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A microscopic model beyond mean-field: from giant resonance properties to the fit of new effective interactions

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Abstract. Self-consistent mean-field models are able to reproduce well the overall properties of nuclei for a wide range of masses. Nevertheless, they are intrinsically unsuitable for the description of some important observables like the single-particle strength distribution or, in connection with collective states, their damping width and their gamma decay to the ground state or to low lying states. For this reason, a completely microscopic approach beyond mean-field has been implemented recently, based on the Skyrme functional.

When beyond mean-field theories are handled, the mean-field-fitted effective interaction should be refitted at the desired level of approximation. If zero-range interactions are used, divergences arise. We present some steps towards the refitting of Skyrme interactions, for its application in finite nuclei.

1. Introduction

Self-consistent mean-field (SCMF) models [1] have become increasingly reliable in the descriptions of ground state (masses, radii, deformations) and of high-energy collective states, as giant resonances (GRs). Nonetheless, the SCMF approaches present well-known limitations. For instance, they do not reproduce, as a rule, the level density around the Fermi energy. Moreover, the fragmentation of single particle and GR strength functions, and the associated decay properties are outside the framework of these models.

A possible solution which can be used to overcome these drawbacks is the inclusion of beyond mean-field (BMF) correlations produced by the interweaving between single particle states and collective phonons. The basic ideas of the so-called particle-vibration coupling (PVC) models have been discussed in Ref. [2]. When these coupling are included, the standard shell model acquires a dynamical content: the average potential becomes non-local in time or, which is the same, energy dependent [3]. Recently, some of us has developed a fully microscopic self-consistent model, based on Skyrme functionals, to treat properly single particle states [4]. In this contribution we report on the application of this model to the calculation of inclusive (strength function) as well as exclusive (γ-decay width) GRs properties.

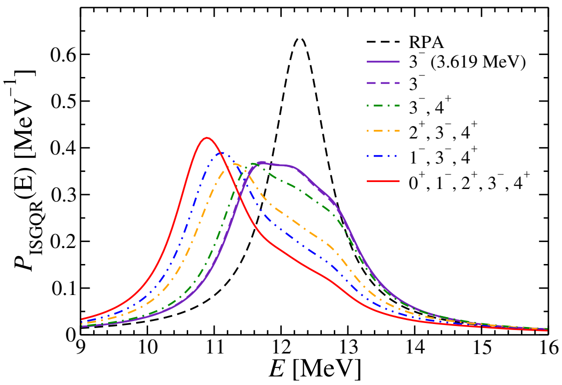

Figure 1. (Color online) Probability P to find the ISGQR state at an energy E. Different curves are obtained when the phonons listed in the legend are used as intermediate states. The label RPA [black-dashed line] refers to the curve calculated in the RPA with a Lorentzian width of 1 MeV.

Table 1. γ-decay widths Γ_γ. The first four rows are from this work, with no adjustable parameters. The following three are previous theoretical calculations. The last one refers to the experiment. See text and Ref. [5].

Interaction	E_{ISGQR} [MeV]	Γ_γ^{GS} (eV)	E_{3^-} [MeV]	$\Gamma_\gamma^{3^-}$ (eV)
SLy5 [7]	12.28	231.54	3.62	3.39
SkP [9]	10.28	119.18	3.29	8.34
Ref. [10]	10.60	130 $\pm$ 40	2.61	5$\pm$5

A problem of overcounting may arise in the BMF realm, since, so far, effective forces have been fitted at mean-field, thus including in an implicit way a class of higher order correlations. Therefore, we should expect to be obliged to re-fit the interactions at the required level of approximation. Moreover, if zero-range forces are used, like the Skyrme one, divergences arise when they are employed at BMF level. In the second part of this contribution, we present some preliminary results on the way to reabsorb these divergences in a simplified Skyrme interaction applied to finite nuclei.

