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Self-consistent calculations of radiative nuclear reaction characteristics for ^{56}Ni, ^{132}Sn, ^{208}Pb

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Abstract. The photon strength functions (PSF), neutron capture cross sections and average radiative widths of neutron resonances for three double-magic nuclei ^{56}Ni, ^{132}Sn and ^{208}Pb have been calculated within the self-consistent version of the microscopic theory. Our approach includes phonon coupling (PC) effects in addition to the standard QRPA approach. With our microscopic PSFs, calculations of radiative nuclear reaction characteristics have been performed using the EMPIRE 3.1 nuclear reaction code. Three nuclear level density (NLD) models have been used: the phenomenological so-called GSM, phenomenological Enhanced GSM (EGSM) and microscopical combinatorial HFB model. For all the considered characteristics, we found a noticeable contribution of the PC effects and a significant disagreement between the results obtained with the GSM and the other two NLD models. The results confirm the necessity of using consistent microscopic approaches for calculations of radiative nuclear characteristics in double-magic nuclei.

1. Introduction

The microscopic approach in the nuclear theory accounts for the specificity of each nucleus through its single-particle and collective (phonon) spectra. Therefore, it allows "some irregular changes" obtained in the global phenomenological models for nuclear reactions data to be seen and checked.

The double magic nuclei were always a polygon for nuclear theory in low-lying nuclear physics. On the other side, they have a noticeable specificity caused by the specificity of their single-particle and collective spectra, which determine their individual properties in many fields of low-energy nuclear physics. These properties are in a bad agreement with the smoothed phenomenological dependencies often used in the nuclear reaction theory, for example, in the calculations of nuclear data with gamma-rays. First of all, we mean the generalized Lorentzian models, which are used [1,2] for photon strength function (PSF) and photoabsorption cross sections.

Probably, since 2006 [1] it has been realized by the nuclear data society that there are structures in the PSFs negating the simple picture based on the dominance of the generalized Lorentzian dependencies, especially in the energy region below neutron threshold (for photoabsorption cross sections it was discussed within the quasiparticle-phonon model [3]). For this reason, mean-field approaches using effective nucleon interactions, such as the Hartree-Fock-Bogolubov method and the quasi-particle random-phase approximation (HFB+QRPA) [4], have been included in modern nuclear reaction codes like EMPIRE or TALYS. Such an approach is of higher predictive power in comparison with phenomenological models.

In our works [5–7] it was shown that, in order to describe the observed PSF structures, it is necessary to take the phonon coupling (PC) into account in addition to the structures caused by the QRPA effects. The calculations of PSF have been performed within the self-consistent version of the extended theory of finite fermi systems in the quasiparticle time blocking approximation (ETFFS(QTBA)) [8,9]. This approach includes the QRPA and PC effects and uses the known Skyrme forces to calculate the mean field, effective interaction and phonon characteristics self-consistently. For calculation of other radiative nuclear characteristics, nuclear code EMPIRE 3.1 [10] has been used. Using these microscopic PSFs, we obtained a reasonable agreement with experiment for the PSFs themselves, neutron capture cross sections, capture gamma-ray spectra and average radiative widths of neutron resonances in many even-even semi-magic Sn and Ni isotopes. Quite recently, a more consistent, than our QTBA, continuum TBA (CTBA) approach has been developed for magic nuclei in [11], which better takes the single-particle continuum and spin-orbit forces into account.

In this work we calculate self-consistently the photon strength functions (PSF), neutron capture cross sections and average radiative widths of neutron resonances for three double-magic nuclei ^{56}Ni, ^{132}Sn and ^{208}Pb using the new CTBA approach for ^{208}Pb and our ETFFS(QTBA) for ^{132}Sn and ^{56}Ni. Our main aims are to study the PSF structures and role of the PC effects in these characteristics for these nuclei.

2. Photon strength functions

In Figs. 1, 2, 3 we show the PSFs for ^{56}Ni, ^{132}Sn and ^{208}Pb calculated, in accordance with the Brink-Axel hypothesis, within our microscopic TBA and RPA methods with

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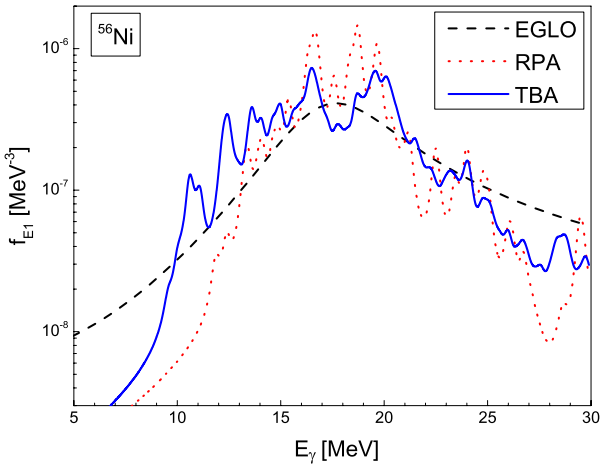

Figure 1. The E1 PSF for ^{56}Ni (S_n = 16.6 MeV). Dotted lines: the self-consistent RPA, solid lines: the TBA (including PC), dashed lines: the EGLO model [1].

