Relativistic many-body models for nuclear structure and astrophysics

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NSCL MICHIGAN STATE UNIVERSITY

NAVI/JINA Collaboration meeting, 2012

A consistent microscopic description

❖ Degrees of freedom
relevant for a description of nuclear dynamics
at ~1-50 MeV excitation energies:
single-particle & collective (vibrational, rotational);
coupling: NO complete separation of the scales!

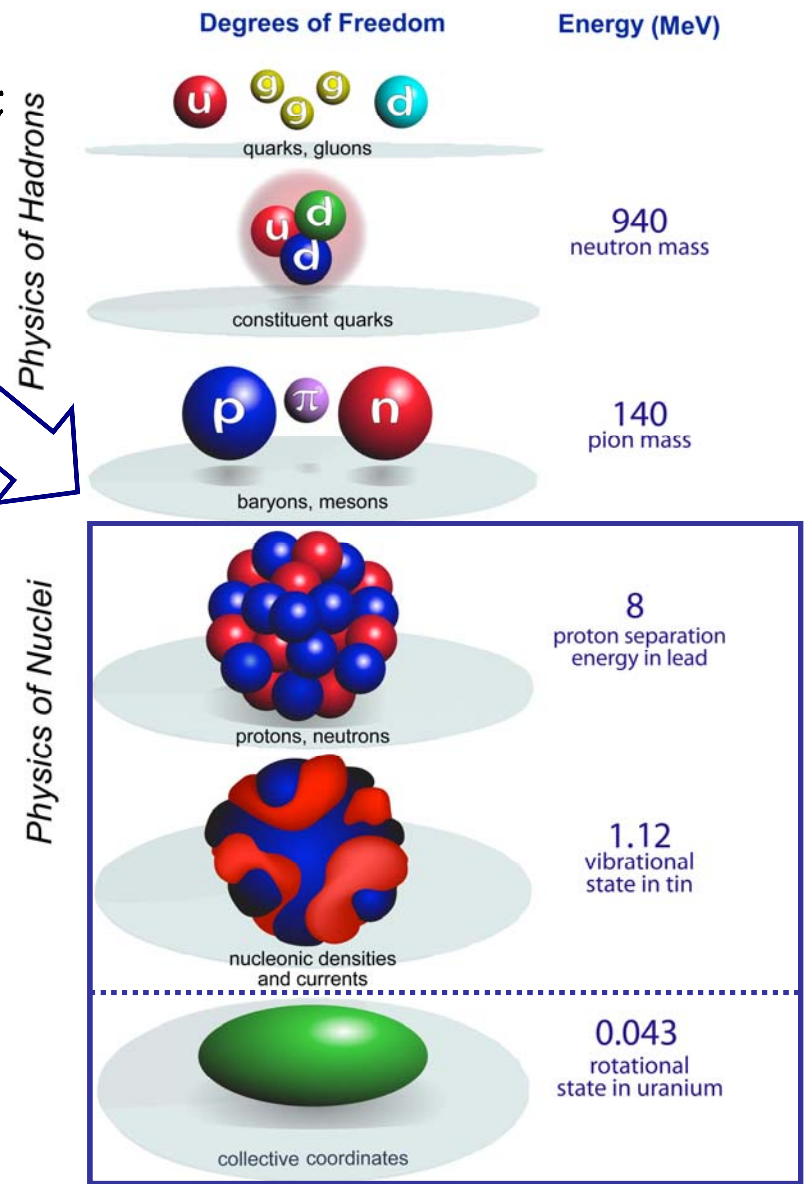
❖ Symmetries -> Lagrangian
->Working basis: mean field,
energy density functional theory
(present work – CDFT)

❖ Beyond static approximation:
energy-dependent nucleonic self-energy:
particle-vibration coupling
(Nuclear field theory, Landau-Migdal theory
of Fermi systems, quasiparticle-phonon model, ...)

❖ Towards spectroscopic accuracy:
Nuclear spectral properties

- Nuclear single-particle structure
- Gross and fine structure of nuclear excited states: giant resonances, soft modes

Separation of the scales

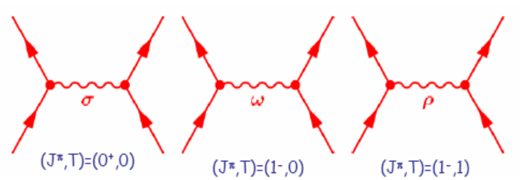


Correlations: beyond mean field and beyond QRPA effects

I. Mean field or energy density functional theory (EDFT)

Covariant EDFT (P.Ring et al.)

