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Abstract. The dipole excitations of nuclei play an important role in nuclear astrophysical processes related to the photoabsorption and the radiative neutron capture that take place in stellar environment. We present here the results of a large-scale axially-symmetric deformed QRPA calculation of the $\gamma$-ray strength function based on the finite-range Gogny force. The newly determined $\gamma$-ray strength is compared with experimental photoabsorption data for spherical as well as deformed nuclei. Predictions of $\gamma$-ray strength functions and Maxwellian-averaged neutron capture rates for Sn isotopes are also discussed.

1. Introduction

The dipole excitations of nuclei play an important role in nuclear astrophysical processes related to the photoabsorption and the radiative neutron capture that take place in stellar environment. Large scale calculations of $E1$ $\gamma$-ray strength functions are usually performed on the basis of the phenomenological Lorentzian model \cite{1}. To improve the reliability of the $\gamma$-ray strength predictions the use of microscopic models is in order. In principle, the more microscopic the underlying theory, the greater the confidence in the extrapolations out towards the experimentally unreachable regions. Microscopic approaches are almost never used for practical applications, because of the numerical difficulty associated with large scale predictions and the fine tuning of the model required to reproduce accurately large experimental data set. A prominent exception is represented by Refs. \cite{2,3} where a complete set of $\gamma$-ray strength functions was derived from microscopic HFB+QRPA calculations. In Refs. \cite{2,3}, zero-range Skyrme forces were considered and deformed nuclei were described through a phenomenological correction.

The present project aims at performing axially-symmetric-deformed HFB+QRPA calculations in a fully consistent way using the finite range Gogny force D1M \cite{4}. This approach is essential in open-shell nuclei, where pairing correlations and deformation affect the $\gamma$-ray strength. It has already been applied to study giant resonances in Si and Mg isotopes \cite{5}, dipole excitations in Ne isotopes and $N = 16$ isotones \cite{6} as well as electromagnetic excitations of the heavy deformed $^{238}$U \cite{7}. We refer to Refs. \cite{5,6,7,8} for further details on this method.

2. Results

The axially-symmetric-deformed HFB+QRPA method is now applied to nuclei for which photoabsorption data exist. The QRPA provides an accurate description of the giant dipole
Figure 1. Comparison of the experimental photoabsorption cross sections for \(^{174}\)Yb, \(^{180}\)Hf and \(^{235}\)U nuclei [1] with the axially-symmetric-deformed QRPA predictions using the D1M Gogny force (solid line) obtained with the phenomenological corrections described in the text.

resonance (GDR) centroid and the fraction of the energy-weighted sum rule exhausted by the E1 mode. However, for a proper description of experimental data, it is necessary to go beyond the QRPA scheme by including complex configurations as well as the coupling with phonons. In particular, the GDR is known experimentally to have a relatively large width and therefore a finite lifetime. Different microscopic theories exist to explain the location and width of the GDR. However, for the sake of simplicity and applicability to a large number of nuclei of astrophysical interest, we restrict ourselves to a semi-empirical broadening of the GDR. Such a broadening is obtained by folding the QRPA strength \(S_{E1}(\omega)\) by a normalized Lorentzian function

\[
L(E, \omega) = \frac{2}{\pi \Gamma} \frac{\Gamma^2 E^2}{(E^2 - (\omega - \Delta)^2)^2 + \Gamma^2 E^2},
\]

where the width \(\Gamma\) is adjusted on experimental data and the energy shift is deduced from the GDR centroid assuming the following energy-dependent parametrization: \(\Delta(\omega) = \Delta_0 + \Delta_{qp}(\omega)\), where \(\Delta_0\) is a constant shift due to the coupling between quasiparticle (qp) states and phonons and the quantity \(\Delta_{qp}(\omega)\) is an extra shift taken to be proportional to the number of 4-qp states. The latter correction therefore varies with the excitation energy \(\omega\) and obviously depends on the nucleus considered. In Fig. 1, QRPA photoabsorption cross sections are compared with experimental data [1] for a sample of 3 deformed nuclei, namely \(^{174}\)Yb, \(^{180}\)Hf and \(^{235}\)U. Similar results can be found in Ref. [9] for \(^{76}\)Ge, \(^{156}\)Gd and \(^{192}\)Os and in Ref. [10] for the \(^{238}\)U. Note that to estimate the strength of odd-A and odd-odd nuclei, we have also derived an interpolation procedure starting from the QRPA calculation of the neighbouring even-even nuclei. This procedure has been tested and found to give satisfactory results as shown in Fig. 1 for \(^{235}\)U. It will be described in a forthcoming paper. A more systematic comparison between our results and experimental data will be provided in a forthcoming paper. We remind here that the split into two components (one for each value of the projection \(K\) of the angular momentum \(J = 1\)) of the dipole response in deformed nuclei is naturally taken into account in our approach. Recently a reasonable agreement of our HFB+QRPA calculations with the experimental photoneutron and radiative neutron-capture cross sections for the Mo isotopes has been found [11].
As a first application, we have applied the present QRPA approach to the prediction of the $\gamma$-ray strength of exotic neutron-rich Sn isotopes, as shown in Fig. 2. Qualitatively speaking, the microscopic E1 strength functions look rather similar to the phenomenological Lorentzian [1] for nuclei close to the valley of $\beta$-stability, major differences are found for exotic neutron-rich nuclei, in particular in the low-energy region where some extra strength, the so-called pygmy resonance, becomes significant in the Skyrme+QRPA predictions [3]. In our Gogny HFB+QRPA calculation, extra-strength is also found in the low-energy tail of the GDR but the strength is more spread than in the Skyrme calculation.

