On microscopic theory of radiative nuclear reaction characteristics

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Plan

1. Phenomenological approaches
2. Recent experiments (Oslo method, Utsunomia; **Ni, Mo**)
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 Skyrme forces

Reference Input Parameters Library (RIPL2, 2006):

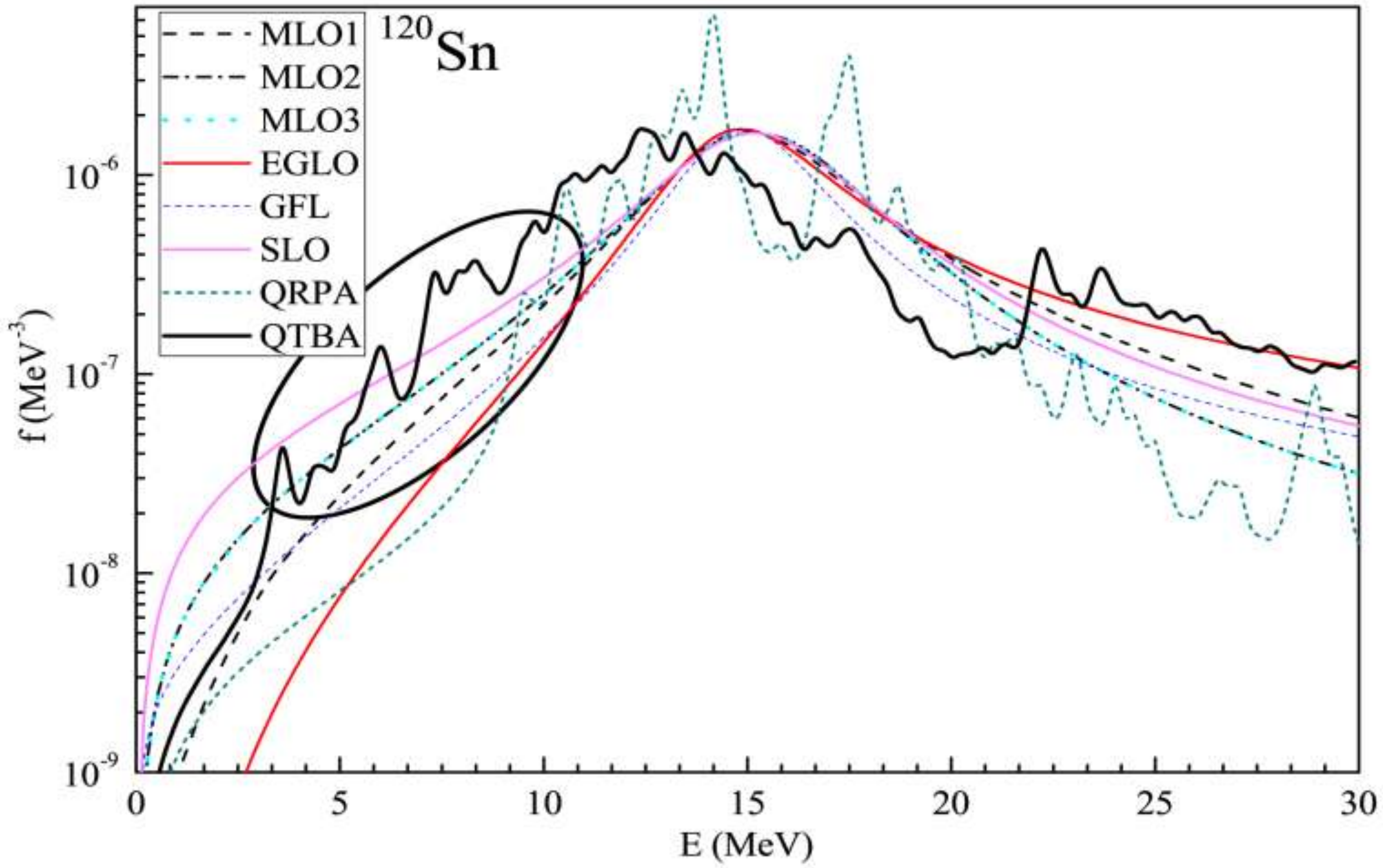
„The Lorentzian and previously described closed-form expressions for the γ-ray strength suffer from various shortcomings:

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. **„This approach lacks reliability when dealing with exotic nuclei.“** 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.

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

However it is not enough !

Photon strength functions: phenomenology vs. microscopy (QRPA and QTBA = QRPA+PC)



Proof of phonon coupling necessity

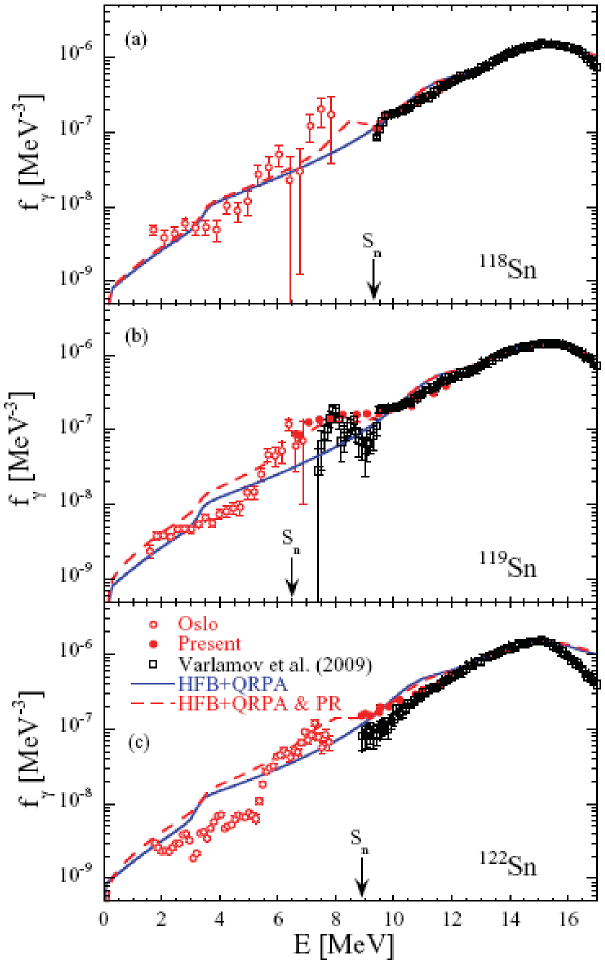


FIG. 10. (Color online) Comparison between the HFB + QRPA strength (with and without the inclusion of the PR) and the experimental data of the Oslo group [9,10], from photodata [18] as well as the present photoemission data, for ^{118}Sn (a), ^{119}Sn (b), and ^{122}Sn (c).

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

This is a direct evidence of necessity of accounting for the phonon coupling, in addition to QRPA, for description of PDR

Low-energy enhancement of magnetic dipole radiation

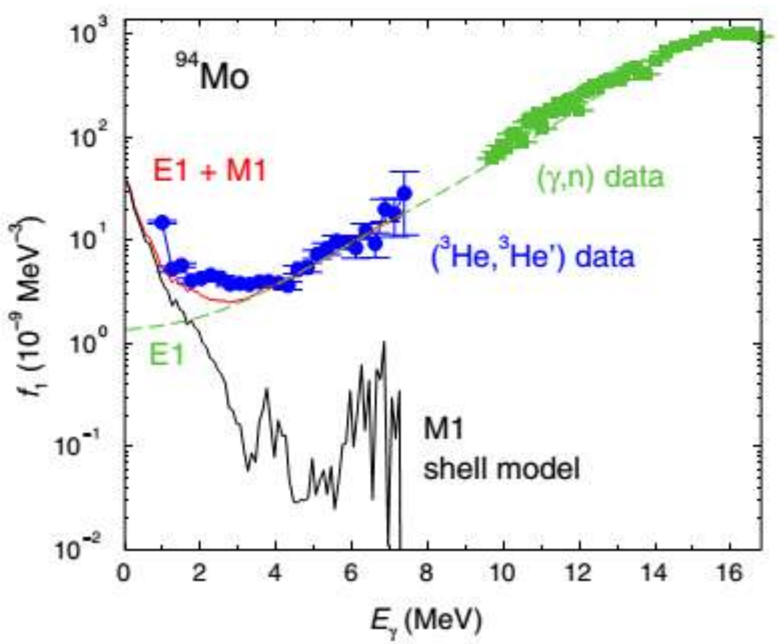


FIG. 1 (color online). Strength functions for ^{94}Mo deduced from (^{3}He, ^{3}He$'$) (blue circles) and (γ, n) (green squares) experiments, the $M1$ strength function from the present shell model calculations (black solid line), $E1$ strength according to the GLO expression with parameters $E_0 = 16.36$ MeV, $\sigma_0 =$ 185 mb, $\Gamma = 5.5$ MeV, $T = 0.35$ MeV (green dashed line), and the total ($E1 + M1$) dipole strength function (red solid line).