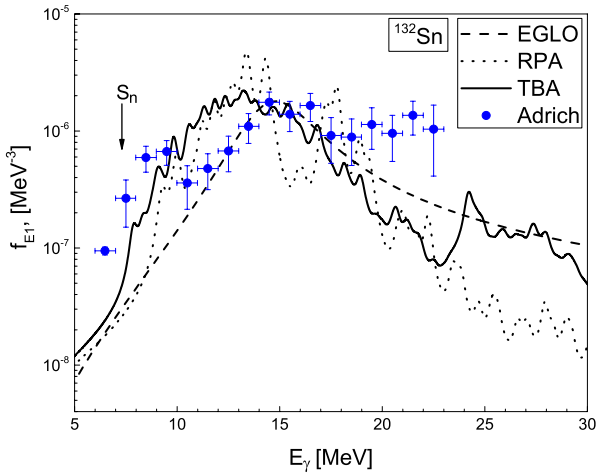

Figure 2. Same as in Fig. 1 for ^{132}Sn. The experimental data [12] were recalculated by us for PSF.

Skyrme forces SLy4. Earlier we have already published the results for ^{132}Sn and ^{208}Pb in [16]. In this work PSF for ^{56}Ni have been calculated for the first time with such an approach. PSFs for ^{132}Sn and ^{208}Pb have been recalculated from the theoretical photoabsorption cross sections taken from [17] (^{132}Sn) and [11] (^{208}Pb). The phenomenological EGLO PSFs are also shown. We see that, in contrast to the phenomenological model EGLO, our microscopic RPA and TBA (i.e., RPA + PC) approaches give some structures in the region of PDR in ^{56}Ni, ^{132}Sn and partly ^{208}Pb, with a considerable part of them being only due to PC, thus improving the agreement with the experiment. For ^{132}Sn, we see the well-known structure at about 10 MeV (our approach gives a lower energy), see discussions in [17, 18].

According to Fig. 3 for ^{208}Pb, the reanalyzed data of Oslo group [15] are in a better agreement with our results at about E > 5 MeV, than those from [14]. We see that the PC contribution is important. Discrepancy between our results and the experimental data at E < 5 MeV should be explained by a relatively large value of the smearing parameter, which is equal to 400 keV. The results of (γ, γ') experiments [19] show that there are no 1^- single-particle

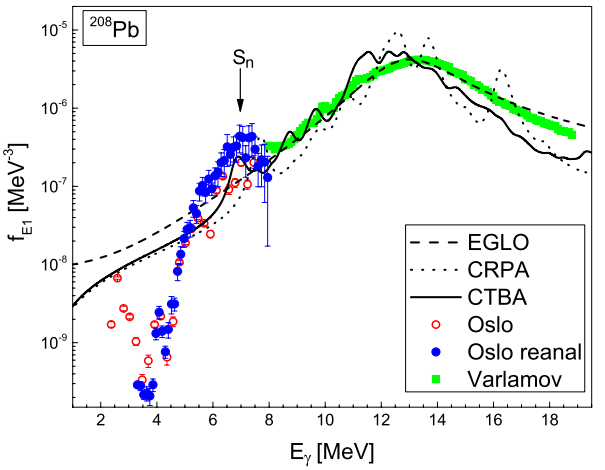

Figure 3. Same as in Fig. 1 for ^{208}Pb and calculated with CRPA and CTBA (see text). The experimental data are taken from Ref. [13–15].