The nuclear fields are obtained by coupling the nucleons through the exchange of effective mesons through an effective Lagrangian.



$$S(\mathbf{r}) = g_\sigma \sigma(\mathbf{r}) \qquad V(\mathbf{r}) = g_\omega \omega(\mathbf{r}) + g_\rho \vec{\tau}\vec{\rho}(\mathbf{r}) + eA(\mathbf{r})$$

Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive

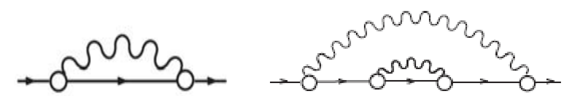
Rho-meson: isovector field

E[R] (7-9 parameters)

Self-consistent Extensions

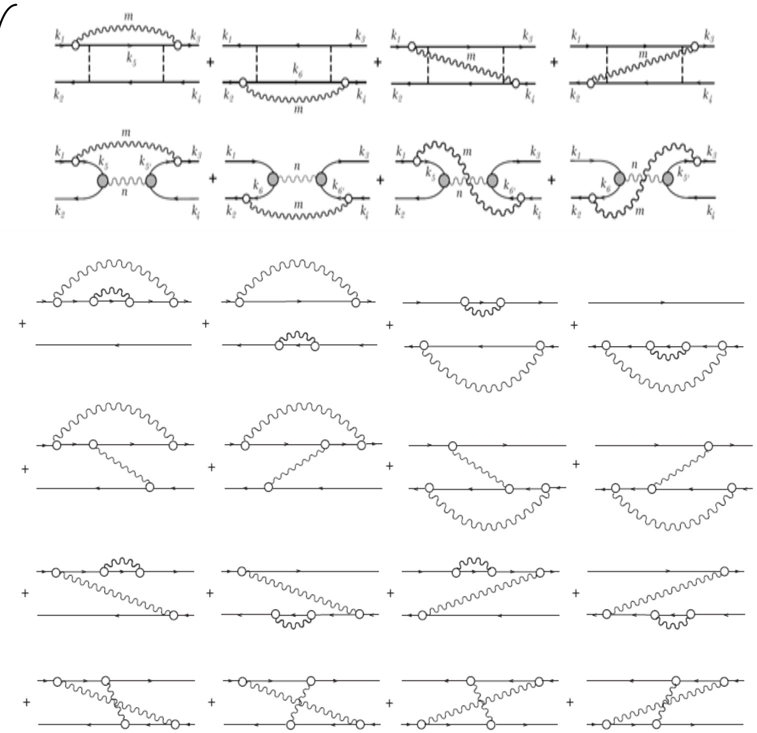
II. „Correlations“: Quasiparticle-vibration Coupling and NpNh correlations derived SC by field theory technique (Nuclear field theory, ext. Landau-Migdal theory)

Single-particle motion: (s.p. levels, spectroscopic factors)



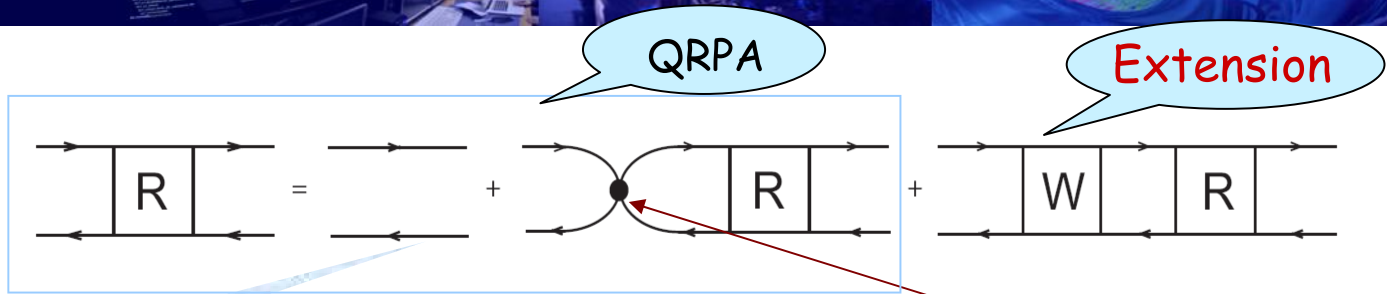
Nuclear Response:

(Excitation spectra of collective and non-collective nature

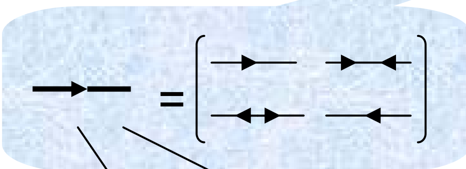


Excited states: nuclear response function

Bethe-Salpeter Equation (BSE):



E.L., V. Tselyaev,
PRC 75, 054318 (2007)