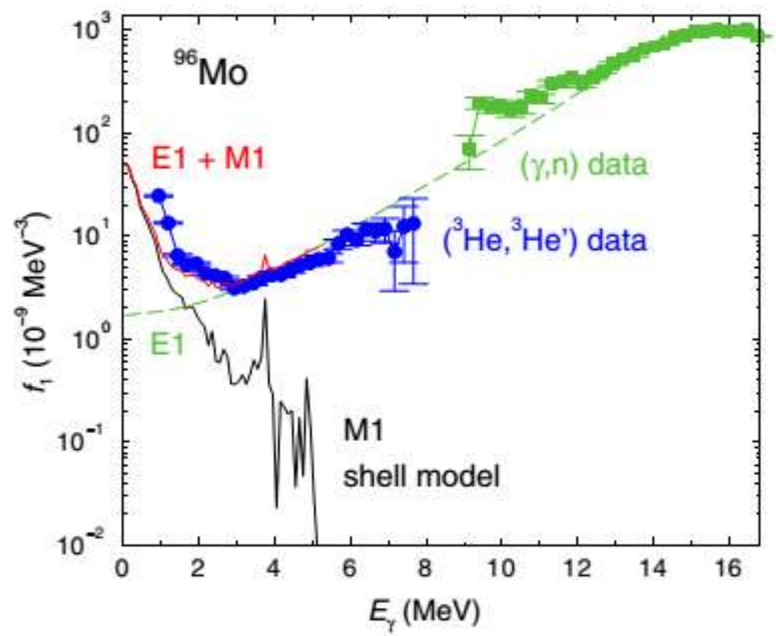


FIG. 3 (color online). As Fig. 1, but for ^{96}Mo.

R. Schwengner, S. Frauendorf, A. C. Larsen;
Phys. Rev. Lett. **111**, 232504 (2013)

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. Kamerdzhiev, Speth, Tertychny, ETFFS[Phys.Rep.2004]

Self-consistent approaches:

4. Self-consistent ETFFS(QTBA) (Avdeenkov, Kamerdzhiev, 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 :

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

3. This effective interactions are used for calculations of phonons

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

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 !

Ours major works:

- S. Kamerdzhiev, J. Speth, and G. Tertychny, Phys. Rep. **393**, 1 (2004).
- A. Avdeenkov, S. Goriely, S. Kamerdzhiev and S. Krewald, Phys. Rev. C **83**, 064316 (2011).
- S. P. Kamerdzhiev, A. V. Avdeenkov, and O. I. Achakovskiy, Phys. At. Nucl. 77, 1303 (2014).

- **O.Achakovskiy, A. Avdeenkov, S. Kamerdzhiev, Proc. Intern. Seminar on Interaction of Nuclei with Nucleons, ISINN22, Dubna, 27-30.05.2014.**

- **O.Achakovskiy, A. Avdeenkov, S. Goriely *et al.*, Phys. Rev. C 91, 034620 (2015)**

- **Kamerdzhiev *et al.*, Accepted to JETPH Lett., June 2015**

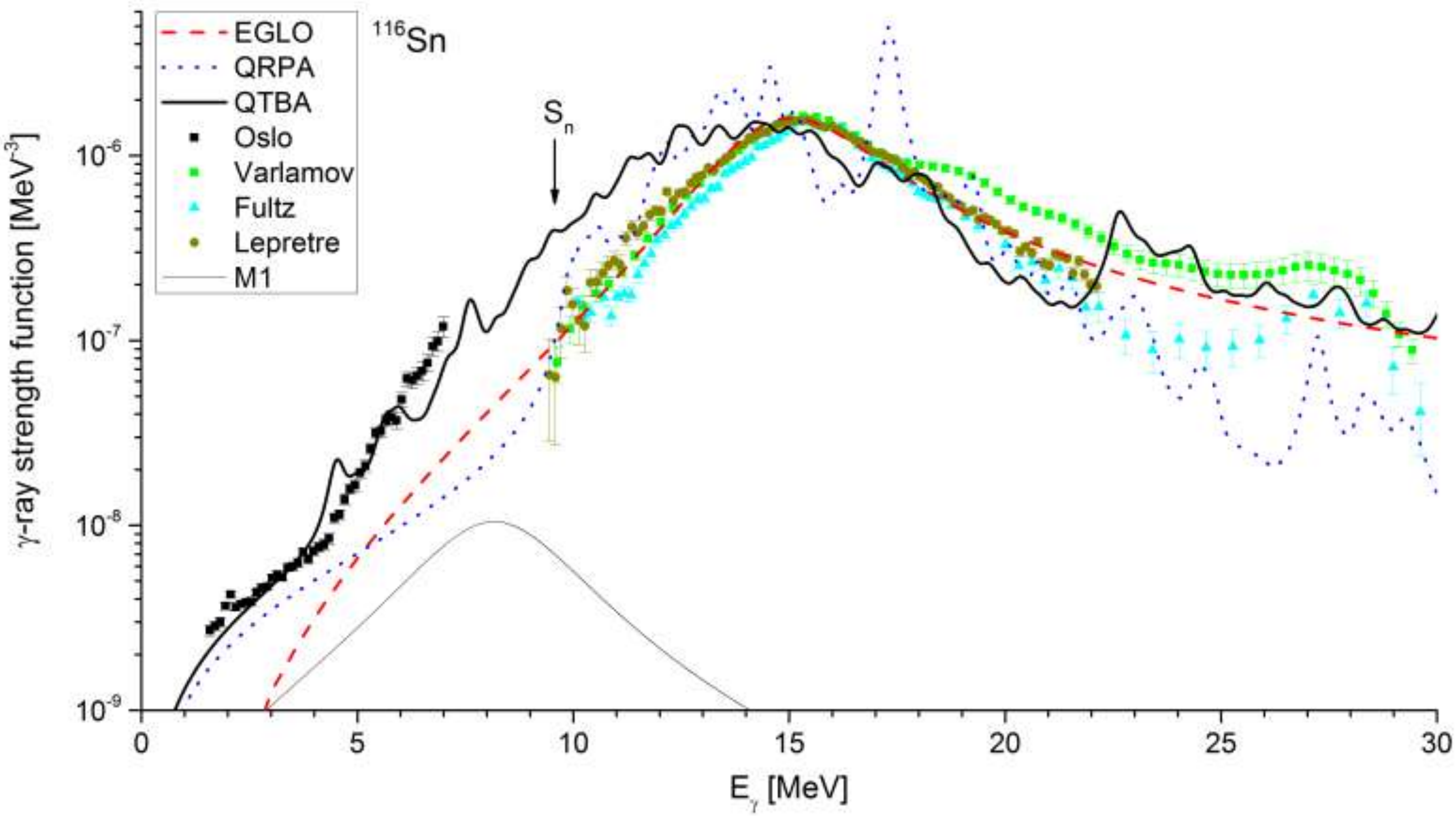
Features of the self-consistent ETFFS(QTBA) approach

- Individual approach to each nucleus due to single-particle and phonon spectra

  Therefore, the PSF structures must exists
- “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, in general, less predictive power as compared with the case when all parameters are taken from experiment !

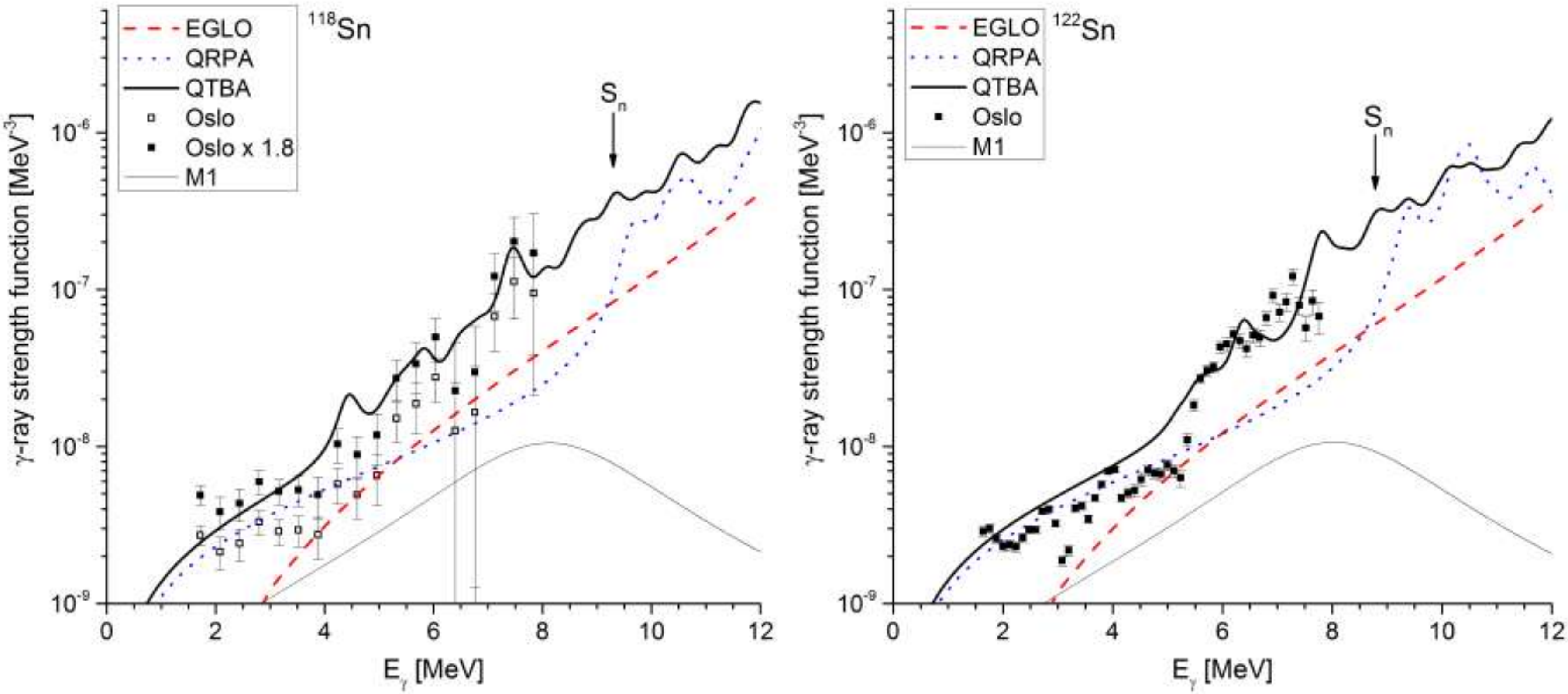
3.Self-consistent calculations :

