Gamma-ray strength at low energies using relativistic QRPA with exact coupling to the continuum.

I. Daoutidis and S. Goriely
Institut d’Astronomie et d’Astrophysique, ULB, CP226, 1050 Bruxelles, Belgium
E-mail: idaoutid@ulb.ac.be, sgoriely@ulb.ac.be

Abstract. Continuum-quasiparticle random-phase Approximation (CQRPA) within the relativistic point-coupling model with density-dependent coupling constants is applied to investigate collective excitations in spherical nuclei. In particular we study the impact of the exact continuum on the giant-dipole and pygmy resonance of several Sn isotopes as well as the radiative neutron capture rates of importance for astrophysical calculations.

1. Introduction
The study of exotic nuclei within the relativistic density functional theory has gained considerable interest in recent years, because these models are based on Lorentz invariance, connecting in a consistent way the spin and spatial degrees of freedom of the nucleus and providing thus a relatively simple phenomenological description for many nuclear properties all over the periodic table. The same functionals can be used to investigate not only the static properties of these systems but also their dynamics, such as collective excitations and nuclear response functions. However, while the static properties can be extracted directly from the relativistic mean field theory, the collective ones can be studied only under the small amplitude variations of the density around the static value, which is done by solving the random-phase approximation (RPA).

This work is devoted to an investigation of relativistic quasiparticle RPA (QRPA) models with an exact treatment of the coupling to the continuum. In addition to this continuum QRPA (CQRPA), the most common spectral representation is also considered for comparison. In both cases, we use a point-coupling Lagrangian which is capable of reproducing a wide range of experimental data [2]. The BCS model with constant pairing force is also applied, in order to treat the pairing correlations of the open-shell nuclei [3].

The basic idea behind the RPA approach is that under the influence of an external field oscillating with the frequency \( \omega \) the nucleus is excited. The cross section of this process is proportional to the strength function:

\[
S(\omega) = -\frac{1}{\pi} Im \int d^3r d^3r' f^*_{ext}(r) R(r,r';\omega) f_{ext}(r'),
\]

where \( f_{ext}(r) \) is the external operator inducing the reaction. The response function of the nucleus \( R(r,r';\omega) \) has been modified in order to incorporate the effect of the exact coupling to the continuum (See [2, 3] for details). The main advantage of this approach is that the
Figure 1. Photoabsorption cross section for the stable isotopes $^{116,118,120,124}$Sn. The red solid line represents the CQRPA calculations, while the blue dashed line shows the conventional DQRPA results. Also shown is the GLO formula, as recommended by Ref. [6]. The experimental results are taken from [7].

large number of antiparticle-hole pairs which is required in conventional methods is taken into account effectively and without any numerical cost. Hence one can reduce the numerical effort up to one order of magnitude, as compared to conventional RPA approaches without losing in predictive power. In addition, the continuum RPA gives automatically information about the escape width, which can be a significant portion of the total width of the multipole giant resonances.

2. Applications
The Isovector Giant Dipole resonance (IVGDR) is the most well studied collective excitation and the first to have been observed experimentally. An external electromagnetic field causes protons and neutrons to oscillate in opposite phases with respect to each other and leading to a pronounced resonance peak in the photoabsorption cross section.

In Fig. 1 we show the excitation energy of the IVGDR strength for several Sn isotopes, using both the continuum and the conventional approach, the latter being referred here as discrete QRPA (DQRPA) model. We see that the agreement with the experimental observations is excellent. The point-coupling force PC-F1 [1] is used for the interaction, while an additional energy-dependent width is considered to account for the spreading width of the resonance.

As expected, the pygmy dipole resonance (PDR) appears at energies around $E \sim 8$ MeV. At such an energy, the PDR may lie below the neutron separation energy and become undetectable through $(\gamma,n)$ experiments. However, recent experiments based on the $(^3\text{He},^3\text{He}'\gamma)$ and $(^3\text{He},\alpha\gamma)$ probes [4, 5] has provided valuable information about the low-lying $\gamma$-ray strength below the neutron threshold. In particular, the $\gamma$-ray strength of the three even-A isotopes $^{116,118,122}$Sn has recently been determined, making these nuclei particularly important in the study of the pygmy mode. In Fig. 2 we compare the recent experimental data with the relativistic QRPA predictions which appear to agree fairly well. Both the CQRPA and DQRPA calculations show a well pronounced PDR around 8 MeV, though the shape of the PDR slightly differs.

Finally, it has been shown that the low-lying E1 strength, close to or below the particle separation energies can affect the neutron capture rates of relevance for r-process nucleosynthesis [9]. For that reason, we have applied the continuum QRPA cross sections to Hauser-Feschbach reaction rate calculations to investigate the impact of the exact coupling to the continuum. We
find that for stable Sn isotopes, CQRPA gives similar results to conventional QRPA approaches, but significant discrepancies are found for heavier isotopes with $A > 132$. In particular, with the CQRPA model, reaction rates are larger by a factor of four larger, as compared to those obtained with the non-relativistic HFB+QRPA [9] and by a factor of 10 to 100 times with respect to those obtained with the Generalized Lorentzian (GLO) model [10], as shown in Fig. 2.

Figure 2. Comparison of the CQRPA (solid line) and DQRPA (dashed line) E1 strength of $^{116,118,122}$Sn with available experimental data. The low-energy data are taken from [4] while the $(\gamma,n)$ data are from [7]. For $^{122}$Sn the data are from [5] and [8].

Figure 3. Ratio of the radiative neutron capture rates obtained with RPA approaches with respect to those obtained with the GLO model [10]. The circles and triangles correspond to the DRPA and CRPA cases, respectively, as studied in the present paper, while the squares correspond to the non-relativistic HFB+QRPA strength of Ref. [9]. The rates are calculated for odd-$N$ Sn targets at a temperature of $10^9$ K.

References
[1] T. Bürvenich, D. Madland, J. Maruhn, and P.-G. Reinhard, Phys. Rev. C65, 044308 (2002).
[2] J. Daoutidis and P. Ring Phys. Rev. C80, 024309 (2009).
[3] J. Daoutidis and P. Ring Phys. Rev. C83, 044303 (2011).
[4] H. K. Toft et al., Phys. Rev. C81, 064311 (2010).
[5] H. K. Toft et al., Phys. Rev. C83, 044320 (2011).
[6] T. Belgya, et al., Handbook for calculations of nuclear reaction data, RIPL-2, IAEA-TECDOC-1506
[7] A. Lepretre et al., Nucl. Phys. A219, 39 (1974).
[8] V. V. Varlamov, Yad. Konst. 1, 52 (1993).
[9] S. Goriely, E. Khan, and M. Samyn, Nucl. Phys. A739, 331 (2004).
[10] J. Kopecky and M. Uhl, Phys. Rev. C41, 1941 (1990).