MICROSCOPIC NATURE OF THE PHOTON STRENGTH FUNCTION: STABLE AND UNSTABLE Ni AND Sn ISOTOPES

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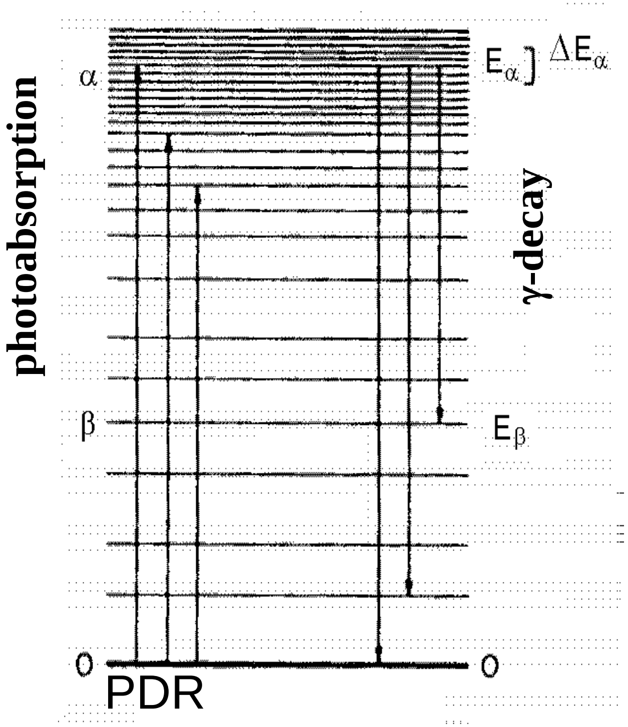
Plan

1. Definitions; phenomenological approaches
2. Recent experiments (Oslo method, [Utsunomia])
3. Self-consistent calculations of PSF
4. EMPIRE and TALYS calculations of neutron capture cross sections, average radiative widths and neutron capture gamma-ray spectra using the microscopic PSF's with SLy4 Skyrme forces

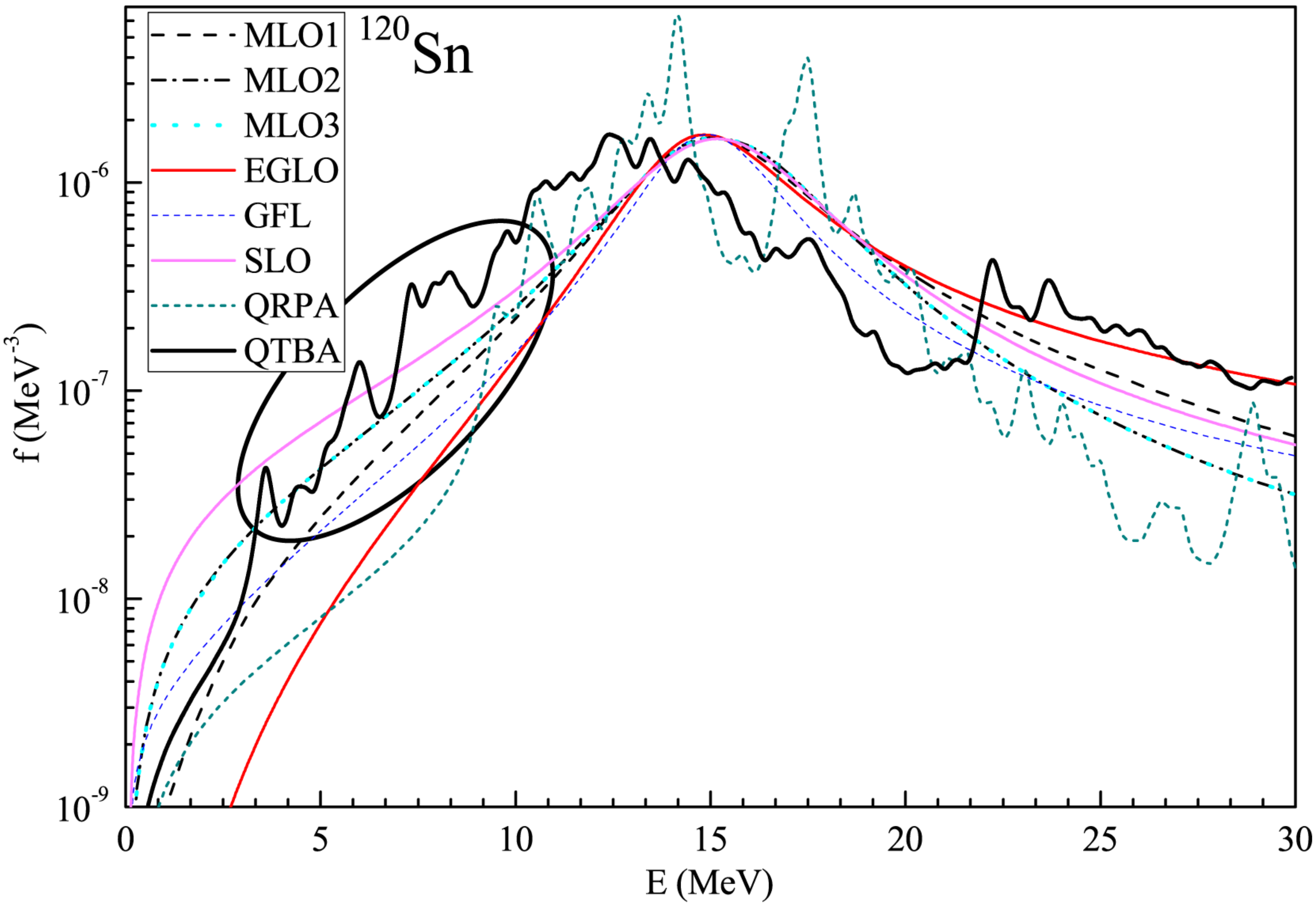
Photon strength function (PSF) (radiative strength function)

The most popular definition of PSF: describes the energy distribution of photon emission between **excited** states

{The PSF and appropriate nuclear data businesses are based on the Axel-Brink hypothesis which was not justified microscopically so far ...}



Photon strength functions: phenomenology vs. microscopy



Reference Input Parameters Library (RIPL2, (2006)):

„The Lorentzian and previously described closed-form expressions for the γ-ray strength suffer from various shortcomings:

1. they **are unable to predict the resonance-like enhancement of the E1 strength at energies below the neutron separation energy** as demonstrated, for example, by nuclear resonance fluorescence experiments
2. they are **unable to describe isospin structure of the PSF**, specifically observed isospin splitting of the GDR in light- and middle-weight atomic nuclei [336]–[339];
3. even if a Lorentzian function provides a suitable representation of the E1 strength, the location of the maximum and width still need to be predicted from some underlying model for each nucleus, as described in the previous sections. **This approach lacks reliability when dealing with exotic nuclei.**"

For these reasons, in [RIPL2, 2006], RIPL3 appeared "Microscopic approach based on the HFB+QRPA method of S. Goriely.