^{116}Sn PSF (the smoothing parameter is 200 keV)



Exp. data: H. K. Toft *et al.,* PRC **81**, 064311 (2010); Varlamov *et al.,* Vop. At. Nauki i Tekhn., Ser. Yad. Kons. 1-2 (2003); Fultz *et al.,* Phys. Rev. **186**, 1255 (1969); Lepretre *et al.,* Nucl. Phys. A**219**, 39 (1974);

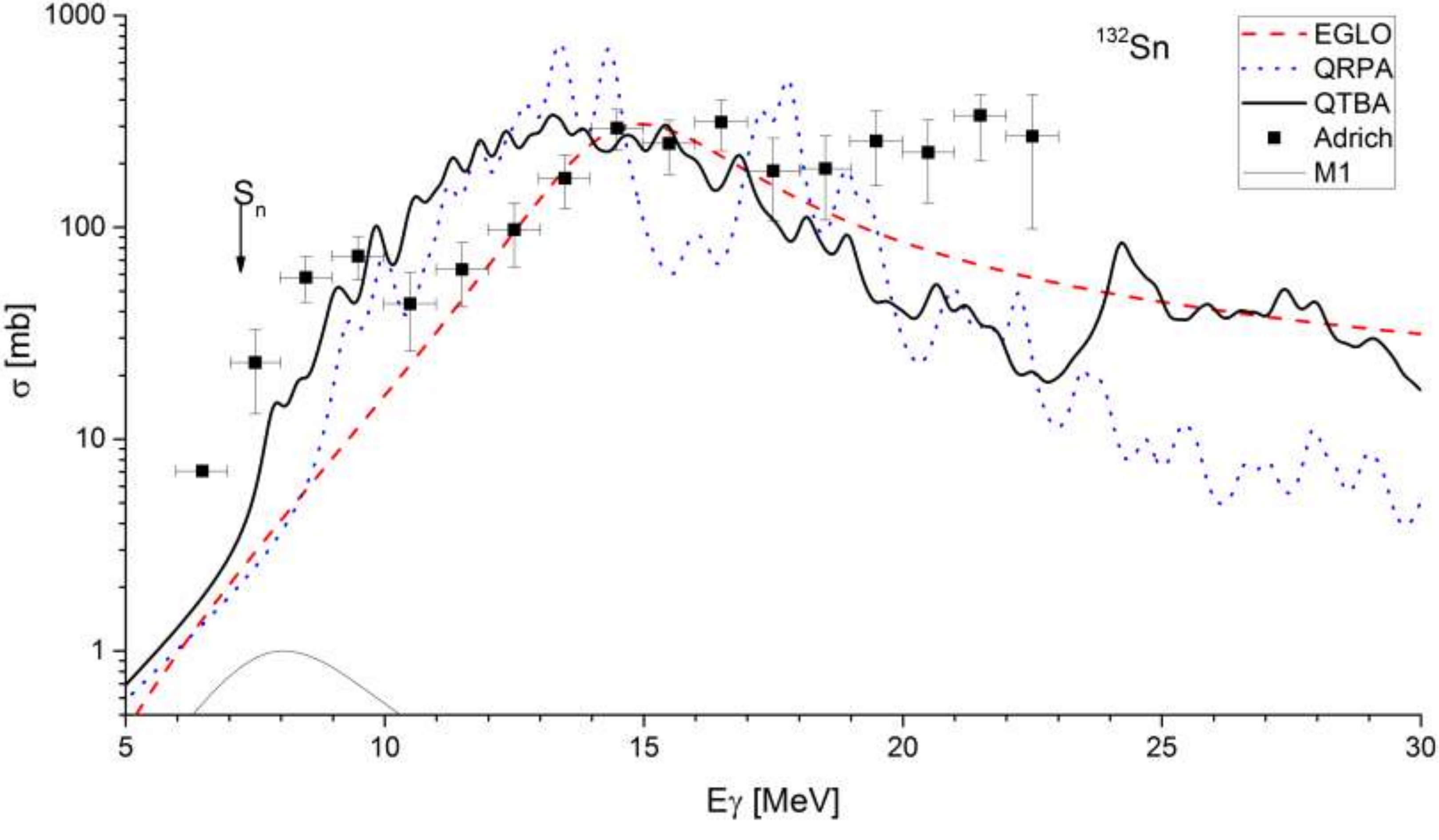
^{118}Sn and ^{122}Sn PSF



An agreement with experimental data at E>5 MeV is only due to PC

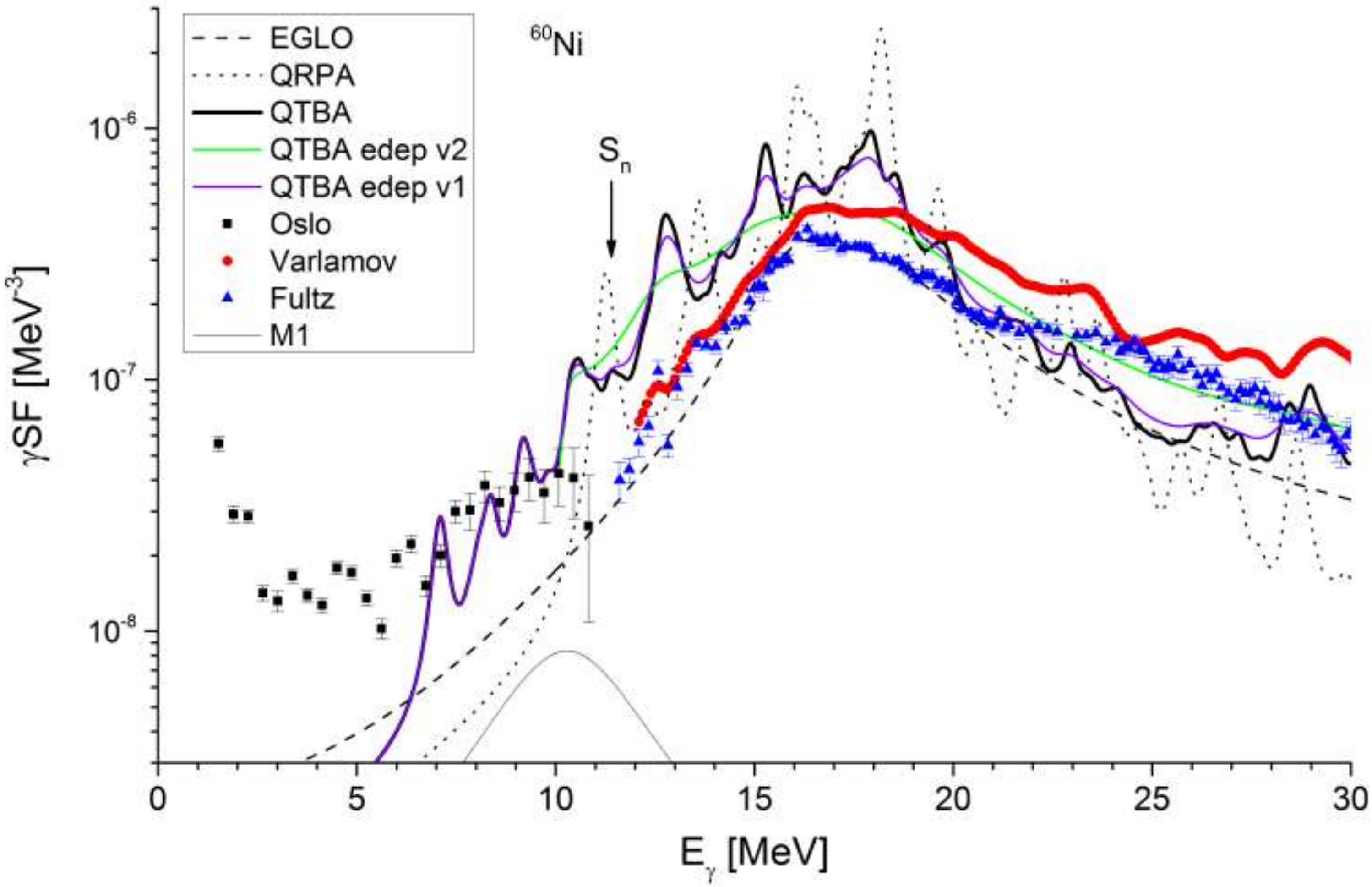
Exp. data: H. K. Toft *et al.*, PRC**81**, 064311 (2010); H. K. Toft *et al.*, PRC**83**, 044320 (2011)

Photoabsorption for double-magic ^{132}Sn



Exp. data: P. Adrich *et al.*, PRL **95**, 132501 (2005)

^{60}Ni PSF (Skyrme SLy5)