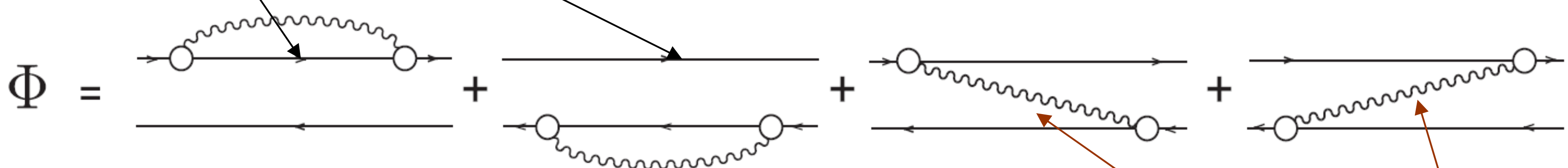


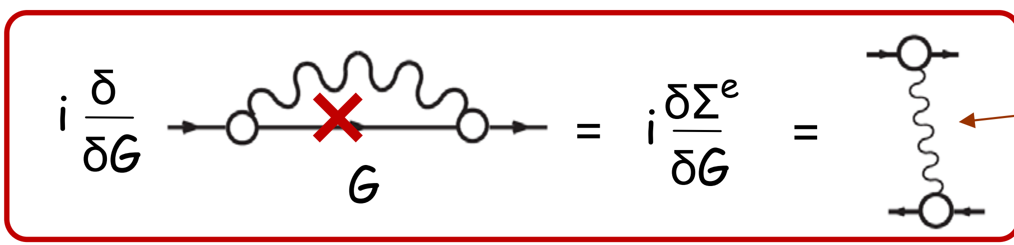
$$V = \frac{\delta \Sigma^{RMF}}{\delta \rho}$$

Self-consistency

$$R(\omega) = A(\omega) + A(\omega)\left[V + W(\omega)\right] R(\omega)$$

$$W(\omega) = \Phi(\omega) - \Phi(0)$$

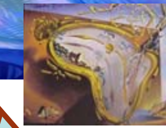




$$U^e = i\,\frac{\delta \Sigma^e}{\delta G}$$

Consistency on 2p2h-level

Time blocking

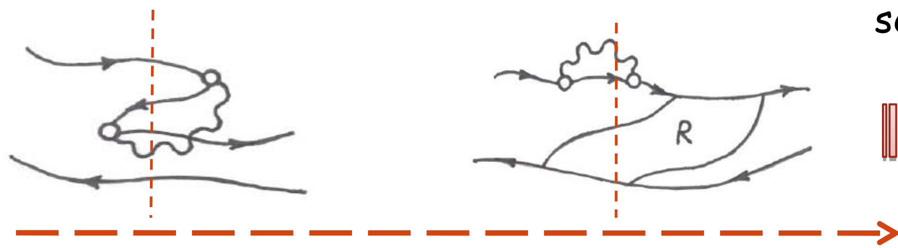


Problem:

'Melting' diagrams

3p3h

NpNh



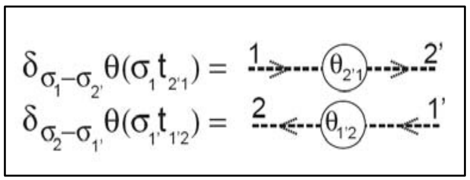
Time

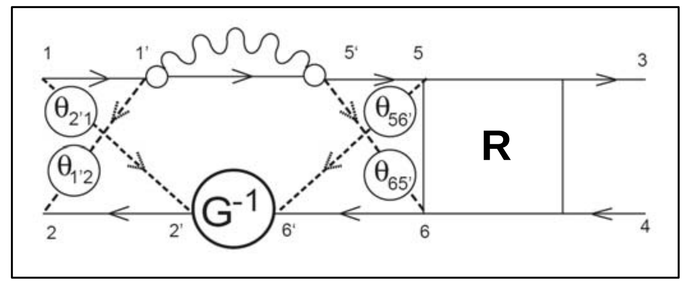
Approx. schemes

Unphysical result:
negative
cross sections

Solution:

Time-projection operator:

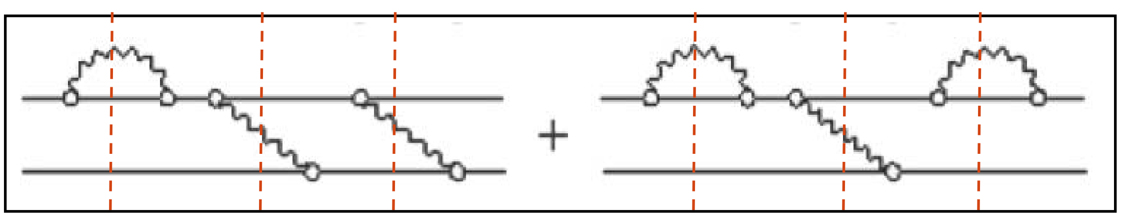




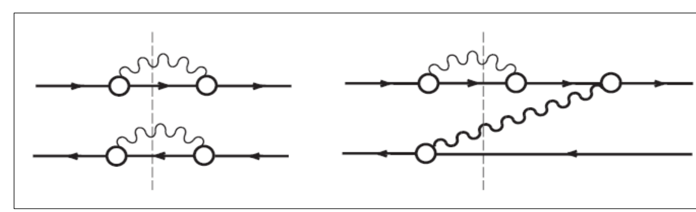
Partially fixed

V.I. Tselyaev,
Yad. Fiz. 50,1252 (1989)

Allowed terms: 1p1h, 2p2h



Blocked terms: 3p3h, 4p4h,...



Time blocking approximation =
= „one-fish" approximation!

- Separation of the integrations in the BSE kernel
- R has the correct pole structure (spectral representation)
  »» Strength function is positive definite!