However it is not enough !

If the Brink-Axel hypothesis is correct:

$$f(E1) = \frac{1}{3(\pi hc)^2}\frac{\sigma(\omega)}{\omega} = 3.487 \cdot 10^{-7} S(\omega),$$

where S is taken in $fm^2 MeV^{-1}$, $f(E1)$ in MeV^{-3}

$$\sigma(\omega) = 4.022\omega S(\omega) \qquad S(\omega) = \frac{dB(E1)}{dE}$$

Problems of PSF are problems of (PDR + BAH)…

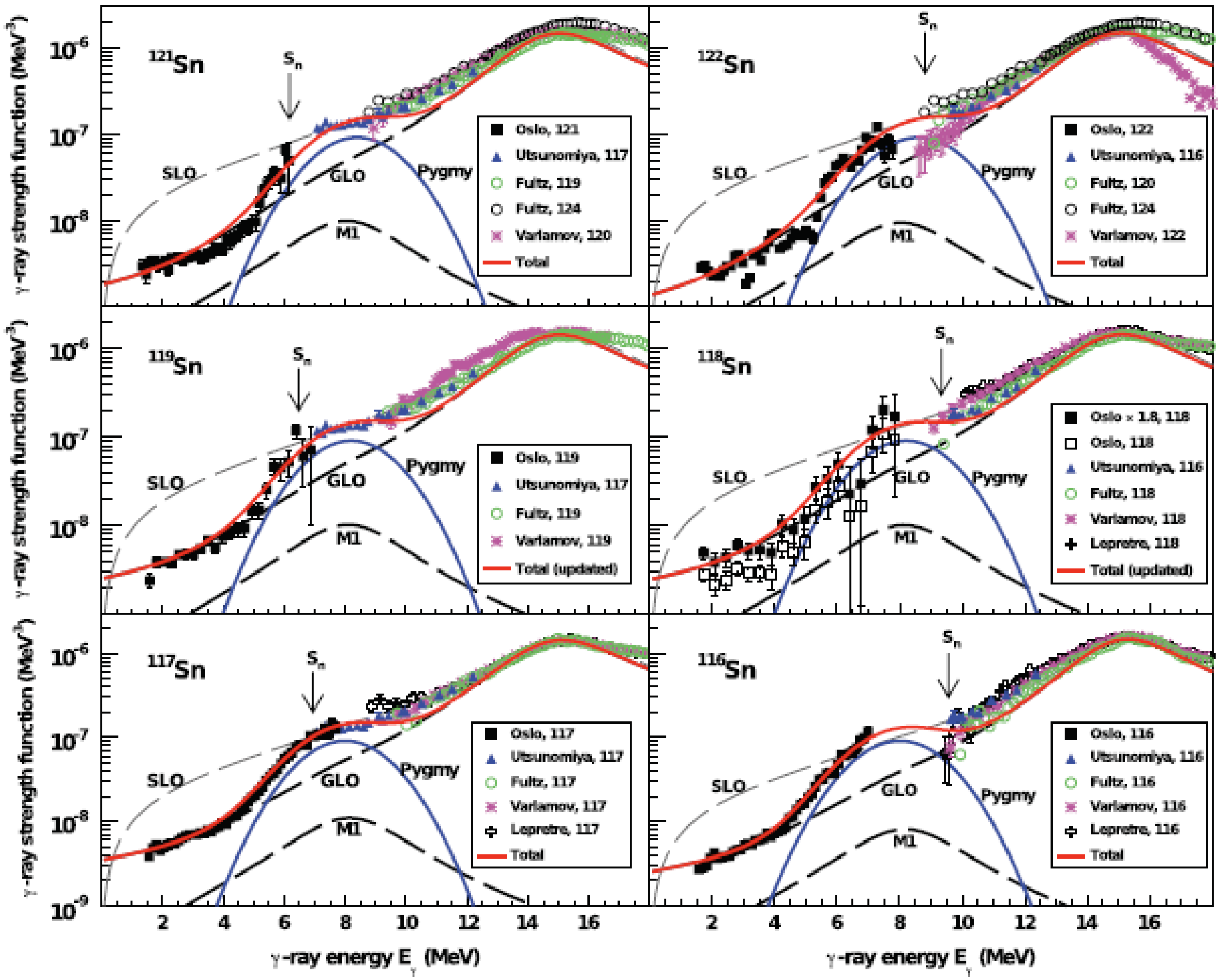


Fig. 25. Comparison of experimental data from the Oslo group (low-energy part) and other experiments with predictions for the γ-ray strength function. The inclusion of a E1 PDR around 8–8.6 MeV is necessary to explain the measured data.
Source: Reprinted figure with permission from [174].