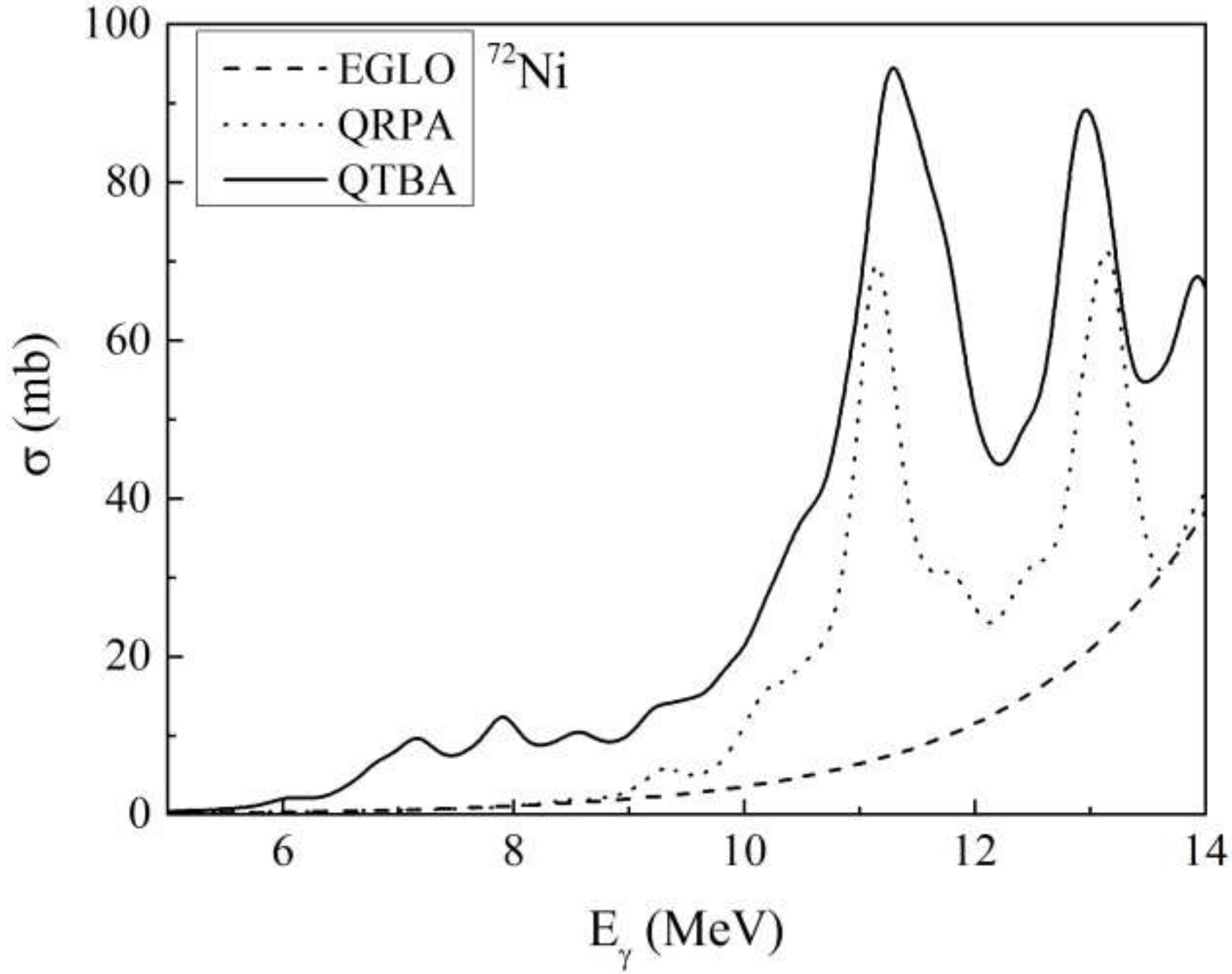
Exp. data: ; V. Varlamov et al., J. Izv., 67, 656, 2003; Fultz et al. PRC 10 608 7408

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

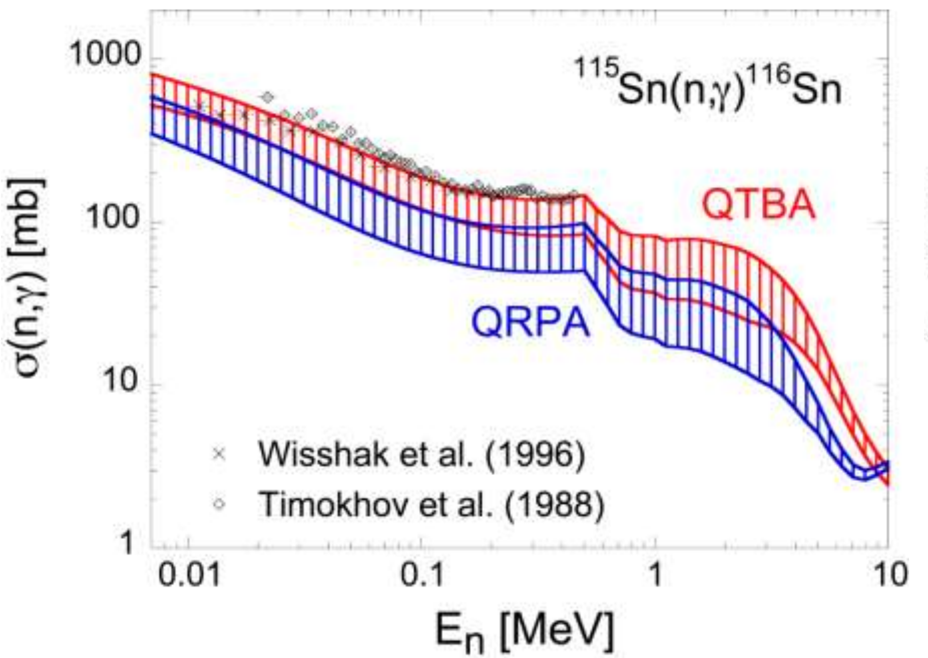
Forces	Interval (0-30) MeV				Interval (7-13) MeV			
	QRPA		ETFFS(QTBA)		QRPA		ETFFS(QTBA)	
	$\langle E \rangle$,MeV	D,MeV	$\langle E \rangle$,MeV	D,MeV	$\langle E \rangle$,MeV	%	$\langle E \rangle$,MeV	%
SLy4	17,48	1,66	18,54	3,97	11,0	4,85	10,75	8,73
BSk17	17,82	1,92	19,03	4,38	10,24	5,32	10,28	6,85
Exp.	[Rossi]		18,1 (5)	6,1 (5)	[Rossi] [Rossi]		10,4 (4) 9,55 (17)	4,1 (1,9) 2,8 (5)
					[Wieland]		≈11	≈5

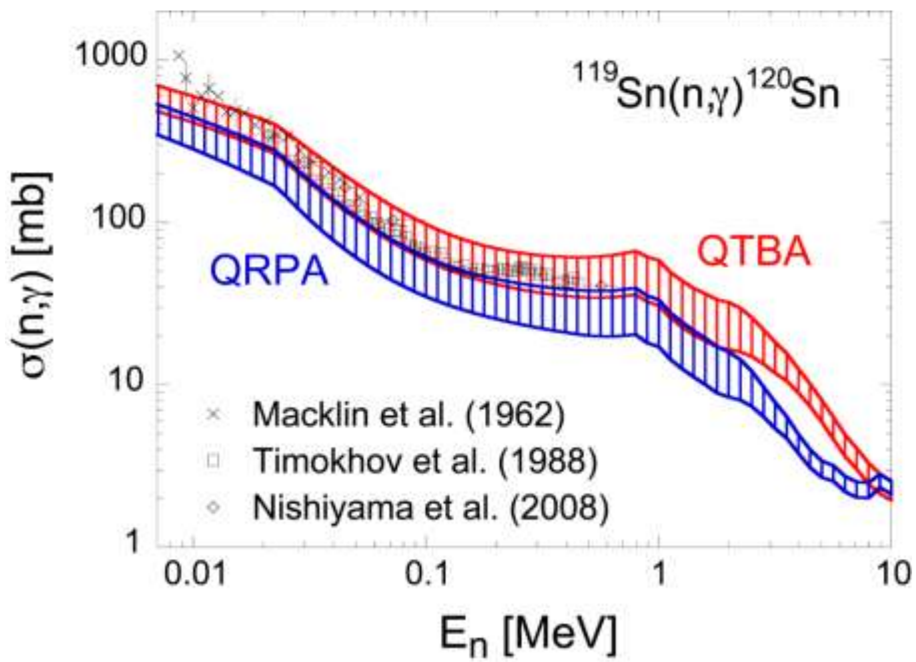
Exp. data: O. Wieland *et al.*, PRL **102**, 092502 (2009); D. M. Rossi *et. al.*, J. Phys. Conf. Ser. **420**, 012072 (2013); D. M. Rossi *et. al.*, J. Phys. Conf. Ser. **420**, 012072 (2013); D. M. Rossi *et. al* PRL**111**, 242503 (2013)

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



4.TALYS calculations of neutron capture cross sections (S.Goriely)