Response to an external field: strength function

Strength function:

$$S(E) = -\frac{1}{\pi} \lim_{\Delta \to +0} Im\, \Pi_{PP}(E + i\Delta)$$

Polarizability:

$$\Pi_{PP}(\omega) = P^{\dagger} R(\omega) P := \sum_{k_1 k_2 k_3 k_4} P^{*}_{k_1 k_2} R_{k_1 k_4, k_2 k_3}(\omega) P_{k_3 k_4}$$

External field

Transition density:

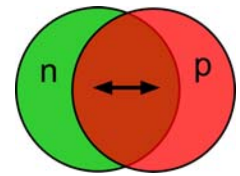
$$\rho^{\nu}_{k_1 k_2} = \langle 0 | \psi^{\dagger}_{k_2} \psi_{k_1} | \nu \rangle$$

Response function:

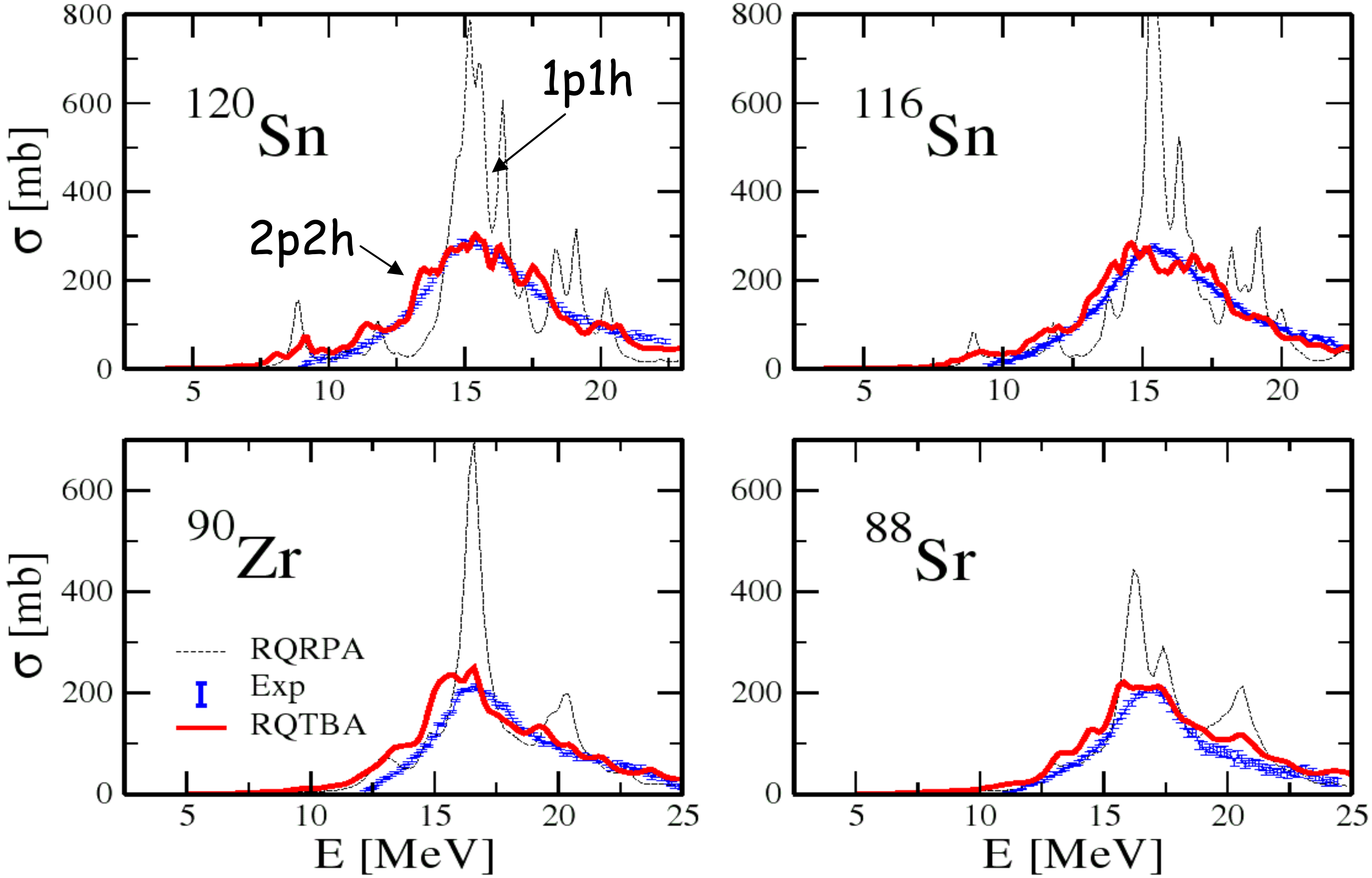
$$R^{\nu}_{k_1 k_4, k_2 k_3}(\omega) \approx \frac{\rho^{\nu}_{k_1 k_2} \rho^{\nu *}_{k_3 k_4}}{\omega - \Omega^{\nu}} \qquad \omega \longrightarrow \Omega^{\nu}$$