The differences illustrated in Fig. 2 between analytical and microscopic $\gamma$-ray strength predictions for nuclei far from the valley of stability are also known to have a significant impact on the predicted neutron-capture cross section of astrophysical interest. This is illustrated in Fig. 3, where the Maxwellian-averaged neutron capture rate calculated with the TALYS code [12, 13, 14] using the $\gamma$-ray strength obtained with the present QRPA approach are compared, for the Sn isotopes, with those obtained using either the Generalized Lorentzian (GLO) model [1] or the Skyrme-HFB+QRPA model of [3]. The ratio between these neutron capture rates is close to one for stable or nearly stable nuclei. However for exotic neutron-rich Sn isotopes our present $\gamma$-ray strength is shown to give rise to reaction rates that can be about 20 times larger than those obtained with the GLO model. Rather similar predictions are found when considering either the Skyrme-HFB plus QRPA calculations of Ref. [3] or our new Gogny-HFB plus QRPA predictions. This similarity can be explained by the rather same strength predicted at low-energy below the GDR, although the Gogny calculation predicts a strength spread on a much wider energy range, as discussed above.

3. Conclusions

The results obtained with the Gogny force for the $\gamma$-ray strength functions are quite promising. The encouraging results obtained in parallel to the nuclear masses [4] and the nuclear level densities [15] allow us to plan to include, one by one, the ingredients required to perform microscopic cross sections calculation on the basis of an optimized Gogny interaction. We believe...
Figure 3. Ratio of the Maxwellian-averaged neutron capture rate (for a temperature of $10^9$ K) for the Sn isotopes predicted with the microscopic $\gamma$-ray strength taken from the QRPA (with the Gogny D1M force) to the one obtained with the generalized Lorentzian model (circles) [1] and to the one predicted with the Skyrme+QRPA of [3] based on the BSk7 force (squares).

that work along such a path is a way to progress and be able, in the future, to obtain satisfactory cross section evaluations and predictions on the basis of reliable and accurate microscopic inputs.

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References
[1] Capote R et al. 2009 Nuclear Data Sheets 110 3107
[2] Goriely S and Khan E 2002 Nucl. Phys. A706 217-232
[3] Goriely S, Khan E and Samyn M 2004 Nucl. Phys. A739 331-352
[4] Goriely S, Hilaire S, Girod M and Pérù S 2009 Phys. Rev. Lett. 102 242501
[5] Pérù S and Goutte H 2008 Phys. Rev. C 77 044313
[6] Martini M, Pérù S and Dupuis M 2011 Phys. Rev. C 83 034309
[7] Pérù S, Gosselin G, Martini M, Dupuis M, Hilaire S and Devaux J-C 2011 Phys. Rev. C 83 014314
[8] Pérù S and Martini M 2014 Eur. Phys. J. A 50 88
[9] Martini M, Goriely S, Hilaire S and Pérù S 2012 AIP Conference Proceedings 1491 160
[10] Martini M, Hilaire S, Goriely S, Koning A J and Pérù S 2014 Nuclear Data Sheets 118 273-275
[11] Utsunomiya H et al. 2013 Phys. Rev. C 88 015805
[12] Hilaire S, Koning A J and Goriely S 2011 Journal of the Korean Physical Society 59 767
[13] Goriely S, Hilaire S and Koning A J 2008 Astronomy and Astrophysics 487 767
[14] Koning A J, Hilaire S and Duijvestijn M 2008 Nucl. Data for Science and technology (EDP Sciences, eds Bersillon et al.) 211
[15] Hilaire S, Girod M, Goriely S and Koning A J 2012 Phys. Rev. C 86 064317