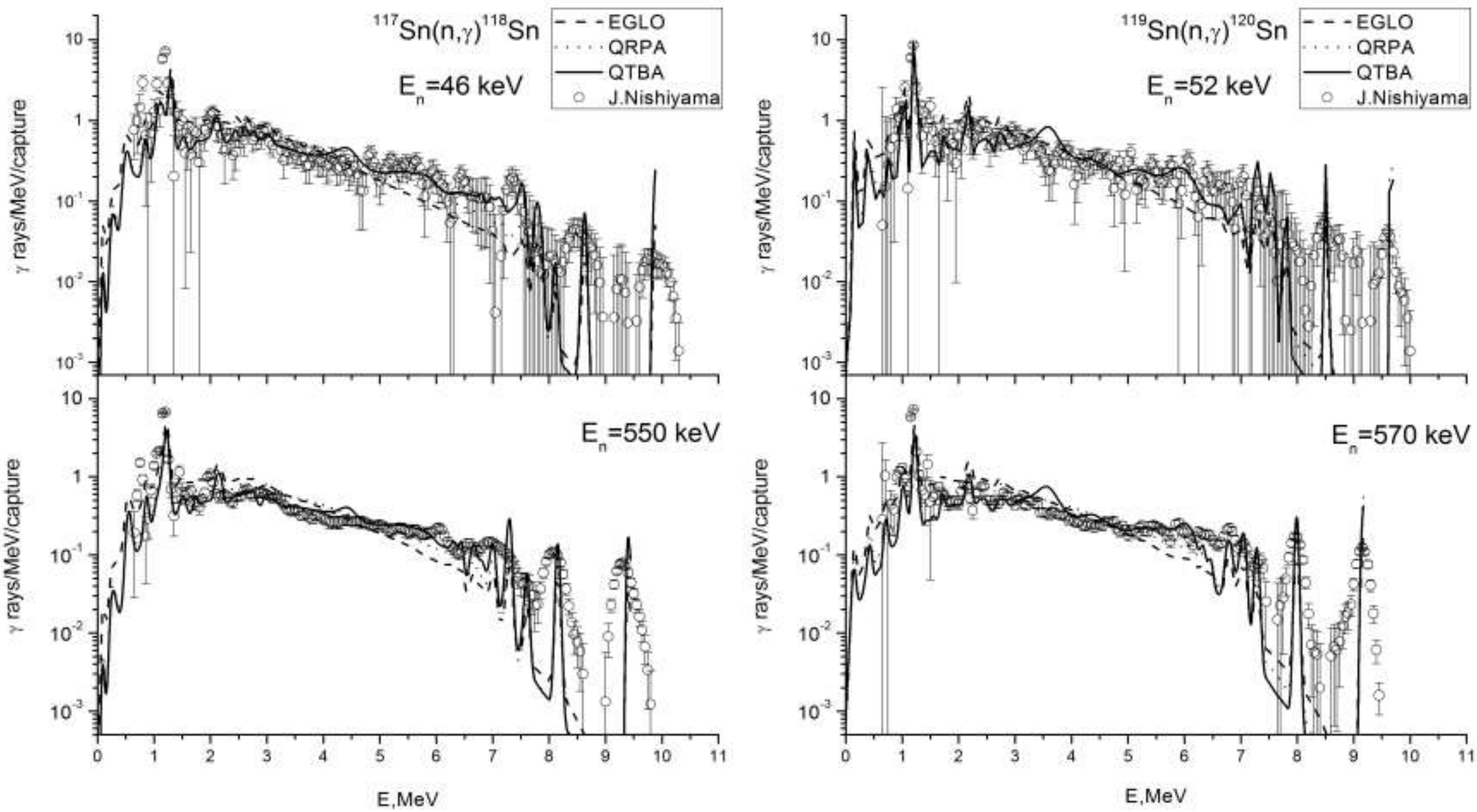
Uncertainty band is due to different NLD's:

- BSFG (A. J. Koning, S. Hilaire, and S. Goriely, Nucl. Phys. A **810**, 13 (2008)
- GSM (RIPL2)
- HFB (S. Goriely, *et al.,* PRC **78**, 064307 (2008))
- HFB (S. Hilaire, M. Girod, S. Goriely, and A. J. Koning, Phys. Rev. C**86**, 064317 (2012))

The agreement with experiment is possible only due to the PC effect

Capture gamma-ray spectra

NLD model is HFB+combinatorial model (S. Goriely, *et al.*, PRC **78**, 064307 (2008))



Exp. data: J.Nishiyama *et al.*, J. Nucl. Sci. Technol. (Tokyo) **45**, 352 (2008)

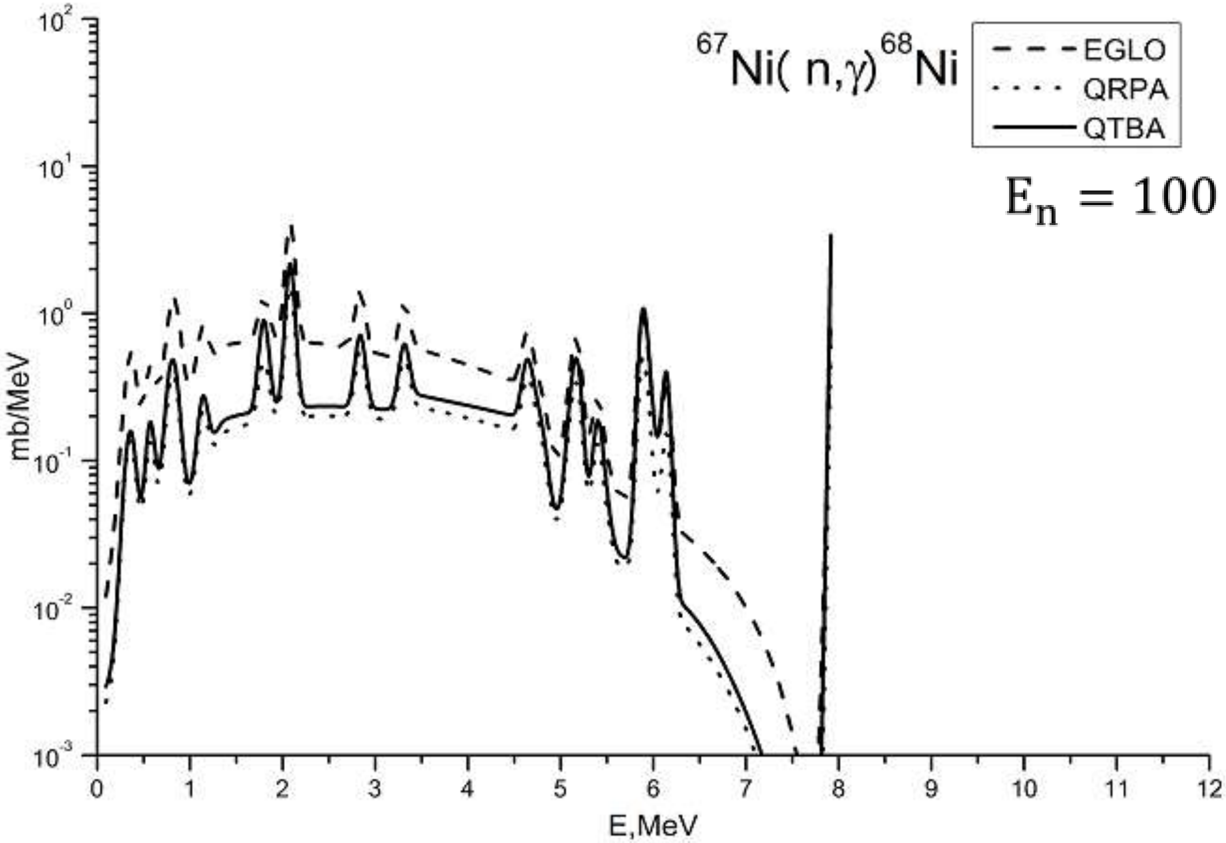
Multiplicity

for GSM NLD model (first line) and HFB NLD model (second line)

	EGLO	QRPA	QTBA	Exp.
117Sn 550 keV	4,03	3,66	3,39	3.45 (9)
	3,48	4,24	3,73	
119Sn 570 keV	3,96	3,55	3,26	3.80 (20)
	4,11	3,59	3,33	
117Sn 46 kev	3,64	3,32	2,99	3.31 (16)
	3,86	3,4	3,12	
119Sn 52 keV	3,57	3,23	2,96	3.66 (19)
	3,74	3,28	3,03	

Exp. data: J.Nishiyama *et al.*, J. Nucl. Sci. Technol. (Tokyo) **45**, 352 (2008)

Capture gamma-ray spectra for ^{68}Ni



$E_n = 100$ kev

NLD model for this case is also HFB+com. model

There is big difference between phenomenological (EGLO) and microscopical (QRPA and QTBA) models since ^{68}Ni is neutron rich nucleus

Average radiative widths for s-neutron

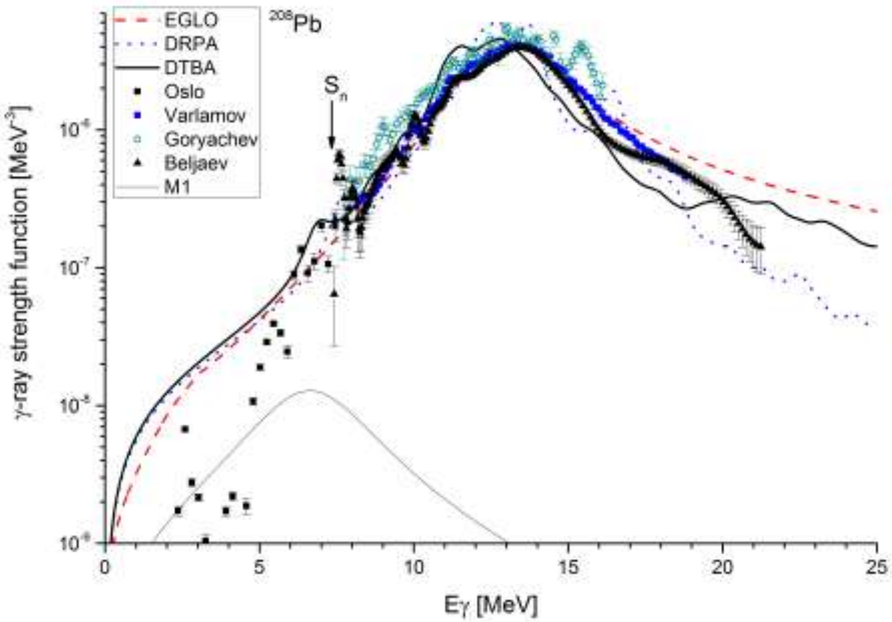
EMPIRE3.1 calculations with microscopic PSF's, GSM model (first line) and HFB NLD model (second line)