Oslo method : H.K. Toft et al., PRC 83 (2011) 044320

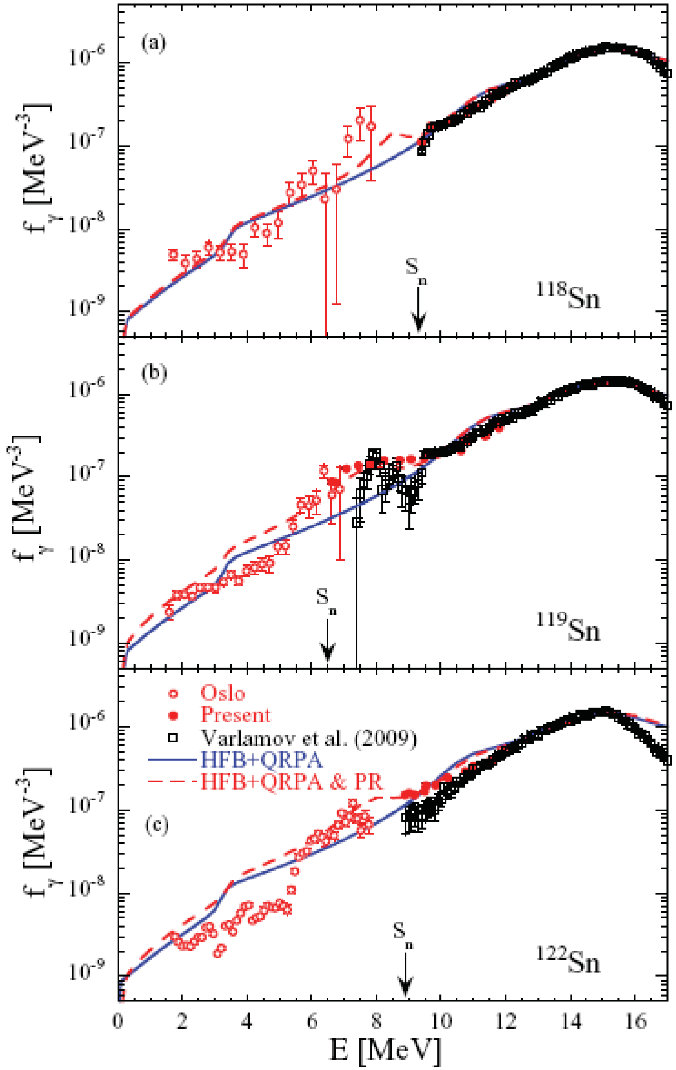


FIG. 10. (Color online) Comparison between the HFB + QRPA strength (with and without the inclusion of the PR) and the experimental data of the Oslo group [9,10], from photodata [18] as well as the present photoemission data, for ^{118}Sn (a), ^{119}Sn (b), and ^{122}Sn (c).

This is a direct evidence of necessity of taking **the phonon coupling** (and M1 ?) into account

Utsunomiya,Goriely et al., PRC 84, 055805(2011)

Phonon coupling has been taken into account in, see review [N.Paar et al.,2007]:

Non self-consistent approaches:

1. NFT (Bohr, Mottelson Vol.2)
2. QPM model by Soloviev et al.
3. Ka-ev, Speth, Tertychny, ETFFS[Phys.Rep.2004]

Self-consistent approaches:

4. Self-consistent ETFFS(QTBA) (Avdeenkov, Ka-ev, Tselyaev)
5. Relativistic QTBA (Ring, Tselyaev, Litvinova)

Self-consistency:

1. Mean field (ground state) is determined by the first derivative of the **functional**
2. Effective pp- and ph-interactions are the second derivative of the same functional :

(No new parameters in calculations ! Therefore, a great predictive power)

$$\mathcal{F} = \frac{\delta^2 \mathcal{E}}{\delta \rho^2} \qquad \mathcal{F}^{\xi} = \frac{\delta^2 \mathcal{E}}{\delta \nu^2}$$

Self-consistent Extended Theory of Finite Fermi Systems in the QTBA approximation

ETFFS(QTBA) contains:

1. (Q)RPA
2. Phonon coupling
3. Single-particle continuum

and uses the known Skyrme forces SLy4

No new parameters !

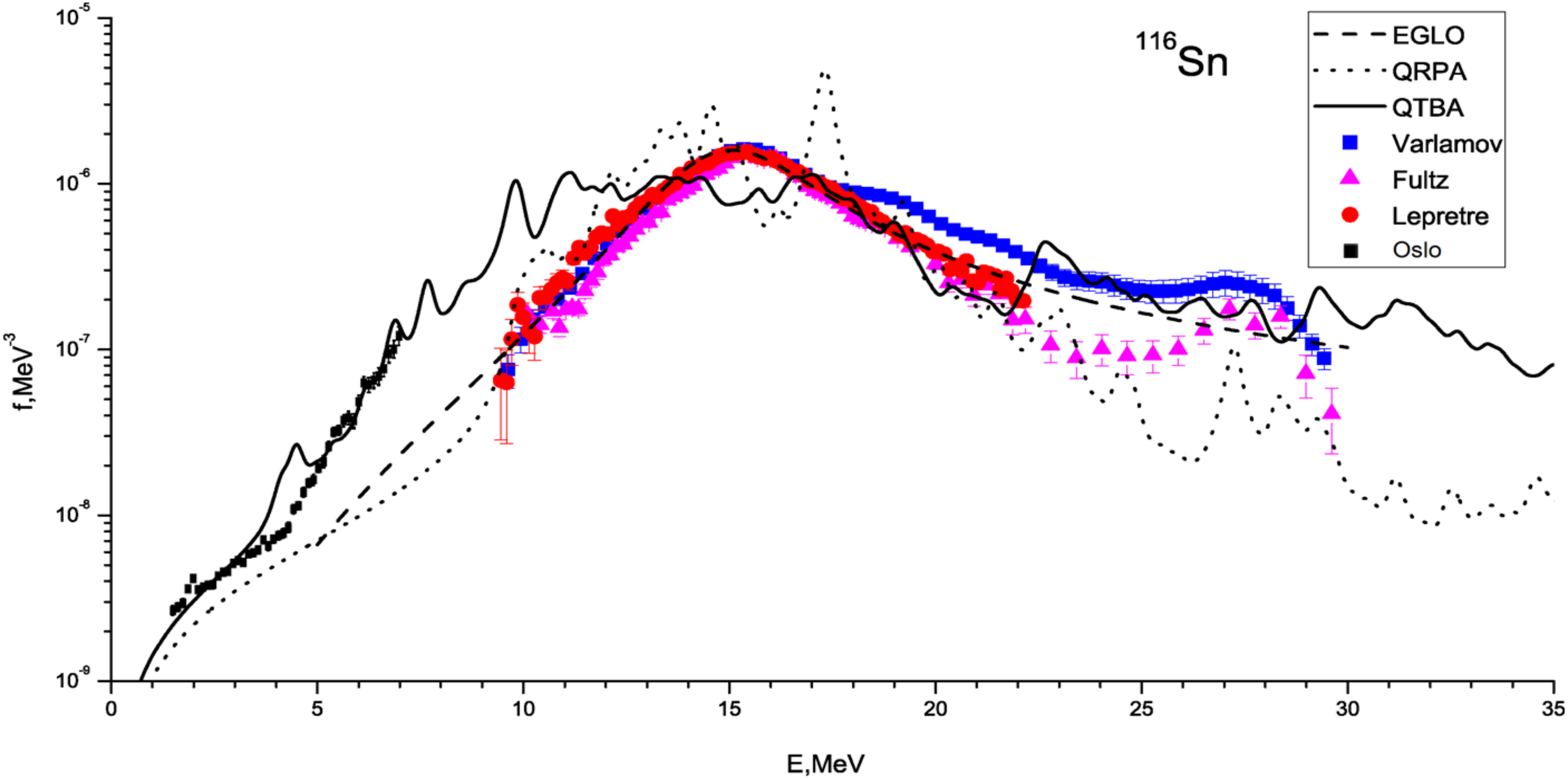
Kamerdzhiev *et al.*, Phys. Rep. 393, 1, (2004)
Tselyaev, Rhys. Rev. C 75, 024306 (2007)
Avdeenkov *et al.*, Phys. Rev. C 83, 064316 (2011)

