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Self-Energy of Single-Particle States in Deformed,Rapidly Rotating Nuclei

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The coupling of the single-particle degrees of freedom to the surface modes introduces an energy dependence in the mean field that can be parametrized for many purposes in terms of an effective mass, the so-called ω-mass. The present work constitutes the first study of the effective mass of nucleons moving in deformed, rapidly rotating nuclei.

1. Introduction

The single-particle potential defines, in the case of the atomic nucleus, a surface which can adopt different equilibrium shapes around which it can vibrate. The variation in density due to these fluctuations produces a corresponding change in the nuclear mean field, in keeping with the fact that the nucleus is a self-sustained system. The consequences of the coupling bewteen the single-particle degrees of freedom, representing the motion of the nucleons in the fluctuating mean field, and the bosons, describing the surface modes, leads to an energy dependent self-energy correction to the Hartree Fock mean field that renormalizes the properties of the bare nucleons as, for example, the energy and the mass.

2. Self-Energy

The definition of the self-energy correction at the lowest-order in the perturbative expansion using Matsubara's formalism for spherical nuclei can be found in the current literature (cf. e.g. [1,4,5]). The main characteristic of the corresponding expression is that one needs to identify and characterize each of the bosons describing the surface modes, that is their energies and the transition matrix elements bewteen ground and excited states. For this purpose the microscopic formalism of random phase approximation (RPA) is employed. This becomes, in the case of a rotating nucleus, quite a numerical challenge, as one has to deal with a system where β-, γ- and pairing- vibrations are coupled together. Moreover, the number of RPA solutions increases considerably due to the lifting of all degeneracies of the system under consideration. This problem has been solved

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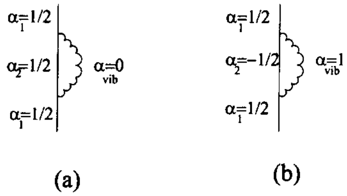

Figure 1. Basic diagrams representing the self-energy of a quasiparticle in a rotating frame. A wavy line stands for a surface mode. Graph (a) corresponds to the case of vibrations with positive signature (α=0), while graph (b) is associated with negative signature vibrations (α =1). The initial state has, in both cases, signature $\alpha = 1/2$

rewriting the self-energy correction in terms of the linear response function [6], making use of a coarse approximation.

Axially deformed nuclei are invariant under space inversion and under rotation by an angle around π around the x-axis perpendicular to the symmetry axis. Consequently the single-particle states can be labelled by the eigenvalues of the corresponding operators, that is parity $\pi = \pm 1$ and signature $\alpha = \pm\ 1/2$ (α=0 or 1). While in a spherical nucleus the particle-vibration vertex conserves angular momentum, for deformed system in a rotating frame, signature and parity are the quantum numbers that are conserved at each vertex (see Fig. 1).

For a separable multipole-multipole interaction, Matsubara's expression for the self-energy (cf. Fig.1), making use of linear response theory, can be written as

$$\begin{aligned}\sum_{\rm ret}(\mathbf{1},\omega+i\eta) &= \sum_{\lambda,\mathbf{2}}\frac{\langle\mathbf{1}||\hat{T}_\lambda||\mathbf{2}\rangle}{2j_1+1}\Big\{\frac{1}{\beta}\sum_{i\omega_n}\frac{\mathcal{R}_\lambda(i\omega_n)}{\omega+i\eta-\varepsilon_2-i\omega_n}\\ &- \left[1-n_F(\varepsilon_2)+n_B(\omega+i\eta-\varepsilon_2)\right]\mathcal{R}_\lambda(\omega+i\eta-\varepsilon_2)\Big\}, \qquad (1)\end{aligned}$$

where λ is the multipolarity of the vibration, ε_2 is the intermediate single-particle energy, $\mathcal{R}_\lambda$ is the linear response function for the multipolarity λ, while β is the inverse of the temperature. The factor in front of the curly parenthesis is the reduced matrix element between single-particle states **1** (initial) and **2** (intermediate) of the single-particle field T_λ entering in the two-body force (for more details cf. e.g. [6]).

A superfluid deformed system violates rotational and gauge invariance. These symmetries broken in the mean-field result in appearance of the symmetry restoration modes [3], i.e. the Nambu-Goldstone (NG) modes. In the RPA formalism these spurious states are decoupled from the physical vibrational solutions (e.g. β-vibrations), but they lead to infinite contributions to the particle-vibration coupling vertices. In numerical calculations these modes cannot be exactly decoupled because of approximations used, e.g the truncation of the model space. We have developed a new technique to eliminate their contributions by using the contour integration of the RPA response function on the complex plane. In Figs. 2 and 3 we show the paths one needs to define to eliminate a real or an imaginary spurious state,respectively (see [6] for details).