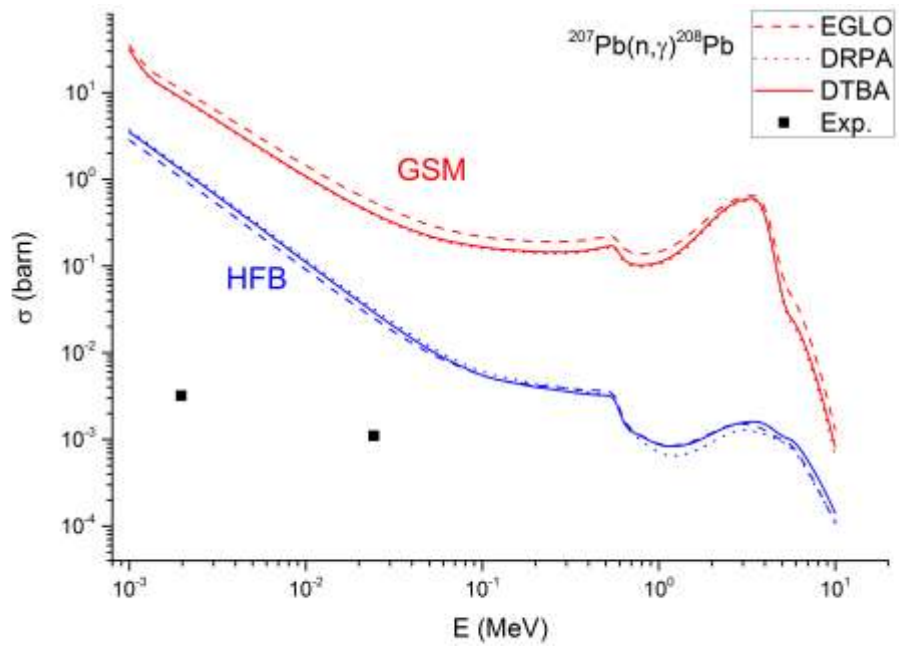
	^{110}Sn	^{112}Sn	^{116}Sn	^{118}Sn	^{120}Sn	^{122}Sn	^{124}Sn	^{136}Sn	^{58}Ni	^{60}Ni	^{62}Ni	^{68}Ni	^{72}Ni
EGLO (E1+M1)	147.4	105.5	72.9	46.6	55.0	56.6	49.9	11.1	1096	474	794	166	134
	207.9	160.3	108.9	106.7	124.3	110.2	128.7	295	2017	1882	1841	982.2	86.4
QRPA (E1+M1)	45.6	34.4	30.4	22.1	23.8	27.9	22.3	11.2	358	594	623	75.4	83.8
	71.0	49.7	44.3	40.3	43.0	50.1	68.9	448	451	1646	491	406	46.7
QTBA (E1+M1)	93.5	65.7	46.8	33.1	34.1	35.8	27.9	12.3	1141	971	1370	392	154
	119.9	87.0	58.4	58.1	61.5	64.0	84.8	509	1264	2800	2117	2330	53.8
Exp.				117 (20) 80 (20)	100 (16)					2200 (700)	2000 (300) 2200 (700)		
M1	13.0	9.6	8.9	6.1	6.6	7.3	4.9	1.3	46.1	32	23.2	36.0	49.6
	29.1	18.1	18.5	13.2	13.4	13.1	15.5	87.2	17.0	52	31.8	81.6	27.5
System.	112	109	107	106	105	104	103	73	2650	1900	1300	420	320

Exp. data: RIPL2 and S. F. Mughabghab, *Atlas of Neutron Resonances, Resonance Parameters and Thermal Cross Sections Z = 1–100* (Elsevier, Amsterdam, 2006)

The double-magic ^{208}Pb

Tselyaev's PSF, smoothing parameter is 400 keV and Skyrme SLy4





N.U.H.Syed *et al.*, PRC **79**, 024316 (2009)

R.C Greenwood et al., PRC,4,2249,1971
O.A.Wasson et al., Rept. USNDC-7 P36

Average radiative widths for double-magic ^{132}Sn and ^{208}Pb (HFB vs. GSM)

		EGLO	QRPA DRPA	QTBA DTBA	System.	M1 contribution
^{132}Sn	GSM	398	133	148		40.9
	HFB	4444	4279	4259		340.7
^{208}Pb	GSM	10.56	7.80	8.24	5070 3770	0.79
	HFB	2733.7	3647.8	3417.1		5.25

For ^{208}Pb D_0^{GSM} =0.00441 keV; D_0^{HFB} =37.6 keV; $D_0^{exp.}$ =30 (8) keV

Here we see that GSM NLD model isn't suitable for double-magic nuclei in contrast HFB NLD model!

Exp. data and system. : S. F. Mughabghab, *Atlas of Neutron Resonances, Resonance Parameters and Thermal Cross Sections Z = 1–100* (Elsevier, Amsterdam, 2006)

Conclusion

1. Microscopic approach gives structures for PSF caused by both the PC and QRPA effects.
2. Phonon coupling in E1 PSF is necessary!
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 (15 isotopes) and a good agreement with the available experiment for (^{118,120}Sn and ^{60,62}Ni) has been obtained
6. The QTBA approach can predict PSF's more reliably than QRPA and can be used in neutron-rich nuclei
7. The **GSM NLD model** is not suitable for double-magic nuclei
8. **M1- ? –**phenomenology ?, new results at E<4 MeV ?

Thank you for your attention and support!

Proof of phonon coupling necessity

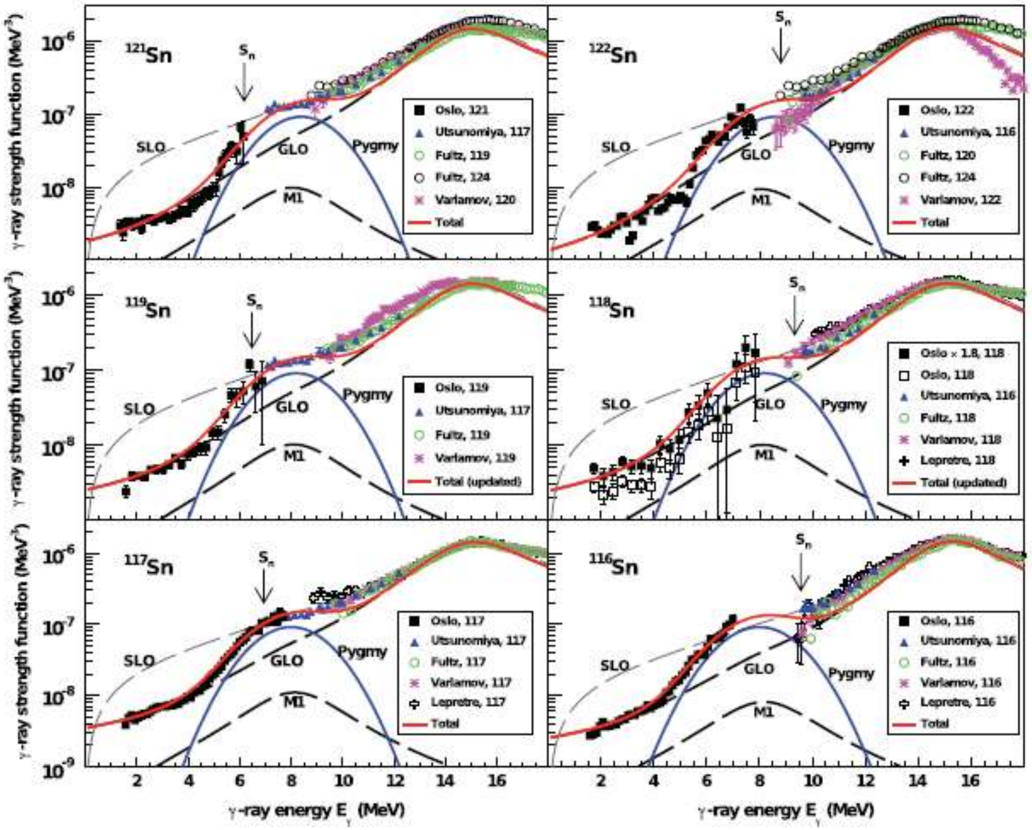


Fig. 25. Comparison of experimental data from the Oslo group (low-energy part) and other experiments with predictions for the γ-ray strength function. The inclusion of a E1 PDR around 8–8.6 MeV is necessary to explain the measured data.
Source: Reprinted figure with permission from [174].