Features of the self-consistent ETFFS(QTBA) approach

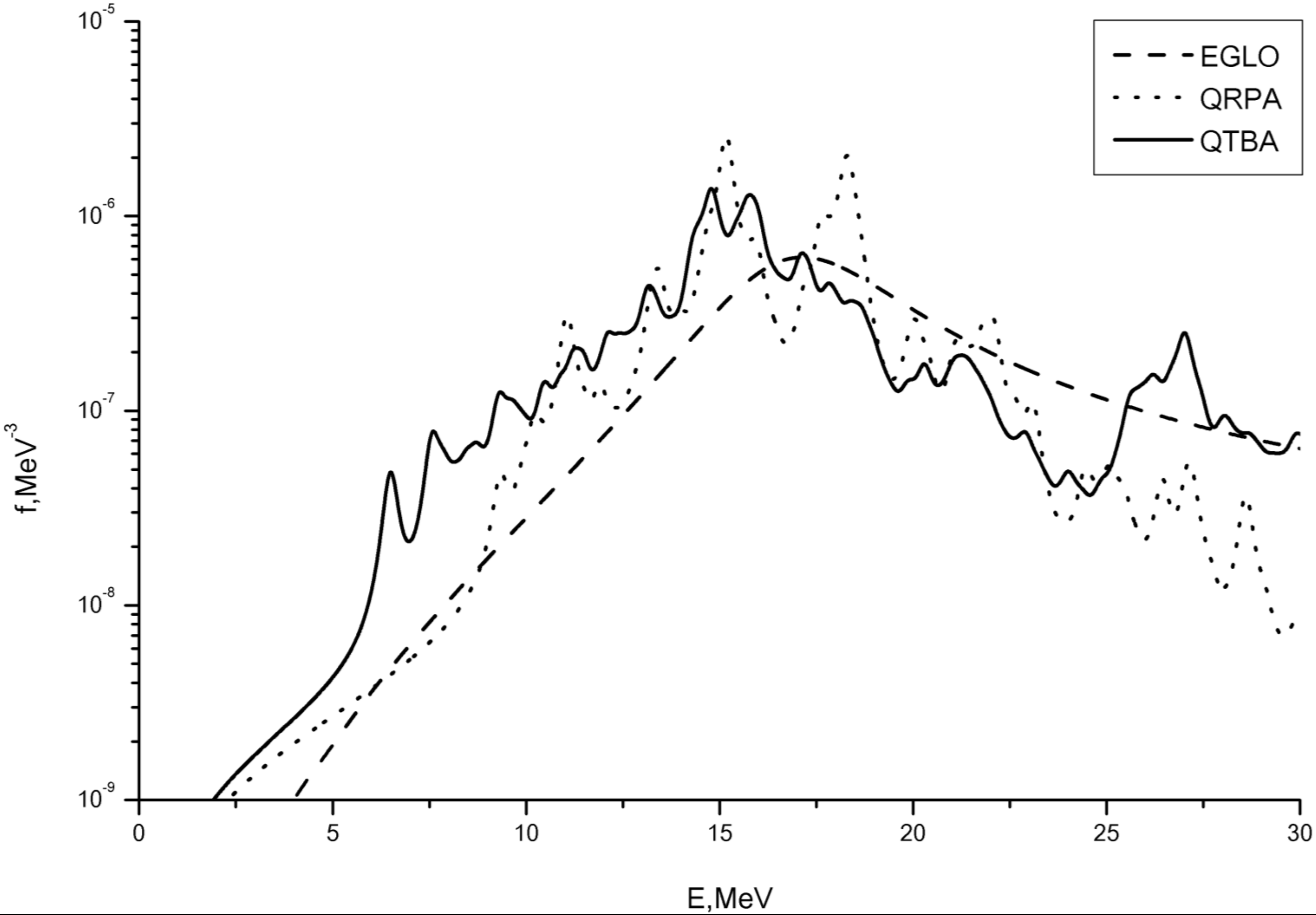
- Individual approach to each nucleus (due to single-particle scheme and , therefore, PSF structures should be)
- “First principle” approach (parameters of the Skyrme forces or functional are universal for all nuclei except for light ones)
- Great predictive power
- However!: much computer time and less predictive power, if all parameters are taken from experiment !