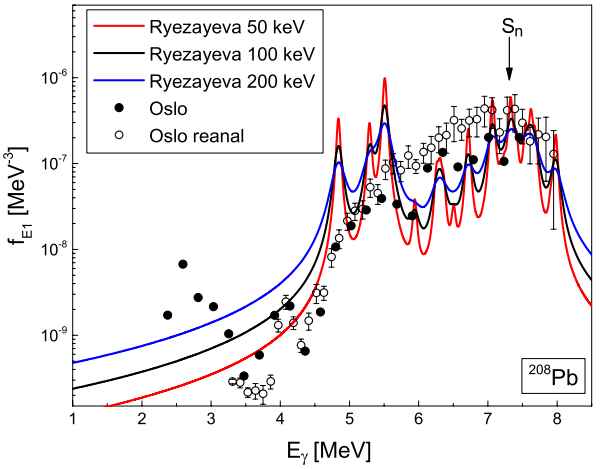

Figure 4. Comparison of the experimetal data: the (^{3}He, ^{3}He$'\gamma$) reactions method [14, 15] and nuclear resonance fluorescence technique [19]. The lowest 1^--level of the data [19] is 4.84 MeV. It was smoothed by us with three smoothing parameters Δ. See text for details.

or two-phonon transitions between the ground and excited states below 4.84 MeV. So we think that the transitions at E < 5 MeV are transitions between excited (probably M1) states.

In Fig. 4, we compare three sets of experimental data for ^{208}Pb: 1) the PSF data from [14, 15] where the transitions between the ground and excited states and also between excited states have been measured and 2) the data [19] (recalculated by us from their B (E1) values) for the transitions between only the ground and excited states. For comparison, we smoothed the data [19] (like in the quasiparticle-phonon model [3]) with three values of smoothing parameter Δ: 50 keV, 100 keV and 200 keV. As it can be seen, in the range of (5.5–7.5) MeV, the reanalyzed experimental data [15] are much higher than those from (γ, γ') experiments, irrespective of the smoothing parameter value. Therefore, it is conceivable that the transitions between the excited states in this energy region could also be measured in the Oslo method.

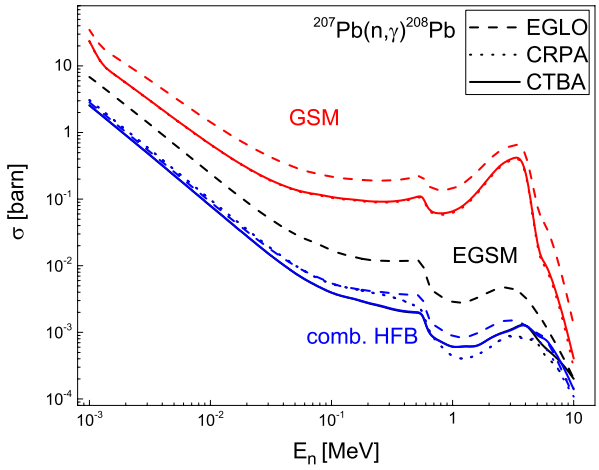

Figure 5. $^{207}Pb(n,\gamma)^{208}Pb$ cross section calculated with the EGLO (dash), CRPA (dot) and CTBA (solid) PSFs. The red curves were calculated using EMPIRE 3.1 with the GSM NLD model, the black ones: the Enhanced GSM NLD and the blue ones: the combinatorial HFB NLD [22].

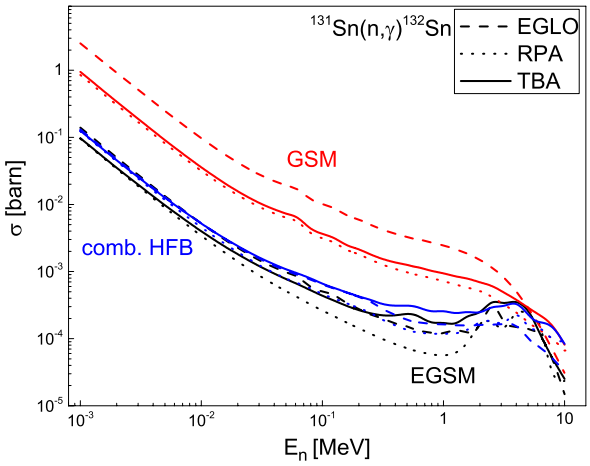

Figure 6. Same as for Fig. 5 for the $^{131}Sn(n,\gamma)^{132}Sn$ cross section calculated with the EGLO (dash), RPA (dot) and TBA (solid) PSFs.

3. Neutron radiative capture cross sections

In Figs. 5, 6, 7 the neutron radiative capture cross sections are shown for the compound ^{56}Ni, ^{132}Sn and ^{208}Pb. Our approach for PSF is non-statistical, so there is no sense to compare its results with the available ^{207}Pb$(n,\gamma)^{208}$Pb cross sections [20,21] because these data (two points) are in the neutron resonance energy region. We see a very large difference between the results obtained with traditional GSM [1] and other NLD models (Enhanced GSM [2] and combinatorial HFB [22]). Namely, the difference for (n,γ) cross sections is about one order of magnitude practically in all the neutron energy up to 2 MeV and 10 MeV for the compound ^{132}Sn and ^{208}Pb, respectively. There is no noticeable difference between the results with phenomenological Enhanced GSM and microscopic combinatorial HFB NLD models. One of the possible reasons is that in both cases the known experimental energies of the first 2^+ levels have been used (and our calculations describe them rather reasonably), which is, generally speaking, important for the phonon enhancement effect in the NLDs.