These Oslo results have shown some additional strength in addition to the standard phenomenological models

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

Definition of smearing parameter (Phys.Rep. 2004)

$$S(\omega, \Delta) = -\frac{1}{\pi} \operatorname{Im} \sum_{12} e_q V_{21}^{0*} \rho_{12}(\omega + \mathrm{i}\Delta)$$

Ours major works

- S. Kamerdzhiev, J. Speth, and G. Tertychny, Phys. Rep. **393**, 1 (2004).
- A. Avdeenkov, S. Goriely, S. Kamerdzhiev and S. Krewald, Phys. Rev. C **83**, 064316 (2011).
- S. P. Kamerdzhiev, A. V. Avdeenkov, and O. I. Achakovskiy, Phys. At. Nucl. 77, 1303 (2014).
- O.Achakovskiy, A. Avdeenkov, S. Kamerdzhiev, Proc. Intern. Seminar on Interaction of Nuclei with Nucleons, ISINN22, Dubna, 27-30.05.2014.
- O.Achakovskiy, A. Avdeenkov, S. Goriely *et al.*, Phys. Rev. C **91**, 034620 (2015)

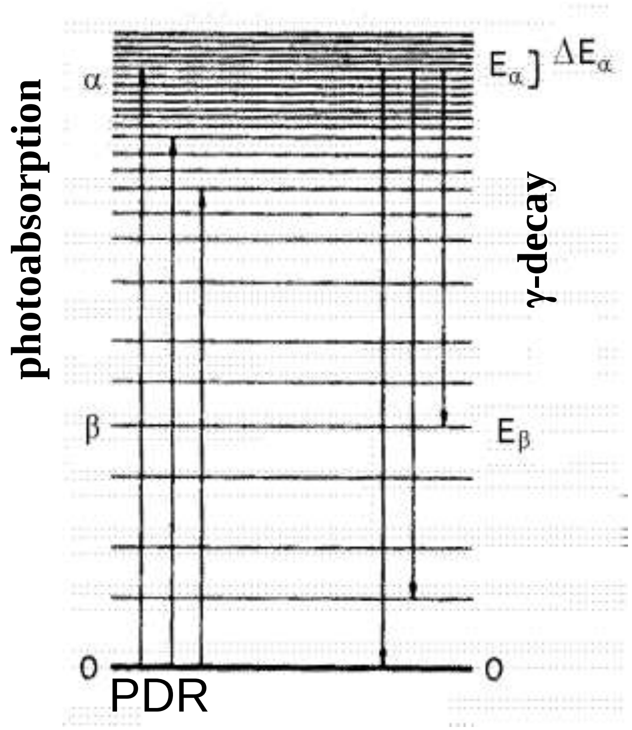
Formula for integrated features (mean energy and width)

$$\langle E \rangle = E_{1,0} = \frac{m_1}{m_0}, \quad D = \sqrt{\frac{m_2}{m_0} - \left(\frac{m_1}{m_0}\right)^2}$$

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 …}



The wave function must contain simple (1p1h) and complex 1p1h⊗phonon configurations :

$$\Psi_i = \underbrace{\sum_{1,2} c^i_{12}\varphi^*_1\varphi_2}_{\text{(Q)RPA}} + \underbrace{\sum_{1,2,s} c^i_{12s}\varphi^*_1\varphi_2\Phi_s}_{\text{Phonon coupling}}$$

where φ – s.p. wave function, Φ_s - phonon wave function

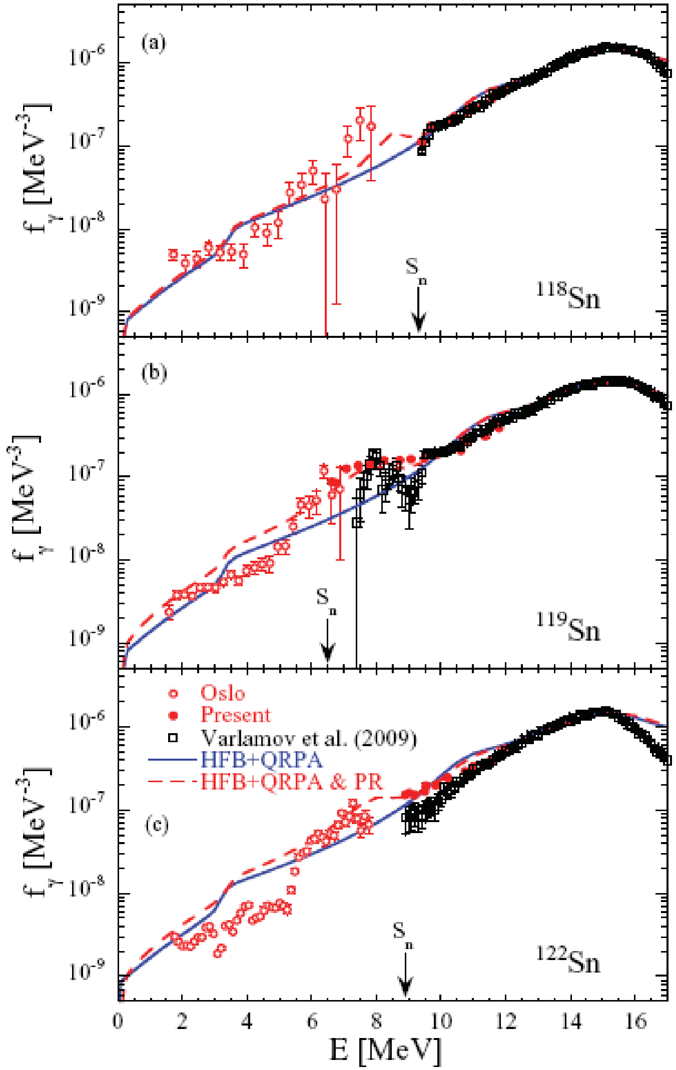
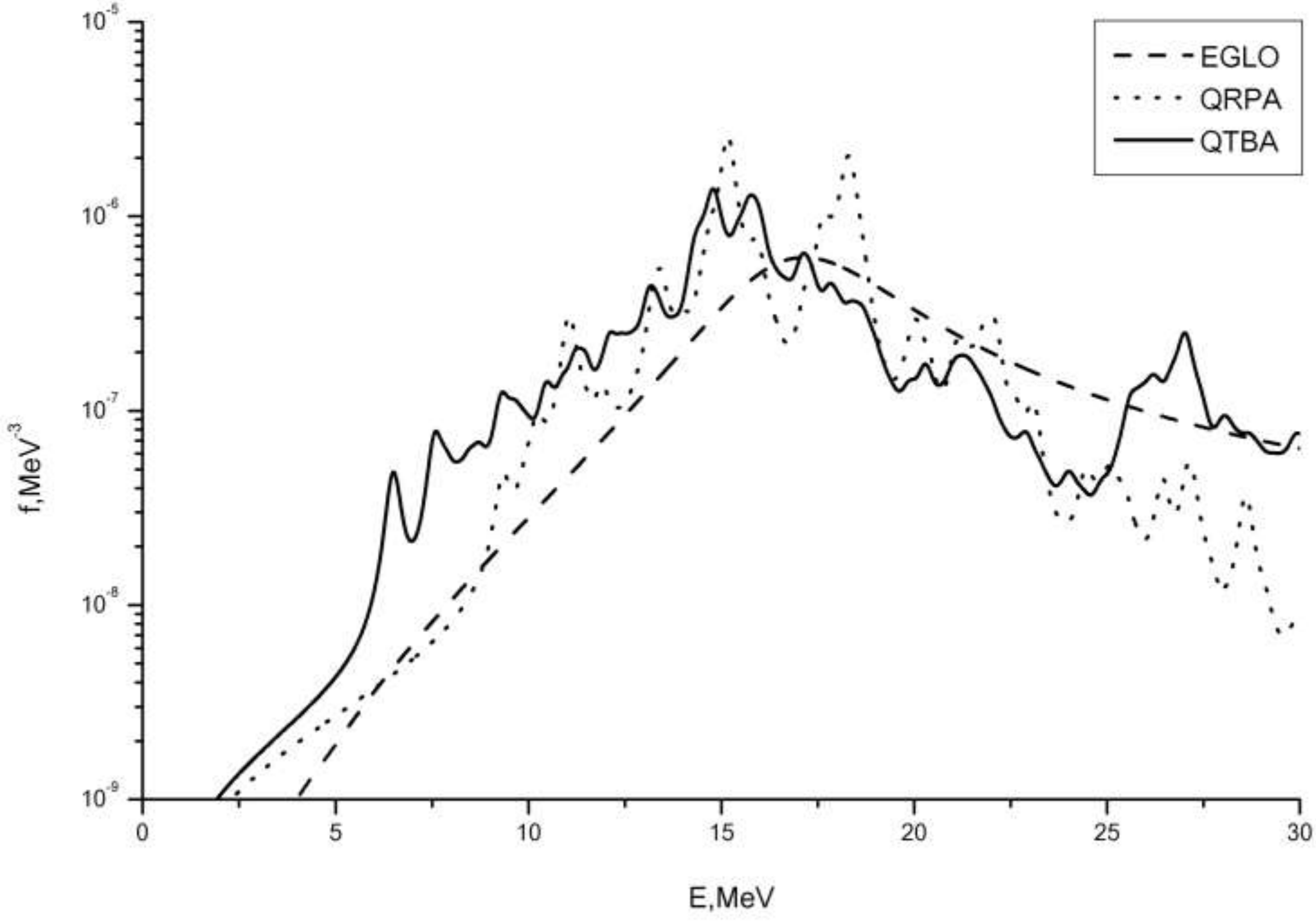


FIG. 10. (Color online) Comparison between the HFB + QRPA strength (with and without the inclusion of the PR) and the experimental data of the Oslo group [9,10], from photodata [18] as well as the present photoemission data, for ^{118}Sn (a), ^{119}Sn (b), and ^{122}Sn (c).