Kamerdzhiev *et al., Phys. Atom. Nucl., october 2014*

3.Self-consistent calculations :
^{116}Sn PSF (smoothing parameter is 200 keV)



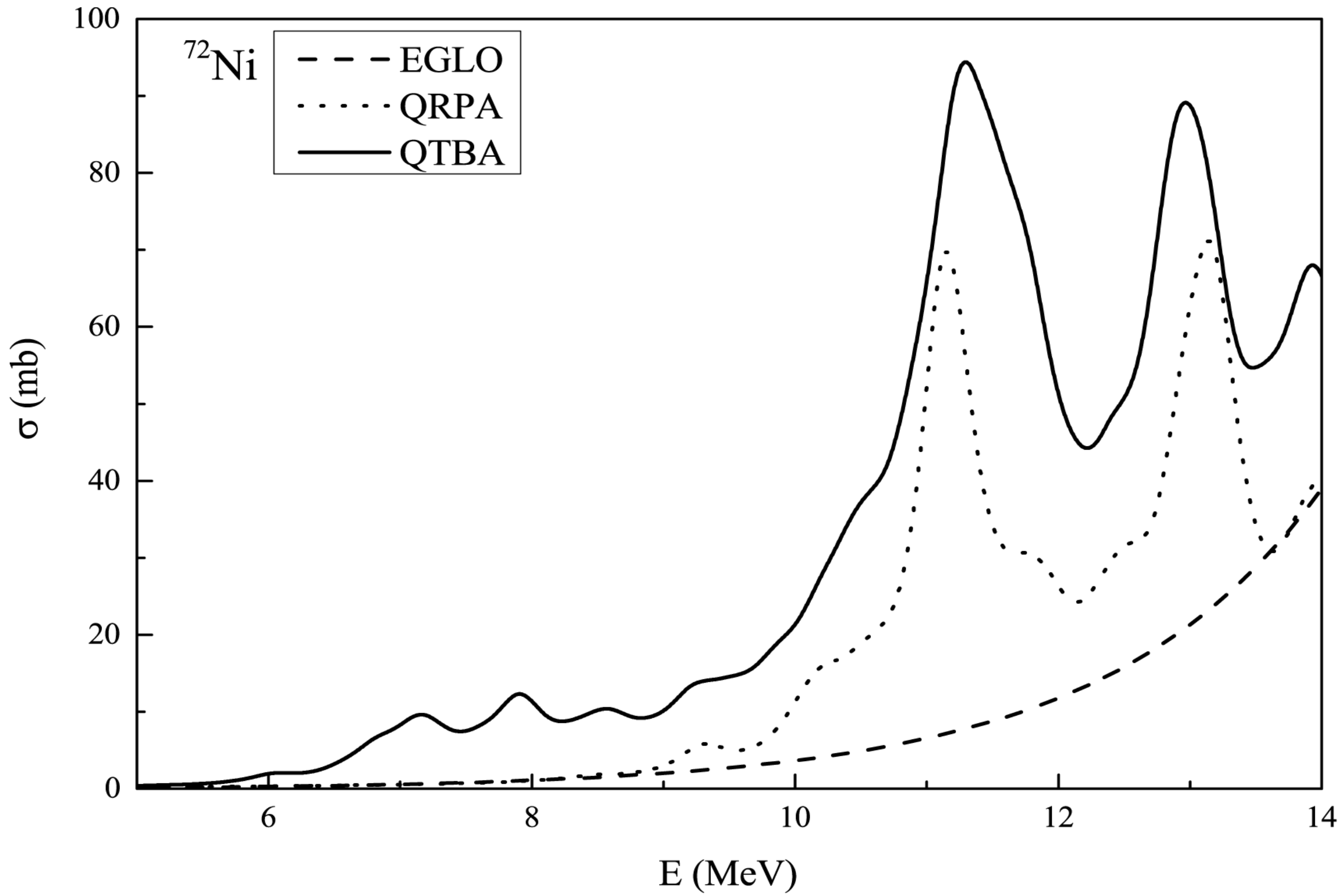
^{68}Ni PSF



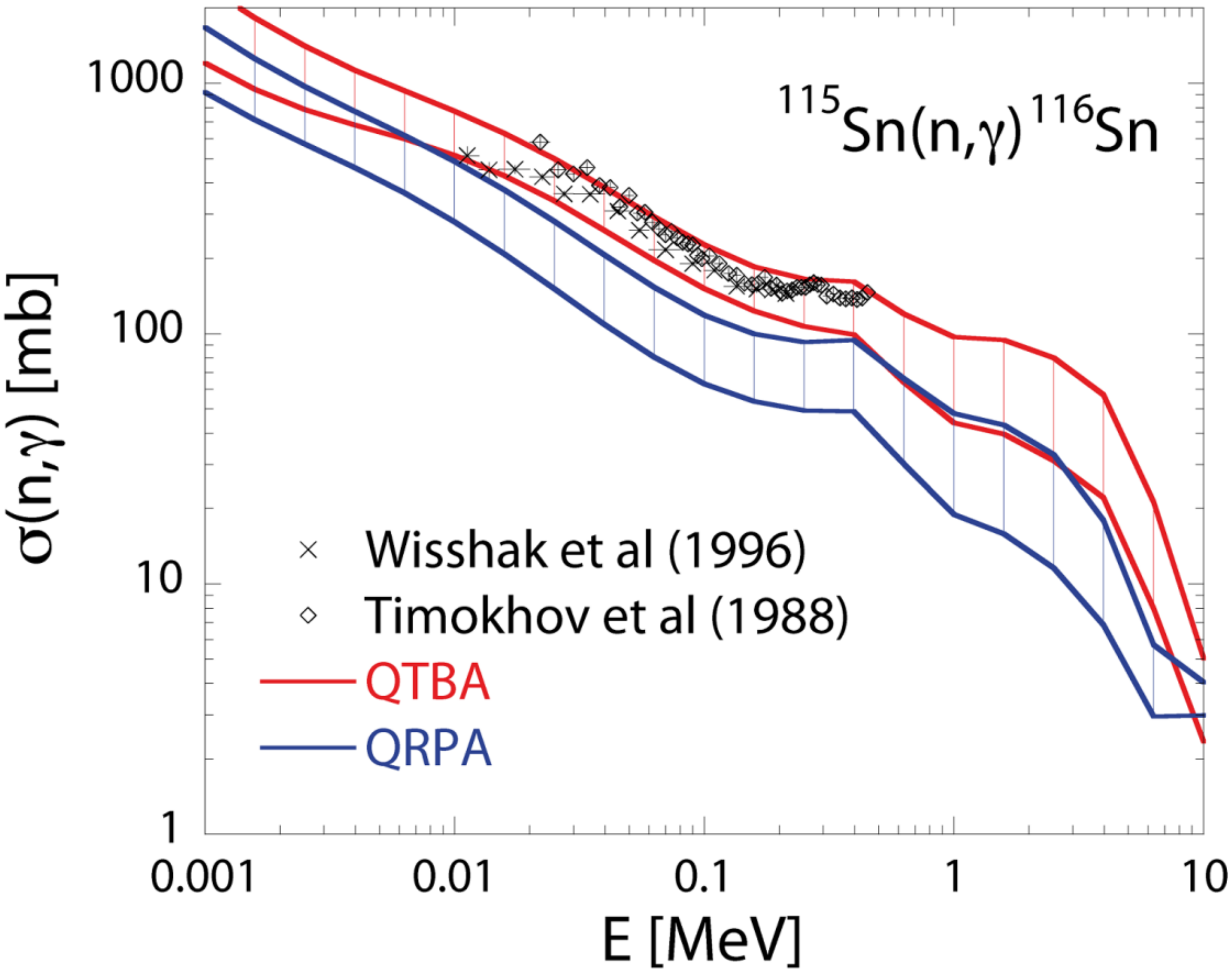
Integral characteristics of GDR and PDR in ^{68}Ni