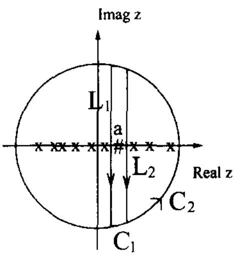

Figure 2. Contour used to eliminate real spurious states

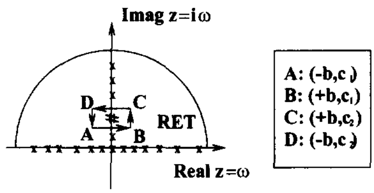

Figure 3. Contour used to eliminate imaginary spurious states.

The quasiparticle energies entering in the equation above are calculated in the framework of the Hartree-Fock-Bogoliubov approximation where the Hamiltonian in a rotating frame can be written as

$$h = h_{\rm def} - \Delta(\hat{P}^{\dagger} + \hat{P}) - \lambda\hat{N} - \omega_{\rm rot}\hat{J}_x. \tag{2}$$

Here $h_{\rm def}$ is the Nilsson Hamiltonian and $\hat{P}^{\dagger}$ is the pair creation operator. The term $-\omega_{\rm rot}\hat{J}_x$ represents the action of the Coriolis and centrifugal forces on the individual nucleons.

3. The nucleus ^{168}Yb

We are now in conditions to apply the formalism developed above to the yrast states of the nucleus ^{168}Yb. The potential energy surface in this nucleus has a stable minimum at prolate deformation up to spin I$\sim$60$\hbar$. The deformation, together with the chemical potential λ, are fixed at ω_{rot}=0 using a Nilsson-Strutinsky technique in order to obtain neutron and proton pairing gaps in agreement with the experimental values. For this purpose we adopt a value of the quadrupole deformation parameter equal to ε=0.262.

The results for the renormalized and for the ω-mass as a function of rotation and deformation are shown in Figs.4 and 5, respectively.

These calculations indicate that, starting with a Hartree-Fock mass (k-mass) equal to the bare mass, the coupling to surface vibrations leads to an increase of the density of the quasiparticles energies with respect to the mean field value. The associated ω-mass is almost 20% larger than the bare nucleon mass. Assuming for the $k - mass$ a more realistic value of 0.85m, one obtains m$_\omega \approx 1.4m$, a number similar to that found in the case of the spherical, tightly bound nucleus ^{208}Pb[2], and considerably smaller than the values m$_\omega \approx 1.7m - 1.8m$ obtained for spherical, open-shell medium heavy nuclei[5]. The reason for this result is directly connected with the fact that, as a rule, surface vibrations are, in deformed nuclei, less collective than in spherical nuclei. The increase in the ω-mass at ε=0.3 for $\omega_{\rm rot}$ might due to a backbending phenomenon.

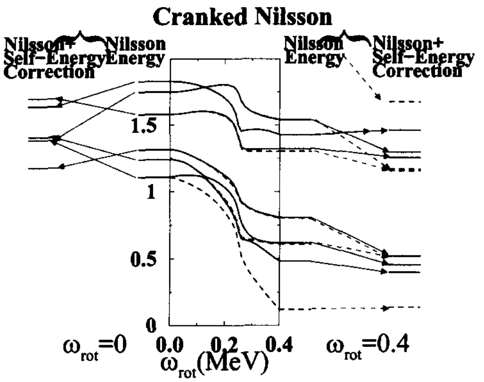

Figure 4. Renormalized neutron quasiparticle energies due to quadrupole coupling

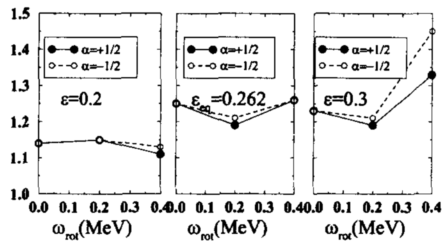

Figure 5. $\frac{m_\omega}{m}$ as a function of rotation and deformation.

4. Conclusions

From the present work one can conclude that: a)The effective mass of nucleons moving close to the Fermi energy displays a modest increase of the value of the ω-mass which reminds of the corresponding quantity calculated in the case of spherical nuclei [2]. The surface rigidity of deformed nuclei is associated with the fact that most of the collectivity associated with the quadrupole degrees of freedom has been absorbed into the static deformation of the mean field. b) In keeping with the fact that the level density parameter is proportional to the nucleon effective mass, it is expected that the level density parameter in deformed nuclei displays a similar value to the corresponding quantity associated with closed shell nuclei and, moreover, that it is rather insensitive to rotational frequency. Taking into account this result, one expects the temperature dependence of the total effective mass to be less important in deformed than in spherical nuclei [5].

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