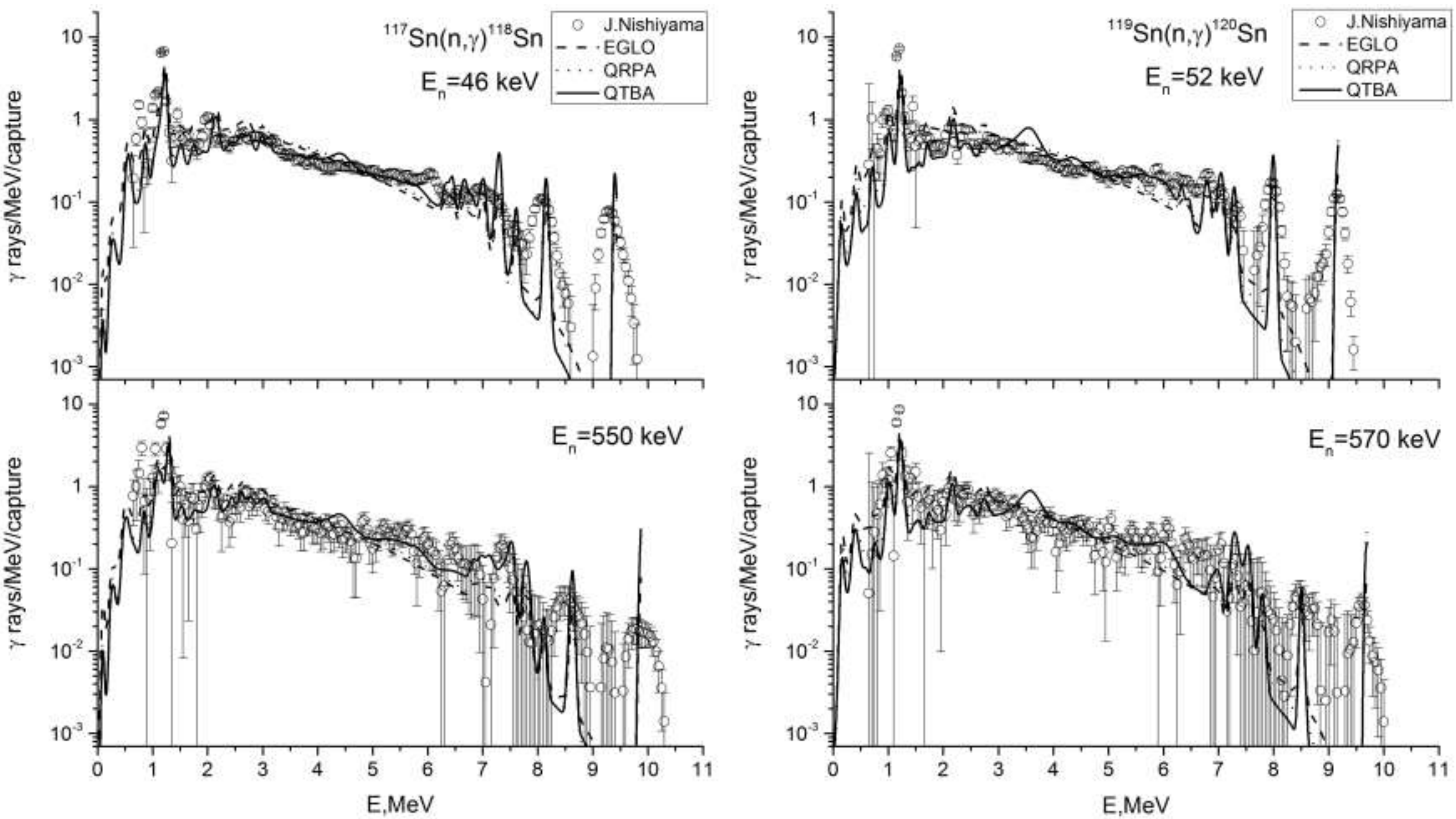
Utsunomiya, Goriely et al., PRC 84, 055805(2011)

^{68}Ni PSF



Capture gamma-ray spectra

NLD is GSM (RIPL2)



Average radiative widths

$$\Gamma_\gamma\left(I_t \pm \tfrac{1}{2}, \Pi_t\right) = \frac{1}{2\rho\left(B_n, I_t \pm \frac{1}{2}, \Pi_t\right)} \int_0^{B_n} d\varepsilon_\gamma \varepsilon_\gamma{}^3 \left(f_{E1}(\varepsilon_\gamma) + f_{M1}(\varepsilon_\gamma)\right) \times \sum_{J=-1}^{1} \rho\left(B_n - \varepsilon_\gamma, I_t \pm \tfrac{1}{2} + J\right)$$

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

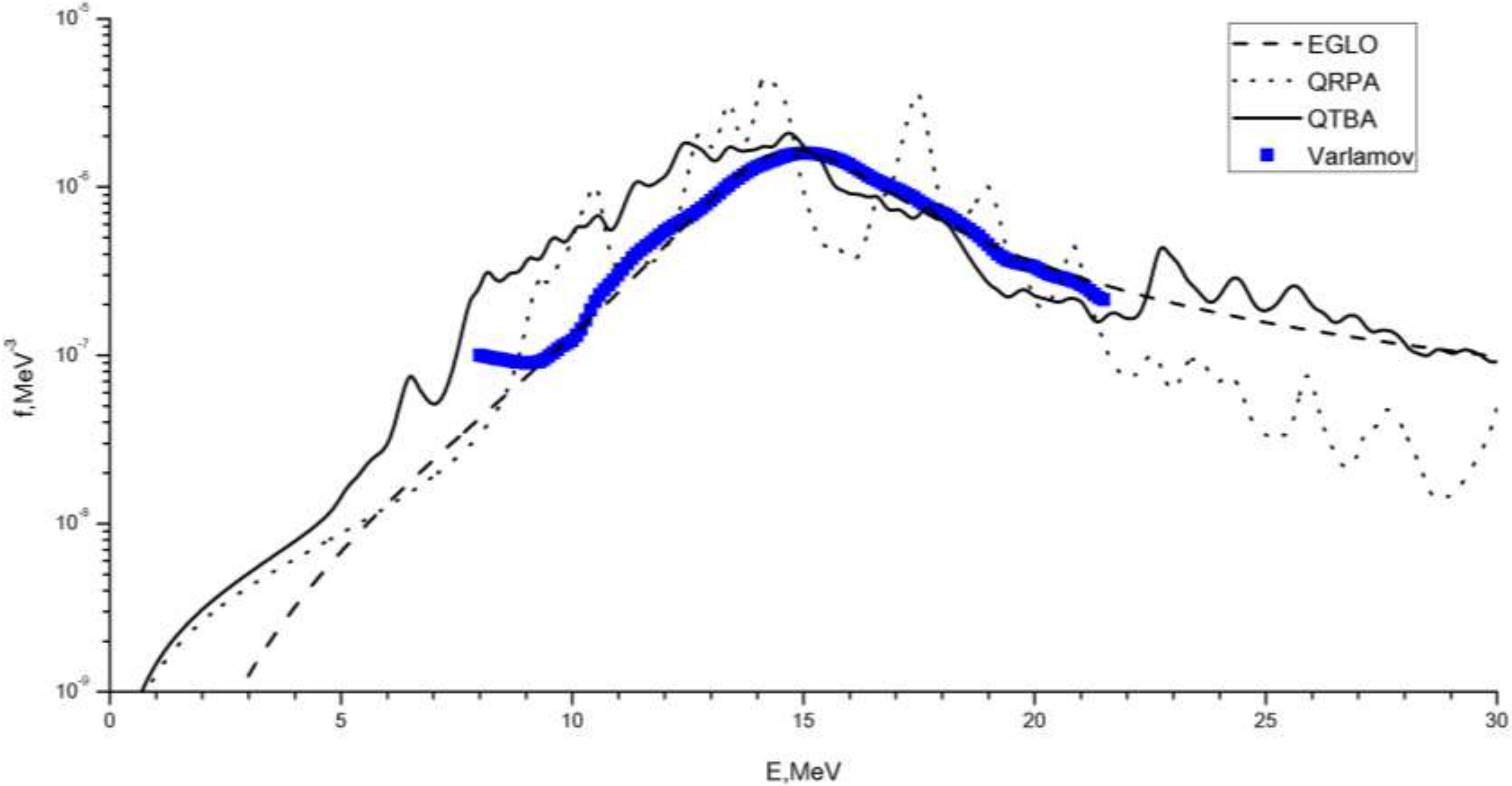
$$\sigma_{n\gamma} \cong \frac{C\pi^2 \lambda_n{}^2}{2I_0 + 1} \frac{\Gamma_\gamma}{D_{0s}}$$

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

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

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

^{124}Sn PSF



In all Sn isotopes considered there is some additional strength due to PC around 8 MeV in according to [Toft]

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)

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

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:

{Isaak,...,Ka-ev !,..., Phys.Rev.C83,034304 (2011) –PDR in 44Ca}

!+4. Relativistic QTBA (Ring, Tselyaev, Litvinova)

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 ...}

The microscopic description is necessary for neutron-rich nuclei, where phenomenological approaches are non-applicable

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

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Dresden (25-29.08.14)