Giant Dipole Resonance
within Relativistic Quasiparticle Time Blocking Approximation (RQTBA)*

$$P = \sum_{i=1}^{A}\left(\tau_z^{(i)} - \frac{N-Z}{2A}\right) r_i Y_{1M}(\hat{\vec{r}}_i)$$

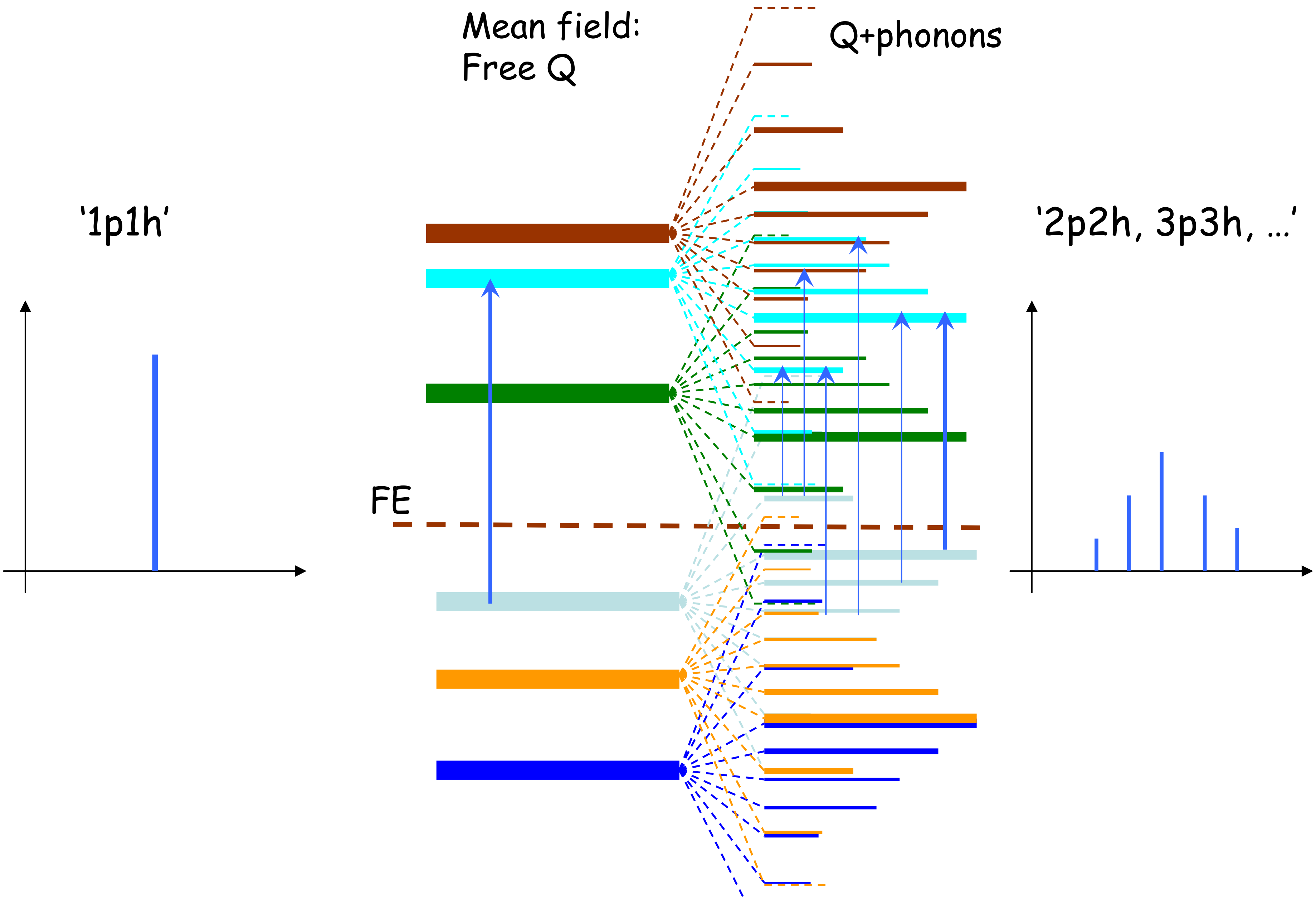


$\Delta L = 1$