2. The giant resonances widths within the PVC approach

In this section we present the results obtained for two observables: the strength function of the isoscalar giant quadrupole resonance (ISGQR) in ^{208}Pb, and the γ-decay width of the ISGQR in ^{208}Pb to the ground state and to the first collective octupole state. The main feature of these calculations is the consistent use of the Skyrme force in both the HF+RPA solution and in the PVC vertex, added on top of the former. Details about the formalism used and a more accurate discussion of the results can be found in [5].

2.1. The strength function

The present calculation follows closely Ref. [6], in which the GR strength functions were computed in the PVC model using a separable phenomenological force. In Fig. 1 the probability per unit energy of finding the ISGQR state is plotted, with the SLy5 [7] parametrization of the Skyrme force. Phonons with multipolarity $L = 0, 1, 2, 3, 4$ and natural parity are included in the model space. The RPA peak is shifted downwards to an energy of $E = 10.9$ MeV, in good agreement with the experiment ($E^{exp} = 10.9 \pm 0.3$ MeV [8]). The main contribution to the width comes from the first 3^- state, producing a spreading width of the order of 2 MeV ($\Gamma^{exp} = 3.0 \pm 0.3$).

2.2. The γ-decay width

In the model described in Ref. [5], the γ decay of the GRs to the ground state is evaluated at the RPA level, while the decay to low-lying collective states is accounted for at the first contributing order beyond the mean-field. It should be noted that only the direct decay, not the statistical one coming from the compund nucleus, can be computed in this model [11]. In this contribution we focus on the ISGQR in ^{208}Pb and its decay to the ground state and to the first 3^- state, using different Skyrme interactions. In table 1, some results for the decay widths (Γ_γ) are listed, together with the experimental outcome.

For the decay to the ground state the main issue is the overestimation of the energy of the resonance: the decay width is proportional to the energy raised to the power $2\lambda+1$, being λ the multipolarity of the transition. If we rescale the energy to the experimental value, all the interactions can reproduce the experimental decay width within the experimental error. On the other hand, concerning the decay to the 3^- state, only two interactions (the ones in table 1) are in agreement with the experiment. Actually, it should be recognized that it is just remarkable that Skyrme interactions can reproduce the order of magnitude (few eV) of this exclusive observable, given the fact that this functional form are fitted to reproduce basically macroscopic properties of nuclei at the scale of hundreds of keV.

3. The problem of the divergences beyond mean-field

If zero-range interactions are used, divergences arise in beyond mean-field quantities. Until now, the problem is circumvented by imposing a truncation to the model space with a somewhat arbitrary recipe, and this is clearly unsatisfactory.

In Refs. [12, 13], the problem of the renormalization of the whole Skyrme interaction was faced in nuclear matter with different degrees of neutron-proton asymmetry (from uniform to pure neutron matter): a new parameter, namely the maximum value of the transferred momentum, was introduced among the Skyrme ones. In a finite system, like the nucleus, because of the absence of translational invariance, the transferred momentum is not well defined. However, we can write the velocity-independent part of the Skyrme interaction as

$$V(\boldsymbol{r}_1',\boldsymbol{r}_2',\boldsymbol{r}_1,\boldsymbol{r}_2)=\frac{1}{2\sqrt{2}}g\left(\frac{\boldsymbol{R}}{\sqrt{2}}\right)\delta_3(\boldsymbol{r}')\delta_3(\boldsymbol{r})\delta_3(\boldsymbol{R}-\boldsymbol{R}')=\frac{1}{2\sqrt{2}}g\left(\frac{\boldsymbol{R}}{\sqrt{2}}\right)v(\boldsymbol{r}',\boldsymbol{r})\delta_3(\boldsymbol{R}-\boldsymbol{R}'),$$