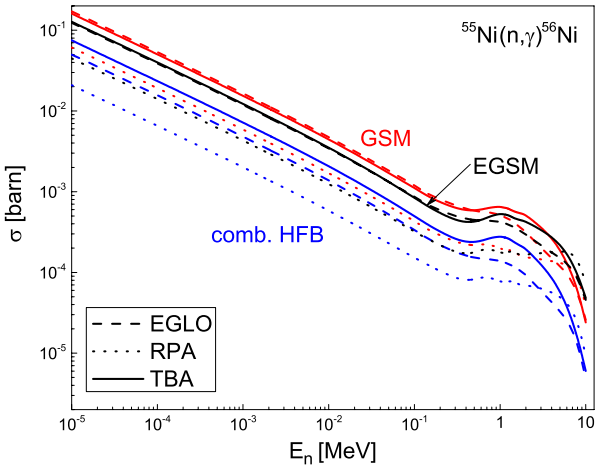

Figure 7. Same as for Fig. 5 for the $^{55}Ni(n,\gamma)^{56}Ni$ cross section calculated with the EGLO (dash), RPA (dot) and TBA (solid) PSFs.

Table 1. Average radiative widths Γ_γ (meV) for s-wave neutrons. For each approach (EGLO, QRPA and QTBA) three NLD models are considered: the phenomenological GSM [1], Enhanced GSM [2] and the microscopic combinatorial HFB model [22]. See text for details.

Nuclei	NLD model	EGLO	RPA	TBA	System.	M1 contrib.
^{208}Pb	GSM	10.56	4.44	4.61	5070	0.79
	EGSM	6292	2562	2109		6.56
	Comb. HFB	2734	2973	2448	3770	5.25
^{132}Sn	GSM	398	133	148		40.9
	EGSM	7340	4675	5186		515.3
	Comb. HFB	4444	4279	4259		340.7
^{56}Ni	GSM	2279	270	656		73.0
	EGSM	8073	1790	4160	2800	201.7
	Comb. HFB	3132	647	1794		128.1

4. Average radiative widths

Unfortunately, the experimental data are very scarce here for the double-magic nuclei ^{56}Ni, ^{132}Sn and ^{208}Pb. However, for ^{208}Pb with EMPIRE 3.1 we found (see Table 1) a reasonable agreement for the average radiative widths Γ_γ values with systematics [10,23] only for Enhanced GSM and combinatorial HFB NLD models. For the average resonance s-wave level spacings D_0 for ^{208}Pb, the following was found: $D_0(GSM) = 0.00441$ keV, $D_0(EGSM) = 32.0$ keV, $D_0(HFB) = 37.6$ keV, while $D_0(exp) = 30\ (8)$ keV).

In the last column of Table 1, the contribution of M1 resonance [1] to Γ_γ calculated with EMPIRE 3.1 is given, which is based on the standard Lorentz approximation with the width $\Gamma = 4$ MeV. It turned out rather small. As discussed in [24], this Γ value is very questionable, especially for ^{208}Pb.

5. Conclusion

In this work two modern self-consistent microscopic approaches for the PSFs calculations for the double-magic

nuclei ^{56}Ni, ^{132}Sn and ^{208}Pb have been used. The EMPIRE 3.1 code has been used to calculate neutron radiative cross sections and average radiative widths. We have a more pronounced structure of PSF for double magic nuclei than for semi-magic nuclei [7]. For ^{132}Sn and ^{208}Pb, the contribution of PC to radiative cross sections and average radiative widths is not so noticeable as compared with the semi-magic nuclei [7,17]. Although we have already considered radiative characteristics for ^{132}Sn and ^{208}Pb in [16], but in this work we also compare our PSF for ^{208}Pb with the new reanalyzed data of Oslo group [15] and present new results for ^{56}Ni.

We have found a great disagreement between the results obtained with the phenomenological GSM and other two NLD models used (the phenomenological Enhanced GSM and microscopic combinatorial HFB). The discrepancies between the results with the phenomenological EGLO PSF and microscopic RPA (or CRPA) or TBA (or CTBA) are much less for the same NLD model. Also, due to comparison of two sets of experimental data [14,15] and [19], it was possible to conclude that the nature of the PSF values observed in [15] at $E < 4.84$ MeV for ^{208}Pb may be only caused by the transitions between excited states. Our results show the necessity to include the PC effects in the theory of radiative nuclear data for double-magic nuclei.

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