$\Delta T = 1$
$\Delta S = 0$

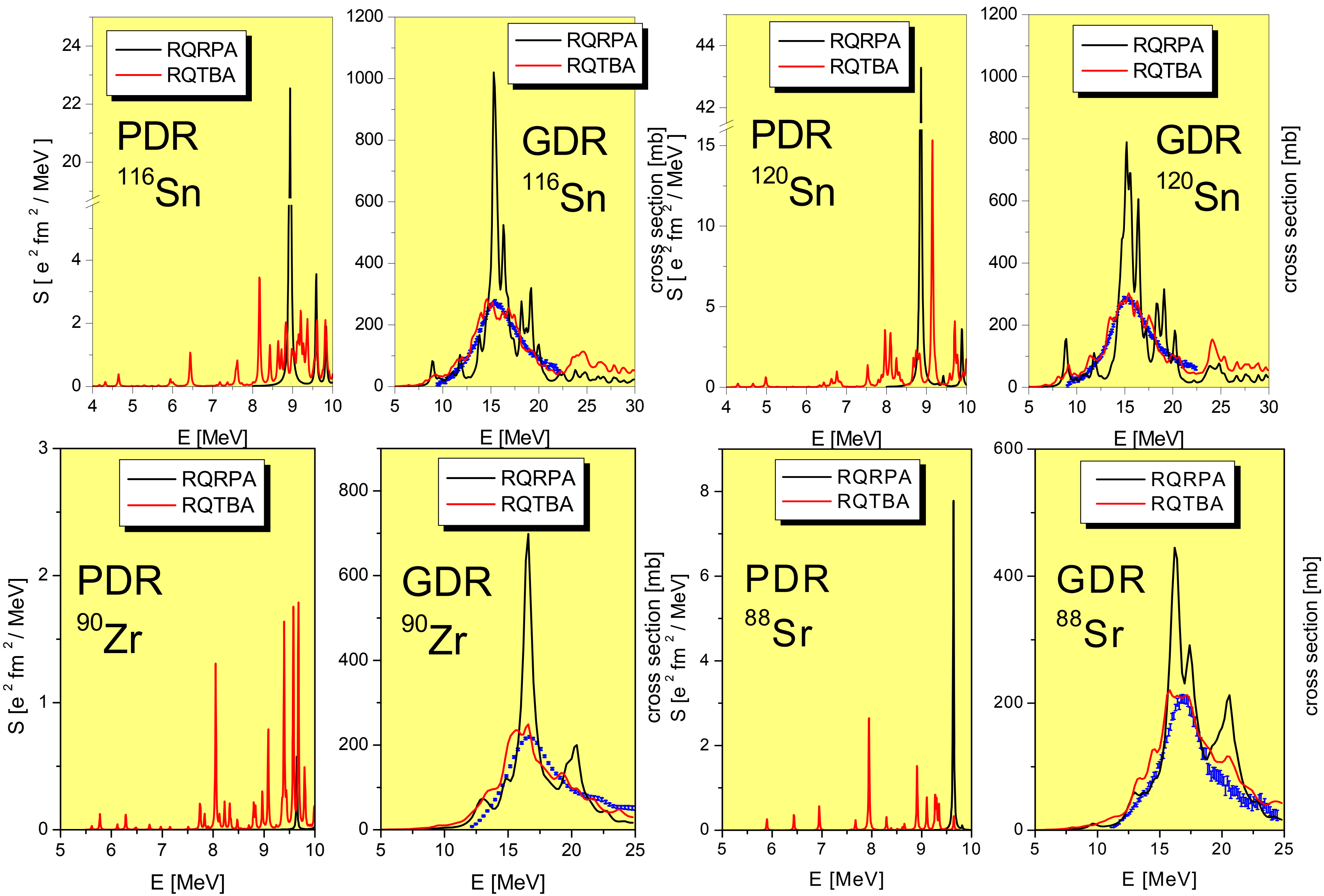


*E. L., P. Ring, and V. Tselyaev,
Phys. Rev. C 78, 014312 (2008)

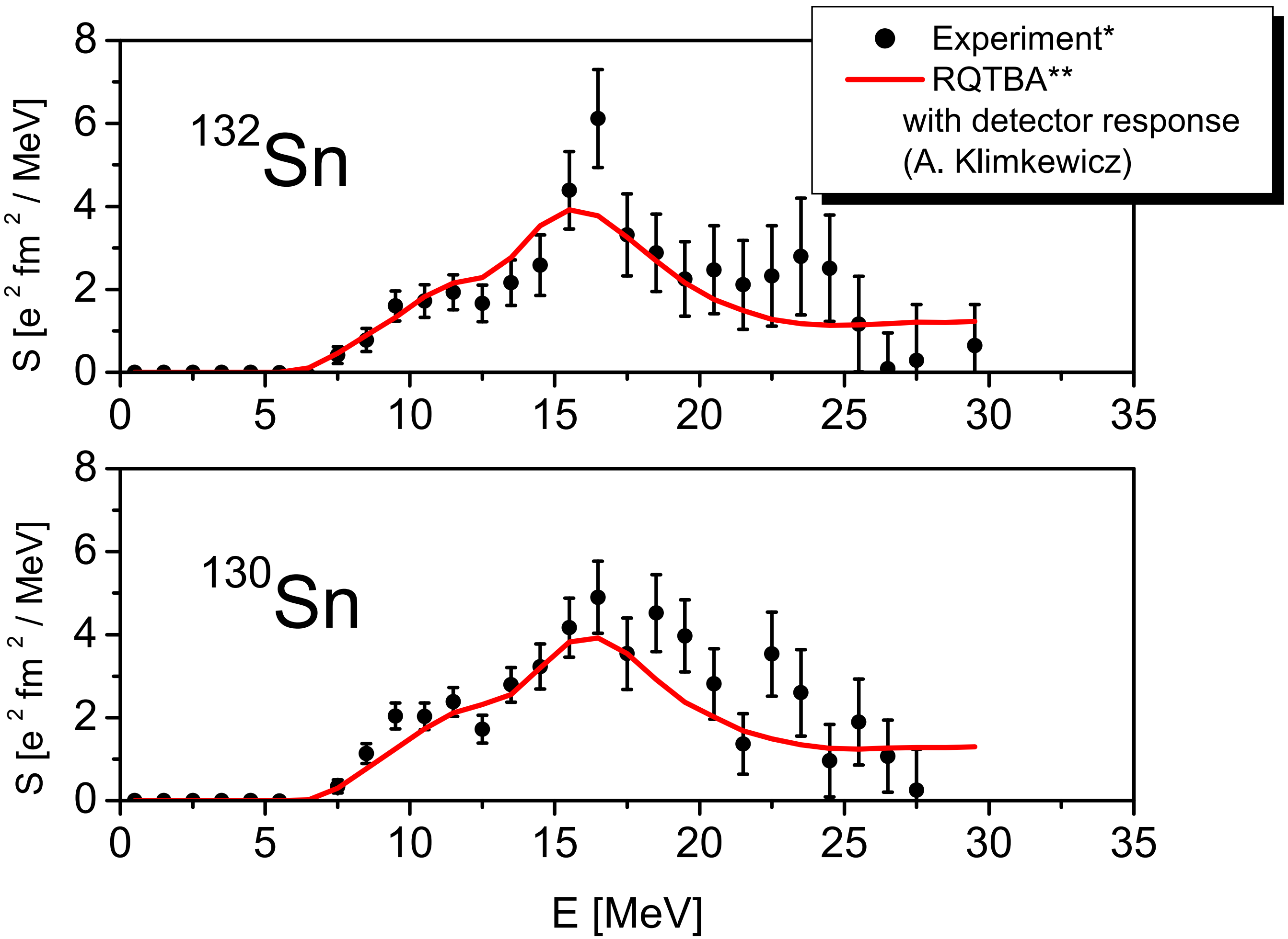
Transitions: fragmentation mechanism (schematic)