<table>
<tr><td rowspan="3">Forces</td><td colspan="4">Interval (0-30) MeV</td><td colspan="4">Interval (7-13) MeV</td></tr>
<tr><td colspan="2">QRPA</td><td colspan="2">ETFFS(QTBA)</td><td colspan="2">QRPA</td><td colspan="2">ETFFS(QTBA)</td></tr>
<tr><td>$\langle E \rangle$,MeV</td><td>D,MeV</td><td>$\langle E \rangle$,MeV</td><td>D,MeV</td><td>$\langle E \rangle$,MeV</td><td>%</td><td>$\langle E \rangle$,MeV</td><td>%</td></tr>
<tr><td>SLy4</td><td>17,48</td><td>1,66</td><td>18,54</td><td>3,97</td><td>11,0</td><td>4,85</td><td>10,75</td><td>8,73</td></tr>
<tr><td>BSk17</td><td>17,82</td><td>1,92</td><td>19,03</td><td>4,38</td><td>10,24</td><td>5,32</td><td>10,28</td><td>6,85</td></tr>
<tr><td rowspan="2">Exp.</td><td colspan="2" rowspan="2">[Rossi]</td><td>18,1 (5)</td><td>6,1 (5)</td><td colspan="2">[Rossi]</td><td>10,4 (4)</td><td>4,1 (1,9)</td></tr>
<tr><td colspan="2"></td><td colspan="2">[Wieland]</td><td>≈11</td><td>≈5</td></tr>
</table>

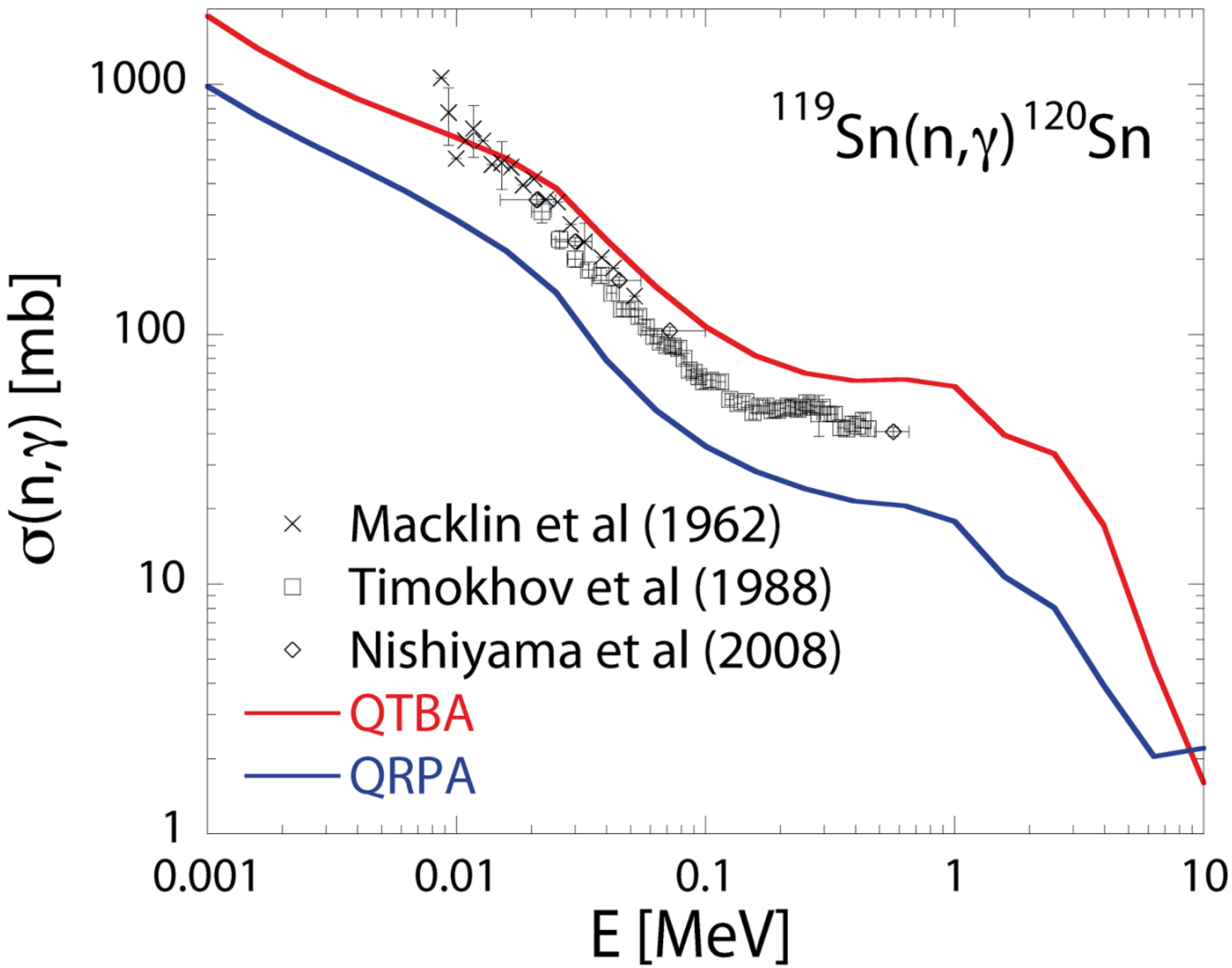
PDR in ^{72}Ni: 14.7 MeV; 25.7% EWSR (!!) (in interval (8-14)MeV)



