Microscopic Structure of Low-Lying 0^+ States in Deformed Nuclei

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Recent high resolution (p, t) experiments have established the existence of a large number of low-lying excited 0^+ levels in the deformed ^{158}Gd [1] and, later on, in some actinide nuclei [2] and ^{168}Er [3]. The number of 0^+ states detected in ^{168}Er is particularly large, the levels below 4 MeV amounting to about 22 [4]. The distribution pattern of the two-nucleon transfer transition strengths shows that one single 0^+ state is strongly populated in all nuclei, with the exception of ^{168}Er where the strength is fragmented into several small peaks.

All theoretical studies performed so far have been confined to ^{158}Gd. The first was a phenomenological investigation [5], which shows that the extended $(sdpf)$ interacting boson model (IBM) can account for a large fraction of the detected 0^+ states. The $(sdpf)$ IBM analysis points out the importance of the octupole degrees of freedom.

In order to account for all detected states and to gain a detailed information on their properties, it is necessary to adopt microscopic approaches. The first calculation of this kind was performed in the framework of the projected shell model (PSM) [6] adopting a restricted space spanned by two and four quasiparticle states. Including the latter states was crucial for covering the whole spectrum. The calculation reproduces well all the energy levels and yields very small $E2$ decay strengths for the corresponding states.

An extensive study of the 0^+ states in ^{158}Gd was carried out recently [7], within the quasiparticle-phonon model (QPM) [8]. Energies, $E2$ and $E0$ transition strengths as well as two-nucleon transfer spectroscopic factors were computed and investigated. It came out that an appreciable fraction of the 0^+ states in ^{158}Gd has large or dominant two-phonon components, mostly built out of collective octupole phonons, in agreement with the IBM results [5]. The calculation has also confirmed the PSM prediction [6] of very weak quadrupole collectivity for all 0^+ states. In fact, the 0^+ one-phonon states came out to be linear combinations of several pairing correlated two-quasiparticle $q\bar{q}$ components. These, however, add coherently only in one state. Such a 0^+ pairing collective state is strongly populated in (p, t) two-nucleon transfer reactions, in agreement with experiments.

In [9] we extend the QPM study to ^{168}Er and some Th and U isotopes. All these nuclei were explored in the latest (p, t) experiments [2, 3, 4]. We intend to test if the QPM can account for the huge number of 0^+ levels observed in ^{168}Er [4] and is able to offer a consistent picture of the properties of the 0^+ states in deformed nuclei of different regions.

Our study shows that it is necessary to go beyond the mean field approximation (RPA) in order to account for the large number of 0^+ levels observed in ^{168}Er. RPA, in fact, generates only 15 0^+ states be low 4 MeV. Moreover, according to our QPM calculation, several levels, specially above 3 MeV, correspond to states with appreciable, often dominant, two-phonon components. A few of these states carry too little (p, t) strength to be accessible to detectors. In the actinides, the RPA 0^+ levels below 3 MeV are comparable in number to the experimental ones. The QPM, however, generates strong mixing among them and few two-phonon intruders.

The role of octupole phonons comes out to be marginal in the 0^+ states of ^{168}Er below 3 MeV, in contrast to the case of ^{158}Gd, where the octupole degrees of freedom play an important role. The content of octupole phonons is modest also in the 0^+ states of the actinides we explored. This sounds as a surprise, since they are the main ingredients of the IBM two-phonon states in these nuclei. Moreover, low-lying collective octupole levels occur in these nuclei. The suppression of the octupole coherence in the QPM is due to the repulsive effect of the Pauli principle which redistribute the strength of the collective octupole phonons amo ng several, closely lying, 0^+ states. The QPM results suggest that the octupole correlation is not a common feature of the 0^+ states in all nuclei, but is to be associated to the peculiar shell structure of some nuclei, in our case ^{158}Gd.

The QPM analysis of the $E2$ and $E0$ transitions leads to a conclusion that the quadrupole collectivity is lacking in all 0^+ states of ^{168}Er and is more appreciable, but still not strong, in the actinides. All one-phonon 0^+ states came out to be built out of $q\bar{q}$ pairing correlated configurations, while the two-phonon components can be coupled to the ground state only by the *boson forbidden* pieces of the $E0$ and $E2$ operators.

No 0^+ state in ^{168}Er is strongly populated in (p,t). The strength is fragmented among different states. The comparison with the RPA (p,t) response shows that such a fragmentation is a pure anharmonic effect due to the mixing between different phonon configurations. Peculiar of ^{168}Er is also the small fluctuation of the pairing field in the ground state, suggesting that the pairing correlations present in the excited 0^+ states are loosely related to ground state fluctuations.

In the actinides, the phonon coupling does not spoil the coherence of pairing correlations in the lowest 0^+ state. This describes a pairing vibrational mode arising from the fluctuations of the pairing field. The remaining low energy states are appreciably affected by the phonon coupling.

On the whole, the present QPM calculation provides a fairly satisfactory description of the existing properties of the 0^+ states in deformed nuclei. In order to assess its complete reliability, however, it is desirable to complete the characterization of those states by systematic measurements of their $E2$ and $E0$ decay strengths.

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