where $\boldsymbol{r}^{(\prime)}=\frac{\boldsymbol{r}_1^{(\prime)}-\boldsymbol{r}_2^{(\prime)}}{\sqrt{2}}$, $\boldsymbol{R}^{(\prime)}=\frac{\boldsymbol{r}_1^{(\prime)}+\boldsymbol{r}_2^{(\prime)}}{\sqrt{2}}$ and $g(\boldsymbol{R})=t_0+\frac{t_3}{6}\left[\rho(\boldsymbol{R})\right]^\alpha$. We introduce a cutoff on relative momenta [14], modifying the term $v(\boldsymbol{r}',\boldsymbol{r})$, by including a cutoff λ and λ',

$$v^{\lambda\lambda'}(\boldsymbol{r}',\boldsymbol{r})=\frac{1}{\Omega}\int \mathrm{d}_3k\mathrm{d}_3k'\,\mathrm{e}^{i\boldsymbol{k}'\cdot\boldsymbol{r}'}v\left(\boldsymbol{k}',\boldsymbol{k}\right)\theta(\lambda-k)\theta(\lambda'-k')\mathrm{e}^{-i\boldsymbol{k}\boldsymbol{r}}=\frac{1}{4\pi^4}\frac{\lambda^2\lambda'^2}{rr'}j_1(r\lambda)j_1(r'\lambda').$$

This choice of the cutoff can be motivated by the fact that the Skyrme interaction can be seen as a low-relative-momentum expansion of the effective nuclear potential. By using the Goldstone theorem [15], the second order contribution to the total energy reads

$$\Delta E=\sum_{pp'hh'}\sum_J\frac{(2J+1)|\langle(pp')J|v^{\lambda\lambda'}|(hh')J\rangle|^2}{\epsilon_h+\epsilon_{h'}-\epsilon_p-\epsilon_{p'}},\tag{1}$$

where $\langle(pp')J|v^{\lambda\lambda'}|(hh')J\rangle$ is the J-coupled matrix element of the truncated interaction and $\epsilon_{h(p)}$ are the Hartree-Fock energies of the holes (particles). The presence of a diverence is caused by the fact that the sum on the particles p and p' is unbound.

In figure 2, the second order contribution to the total energy in ^{16}O is shown as a function of the maximum energy $\epsilon_p^{\max}$ of the particles included in the model space. The existence of a divergence is clear and it is linear with $\epsilon_p^{\max}$.

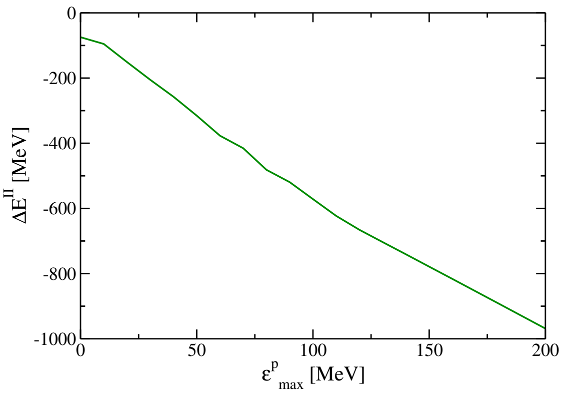

Figure 2. (Color online) Second order contribution to the total energy of ^{16}O as a function of the maximum energy of the particles included in the model space. The $t_0 - t_3$ part of the SkP [16] Skyrme interaction is used.

The analysis of the results are currently undergoing, in order to verify how the interactions fitted in nuclear matter can cure the divergence in nuclei.

4. Conclusion

Beyond mean-field correlations are important to overcome some intrinsic limitations of the SCMF approach in nuclei. A completely microscopic model, based on the particle-vibration coupling idea, was recently developed. This model has been so far applied to single particle observables, like the self-energy, and, as reported here, to inclusive (strength and energy) and exclusive (γ decay) properties of the GRs. The results obtained for the strength function of the ISGQR and its γ decay in ^{208}Pb are in fairly good agreement with the experimental findings.

Anyhow, the employment of interactions fitted at mean-field level in a higher order framework is the main limitation of these works. Moreover, zero-range forces cause the divergence of beyond mean-field quantities. We presented here a first attempt to treat this problem in finite systems.

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