4.TALYS calculations of neutron capture cross sections (uncertainty band is due to different NLD's)



Cross-section of radiative neutron capture (experimental S-wave spacing)



Average radiative widths

$$\Gamma_\gamma = \sum_{I=|I_0-1|}^{I=|I_0+1|} \int_0^{B_n} {\varepsilon_\gamma}^3 f_{E1}(\varepsilon_\gamma) \frac{\rho(B_n - \varepsilon_\gamma, I\ )}{\rho(B_n, I\ )} d\varepsilon_\gamma$$

$${D_{0s}}^{-1} = \begin{cases} \left(\rho\left(B_n, I_0 + {}^1/_2\right) + \rho\left(B_n, I_0 - {}^1/_2\right)\right)/2 & for\ \ I_0 \neq 0 \\ \rho\left(B_n, {}^1/_2\right)/2 & for\ \ I_0 = 0 \end{cases}$$

$$\sigma_{n\gamma} \cong \frac{C\pi^2 {\lambda_n}^2}{2I_0 + 1} \frac{\Gamma_\gamma}{D_{0s}}$$

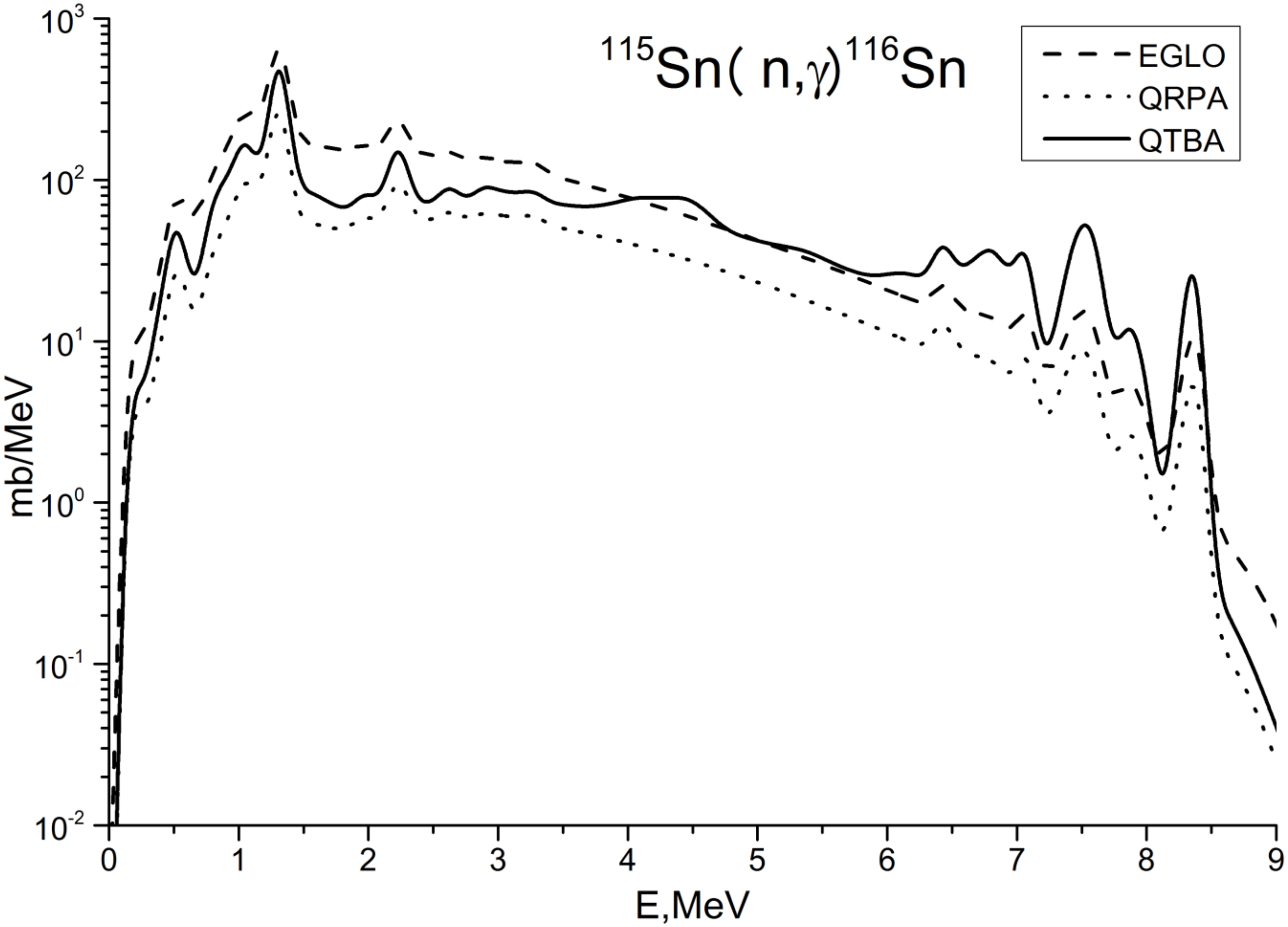
Average radiative widths
(EMPIRE3.1 calculations with microscopic PSF's and GSM NLD model)

