Low lying magnetic states of double magic nuclei within Random Phase Approximation theory

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In the last thirty years electron-nucleus scattering experiments have produced a large amount of high precision data, which impose severe constraints on nuclear models and effective theories, such as the Random Phase Approximation (RPA). In particular the description of low energy excited states within the RPA is known to be very sensitive to the details of the effective nucleon-nucleon (NN) interaction used in the calculations.

We present here a selection of results from a systematic study of the low energy spectra of several doubly-closed-shell nuclei we have made within the RPA theory [1]. We have focused our attention on the unnatural parity states, which are sensitive to the spin, spin-isospin and tensor channels of the residual NN interaction [2].

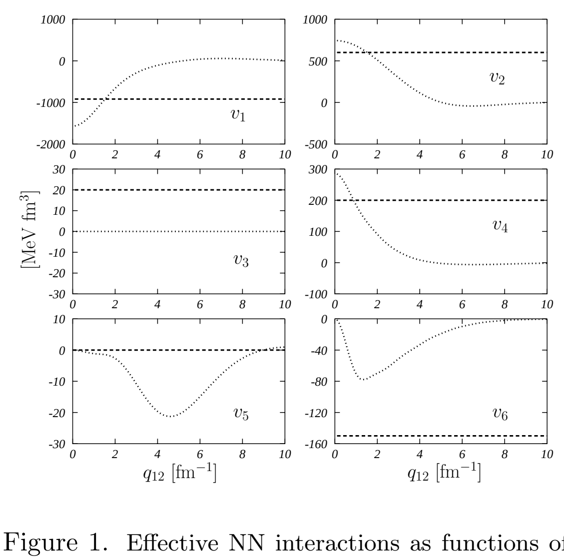

Figure 1. Effective NN interactions as functions of the relative momentum. The dashed lines represent the LMtt interaction, the dotted the FRtt. The central channels v_i (i=1-4) of the LMtt and FRtt interactions are identical to those of LM and FR, respectively.

The inputs required by RPA calculations are a set of single-particle energies and wave functions and a residual NN interaction. In a purely phenomenological approach we have used the single-particle basis generated by a Woods-Saxon well, whose parameters are taken from the literature [3]. The generic residual interaction has been written as:

$$
\begin{aligned}
V_{\rm eff}(1,2) = v_1(r_{12}) \,+\, v_1^\rho(r_{12})\,\rho^\alpha(r_1,r_2) \\
+\,[v_2(r_{12}) \,+\, v_2^\rho(r_{12})\,\rho^\alpha(r_1,r_2)]\;\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2} \\
+\,v_3(r_{12})\,\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2} \,+\, v_4(r_{12})\,\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}\,\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2} \\
+\,v_5(r_{12})\,S_{12}(\hat r_{12}) \,+\, v_6(r_{12})\,S_{12}(\hat r_{12})\,\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2}\,, \quad (1)
\end{aligned}
$$

where $\boldsymbol{\sigma}$ and $\boldsymbol{\tau}$ are the usual spin and isospin operators and S_{12} is the tensor operator. As suggested by past phenomenological RPA studies [4,5] we have included density dependent terms in the central and isospin channels. We have parametrized the interactions according to the following criteria: *(i)* we have chosen a unique set of parameters for all the nuclei under investigation, with the exception of the density dependent terms which are different for each nucleus; *(ii)* the density dependent terms have been set to reproduce the first 2^+ state in ^{12}C and the first 3^- states in the other nuclei; *(iii)* the remaining contributions in the central and isospin channels have been chosen to get a reasonable description of the centroid energy of the isovector giant dipole resonance; *(iv)* the spin, spin-isospin and tensor channels have been adjusted to describe the low energy (below 8 MeV) magnetic spectrum of ^{208}Pb , with particular attention to the 12^- and 1^+ states and, in addition, taking care that the energy of the first 4^- state of ^{16}O is reproduced reasonably.

Following a Landau-Migdal approach, we have first considered zero-range interactions without and with a tensor-isospin channel contribution (LM and LMtt in the following).We have then constructed finite-range interactions (FR and FRtt), by keeping the long-range behavior of the Argonne v_{18} potential [6] and substituting its short-range part with a sum of Gaussians. We have also used Gaussians to parametrize the density dependent terms of the interaction and, for

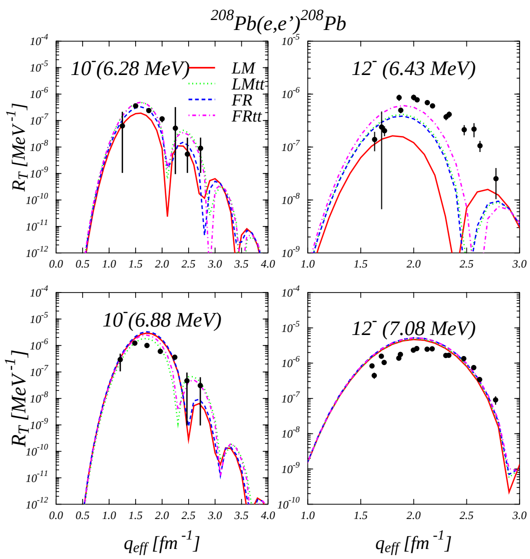

Figure 2. Right panels: electron scattering transverse responses for the first 12^- states of ^{208}Pb , versus the effective momentum transfer. Different residual interactions are used as indicated. Left panels: the same for the first 10^- states. Experimental data from [7].

the FRtt case, we have obtained the tensor channel terms by multiplying the corresponding terms of the v_{18} interaction by a correlation function obtained in variational calculations [3].

The behavior of the various interactions we have considered is shown in Fig. 1 as a function of the relative momentum of the interacting pair. We have performed systematic calculations of the low energy spectra of ^{12}C , ^{16}O , ^{40}Ca , ^{48}Ca , ^{90}Zr and ^{208}Pb . For each state we have also computed electromagnetic response functions, and we have compared them with the available experimental data. We have observed a general good agreement and, except for some cases, little sensitivity of the various energies to the details of the interactions.

The transverse response functions of the 12^- states of ^{208}Pb are shown in the right panels of figure 2. We can see that for the higher state at 7.08 MeV (lower right panel) the experimental data are rather well reproduced with all NN interactions, which do not produce significant differences in the curves. On the other hand, for the lower energy state (upper right panel) we observe a very strong dependence on the residual interaction, both when finite-range and when tensor channel contributions are included. We remark that a better description of this state alone could be obtained with a different choice of the parameters of the residual interaction, but this would worsen the global description of the various magnetic spectra we have considered.

In the left panels of the same figure the transverse responses of the 10^- states are also shown. It is interesting to notice that, in this case, only the curves which include tensor contributions are able to reproduce the second peak shown by the data, for both states.

In conclusion, our study indicates that a simultaneous description of all states imposes strong constraints on the residual NN interaction. Within a purely phenomenological approach it is possible to get a good description of the spectra and of the response functions of most of the states, thus obtaining an “optimal” RPA approach. Some states which are not well described exhibit a strong sensitivity to some details of the residual interaction, and a deeper investigation could be used to obtain further constraints on it.

As a further independent extension of this approach, we have also considered the computation of neutrino cross sections in a test-case: the low energy 0^- states of ^{16}O [1]. We have observed extremely large differences in the cross sections obtained when tensor channel contributions are included in the effective NN interaction. This indicates that the role of the residual interaction in neutrino scattering cross section is a very interesting topic, for example in connection with the problem of nuclear uncertainties in the detection of supernova neutrinos [8].

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