Electric dipole excitations in stable nuclei



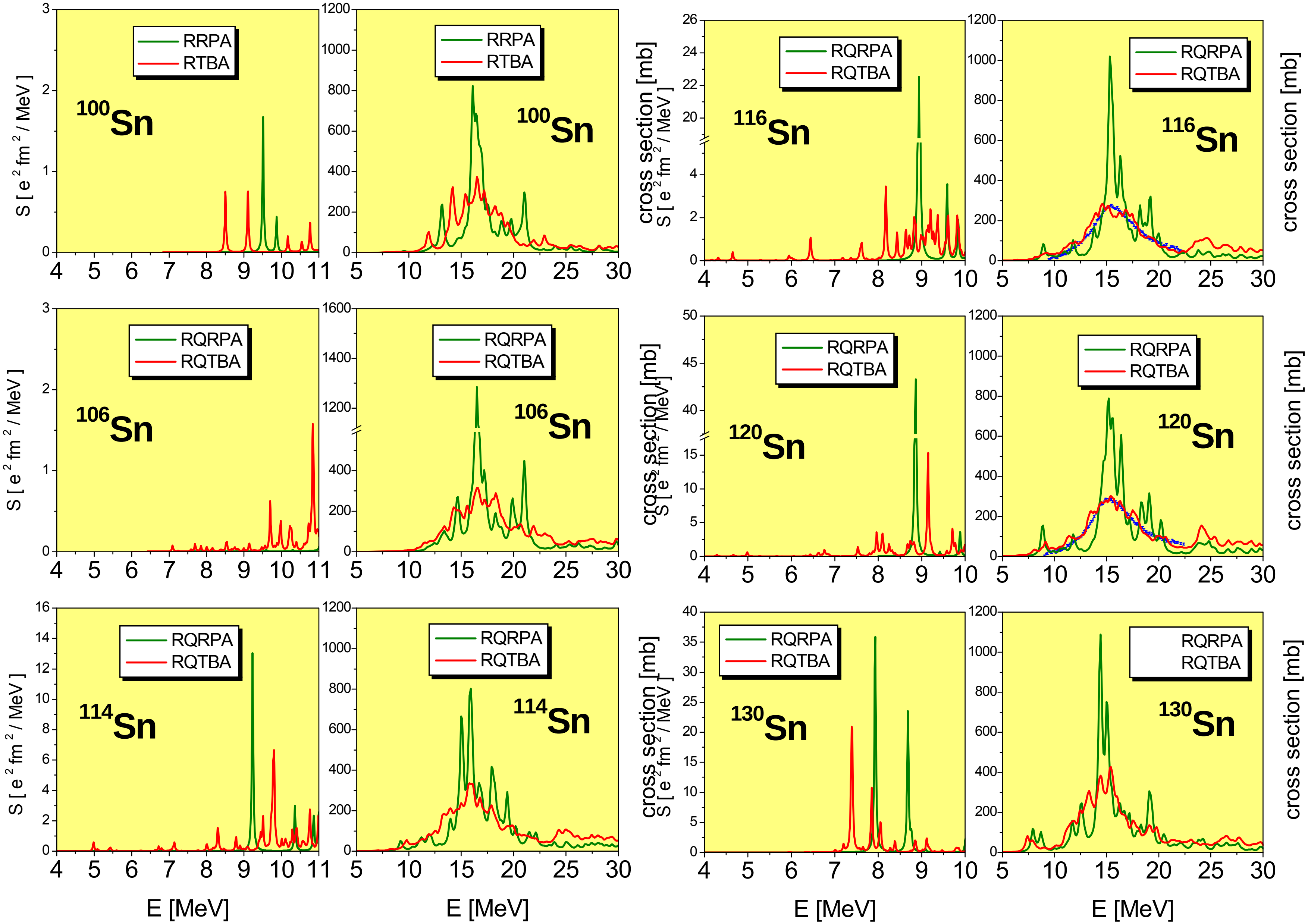
Dipole strength in neutron-rich Sn: Coulomb dissociation data & RQTBA calculations