$$2\pi \frac{\Gamma_\gamma}{D_0}$$

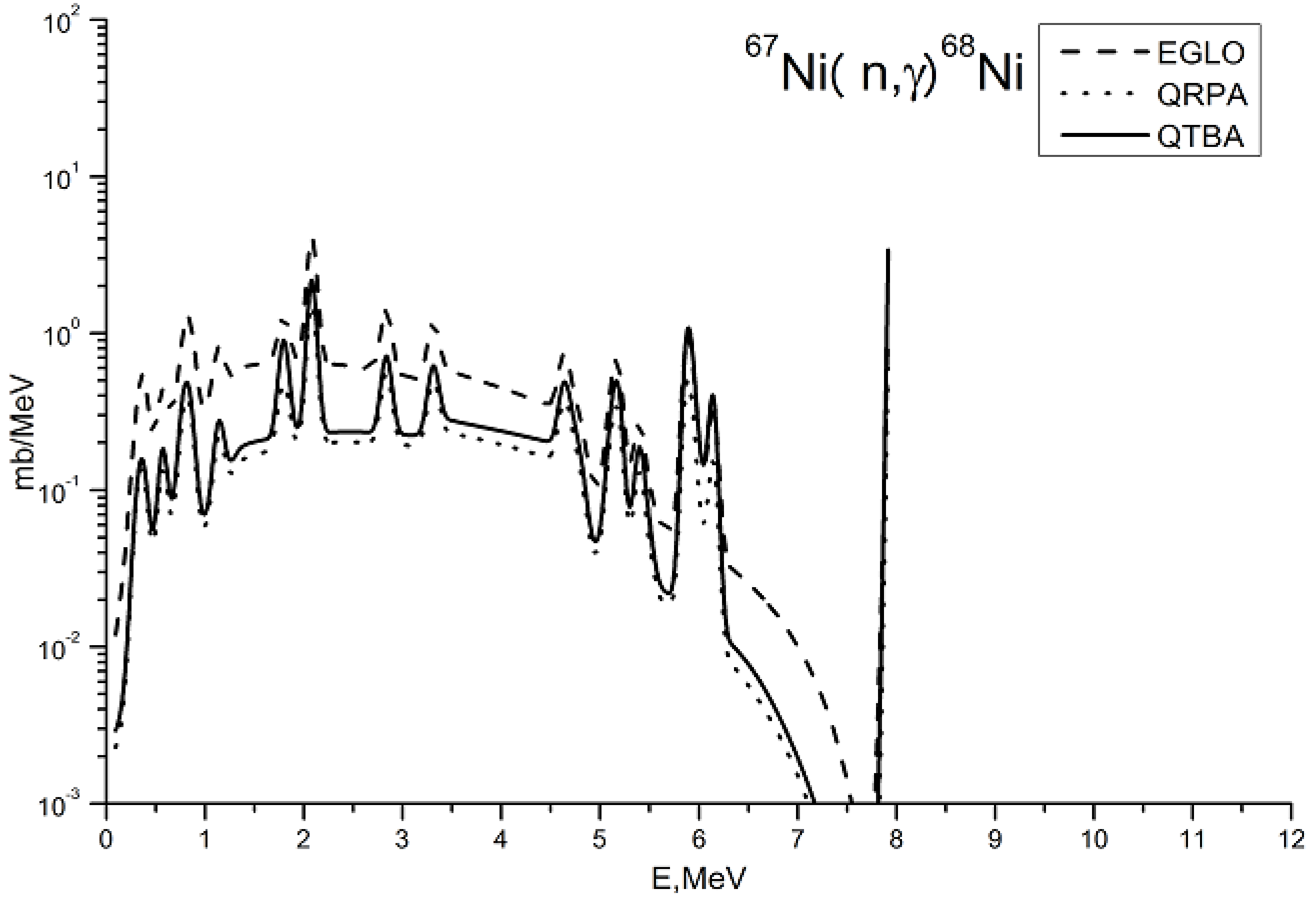
	^{110}Sn	^{112}Sn	^{116}Sn	^{120}Sn	^{124}Sn	^{132}Sn	^{136}Sn	^{58}Ni	^{62}Ni	^{68}Ni	^{72}Ni
EGLO	12,6*10^{-2}	9,44*10^{-2}	7,99*10^{-2}	5,77*10^{-2}	4,77*10^{-2}	6,53*10^{-4}	9,90*10^{-7}	7,04*10^{-2}	2,51*10^{-2}	1,04*10^{-3}	2,12*10^{-5}
QRPA	3,90*10^{-2}	3,08*10^{-2}	3,33*10^{-2}	2,52*10^{-2}	2,137*10^{-2}	2,18*10^{-4}	9,97*10^{-7}	2,30*10^{-2}	1,97*10^{-2}	4,73*10^{-4}	1,33*10^{-5}
QTBA	7,99*10^{-2}	5,88*10^{-2}	5,79*10^{-2}	7,07*10^{-2}	2,67*10^{-2}	2,42*10^{-4}	1,10*10^{-6}	7,33*10^{-2}	4,33*10^{-2}	2,46**10^{-3}	2,45*10^{-5}
Exp. or systematics	9,57*10^{-2}	9,76*10^{-2}	11,73*10^{-2}	(7,0±1,9)*10^{-2}	9,84*10^{-2}	1,39*10^{-4}	6,51*10^{-6}	17,02*10^{-2}	(6,0±1.6)*10^{-2}	2,64*10^{-3}	5,08*10^{-5}

Capture gamma-ray spectra

(E_n =100keV, NLD is GSM (Ignatyuk))



Capture gamma-ray spectra



Conclusion

1. Microscopic approach gives structures for PSF caused by both the PC and QRPA effects.
2. Phonon coupling in E1 PSF is necessary! (M1 ?)
3. On the whole, the QTBA results are in a better agreement with EGLO than with the QRPA values (for stable nuclei !). This fact confirms the necessity of phonon coupling too.
4. Integral characteristics of the pygmy-dipole resonance in ^{68}Ni have been explained within ETFFS and predicted in ^{72}Ni (with a very large % !)
5. For the first time the Γ_γ values have been calculated (10 isotopes) and a good agreement with experiment for (^{116}Sn and ^{62}Ni) has been obtained
6. The approach can predict PSF's in neutron-rich nuclei

Thank you for your attention!

Photoabsorption cross section and strength function S are connected as follows (QPM, ETFFS):

$$\sigma(\omega) = 4.022\omega S(\omega)$$

$$S(\omega) = \frac{dB(E1)}{dE}$$

Two self-consistent approaches

Two self-consistent approaches with small number universal phenomenological parameters:

- self-consistent mean field theories (beginning: parameterizing of the interaction by (usually) Skyrme forces parameters to solve HFB equations)
- energy density functional (EDF) theory (beginning: parameterizing of the functional itself)