\nu\rangle = |n\rangle\)

\[
\sum_{\nu'} \left[ (E_{\nu} - E)\delta_{\nu\nu'} - M_{\nu\nu'}(E) \right] z_{\nu'} = 0. \tag{2}
\]

The radial mixing is due to the non-diagonal parts of the self-energy operator

\[
M_{\nu\nu'}(E) = \sum_{\mu\mu'} \frac{\langle \nu | V_{13} | \mu\mu' \rangle \langle \mu\mu' | V_{13} | \nu \rangle}{E_{\mu} + E_{\mu'} - E}, \tag{3}
\]

where the QRPA-core excitations are denoted by \(|c\rangle/4,5/\). In one-step transfer and knock-out reactions the 1-QP component of Eq.(1) is directly observed. After projection onto the physical nucleon states the spectroscopic factors for e.g. a stripping reaction are found as

\[
S_j(\lambda) = \sum_n |u_{nj}|^2 z_{nj}(\lambda)^2, \tag{4}
\]

and the normalized form factors are defined by

\[
\Phi_{j\lambda}(\vec{r}) = \sum_n z_{nj}(\lambda) u_{nj} \varphi_{nj}(\vec{r}) / \sqrt{S_j(\lambda)}, \tag{5}
\]

where \(u_{nj}\) are particle-type BCS-amplitudes and \(\varphi_{nj}\) denotes a single particle wave function. In knock-out and pick up reactions the occupancies \(v_{nj}^2 = 1 - u_{nj}^2\) enter instead into the above expressions.

3. RESULTS FOR \(^{41}\text{Ca}\).

Typical results for strength functions in \(^{41}\text{Ca}\) obtained with large-scale QRPA-calculations using Wood-Saxon single particle functions and a realistic interaction derived from a G-matrix are shown in Fig.1/4/. Mixing of wave functions with \(n\leq4\) has been included. The strength functions were folded by a Lorentzian of FWHM \(\Delta=0.5\text{MeV}\) for reasons of presentation. The BCS-ground state correlations in \(^{40}\text{Ca}\) are rather moderate for usual values of the pairing strength \(G_p=25.5\text{MeV}\) and \(G_n=23.5\text{MeV}\) for protons and neutrons, respectively, leading e.g. to \(u^2=0.13\) for \(1d_{3/2}\) (neutron), but clearly needed in order to understand the occurrence of low-lying positive-parity states in \(^{41}\text{Ca}\). A detailed comparison with recent high-resolution \(\text{Ca}(\vec{p},p)\)-data is discussed in /3,4/ and applications to proton and neutron transfer processes in \(^{48}\text{Ti}+^{42}\text{Ca}\)-reactions are found in /5/. In both cases the overall features of spectra are well described.

An important effect of the radial mixing is that strength from higher shells is partially shifted into the low energy region. This increases for example the \(\frac{3}{2}^+\)-strength for \(E_x \leq 8.8\text{MeV}\) in \(^{41}\text{Ca}\) by a factor of 1.8 over the sum rule limit /4/. Apparently this poses a severe problem to the determination of "absolute" spectroscopic factors and ground
state correlations because they would be overestimated by the same amount. Generally the radial correlations are most important for states with a small 1-QP partial width. In reactions they are only weakly excited but for an accurate determination of strengths their contributions are important as well. In many cases the form factors differ strongly from those of phenomenological mean field approaches like the "well depth" (WD) or "surface peak" (SP) method /4/. Results for several $\frac{5}{2}^+$-states which are of particular interest for investigations of ground state correlations are displayed in Fig.2. For the first few states form factors of $d$-shape are obtained which essentially vary according to the binding energy. Phenomenological potential models are likely to reproduce this behaviour. However, as seen in the lower part of Fig.2 at $E_x=6.28$ MeV the shape changes to $2d$. At higher excitation energies the shapes are varying between $n=1$ and $n=2$. The momentum structure of the form factors is altered accordingly. In Fig.3 the Fourier transforms of the same wave functions are displayed. Apparently strong admixtures of large momenta occur for the $E_x=6.28$ MeV-state. Similar results are obtained for states of other angular momenta and parities as well. The radial mixing is most pronounced for reactions leading to configurations involving mostly filled shells, i.e. the $(2s,1d)$-shell for $^{41}$Ca. Similar results are obtained for states of other angular momenta and parities as well. For the negative parity configurations the nodal structure is determined by the $(2p, 1f)$-orbital involved but strong variations in the spatial extension occur. This was studied already in /3,4/ where rms-radii from the microscopic approach and the WD and the SD method have been compared. As expected neither of the phenomenological methods is able to describe the strong variations of the microscopic rms-radii but in the average the WD-method reproduces at least the general increase with excitation energy.

Fig.1: Single particle strength distributions for $^{41}$Ca for "hole-type" (upper part) and "particle-type" (below) states folded with a Lorentzian of FHWM $\Delta=0.5$ MeV. Note the change of scale for $\frac{9}{2}^-$ and $\frac{3}{2}^+$-states, respectively. The fragmentation increases with the distance from the Fermi-surface. A comparison to $^{41}$Ca($^{23}$F,$p$)-data is found in /4/.
4. SUMMARY AND CONCLUSIONS

In summary, it was shown that the quasiparticle-core interactions in odd-mass nuclei lead to "major shell" mixing of radial wave functions. The QPC-model includes these correlations consistently in spectroscopic factors and wave functions. Thus state-dependent features of transfer and knock-out form factors can be studied on safe theoretical grounds. Large configuration spaces were used. The model calculations therefore cover long and to a large extend also short range correlations. The latter are mainly responsible for the radial mixing. They are seen most clearly in the Fourier-transforms as admixtures of large momentum components. The results imply that measurements of absolute spectroscopic factors and the derivation of ground state correlations from transfer and knock-out reaction data will hampered by the radial correlations which can only partly accounted for in potential models.

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