*P. Adrich, A. Klimkewicz, M. Fallot et al., PRL 95, 132501 (2005)
** E. Litvinova, P. Ring, V. Tselyaev, PRC 75, 064308 (2007)
E.L. et al, PRC 79, 054312 (2009)

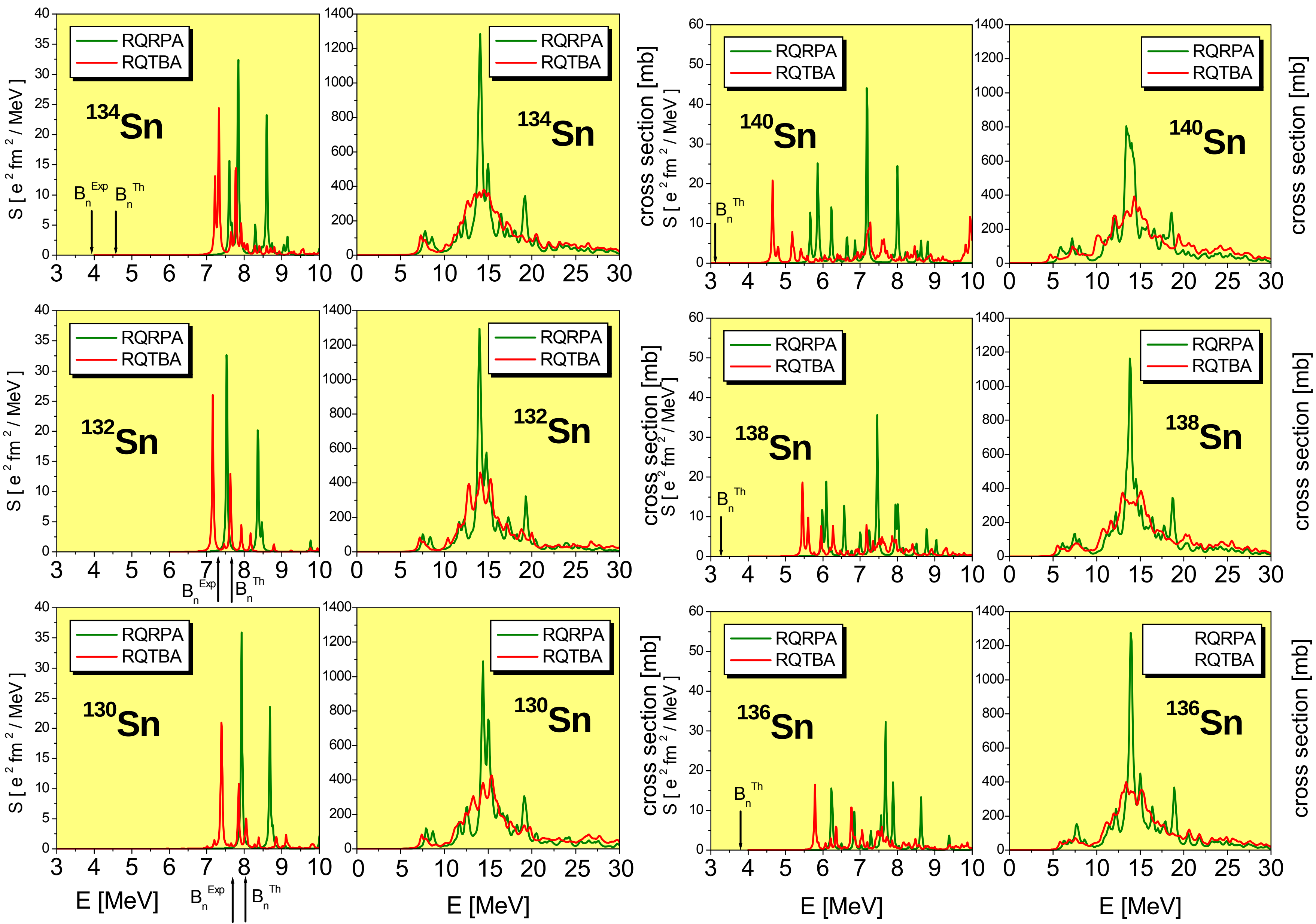
Dipole strength in Sn isotopes

E.L. et al, PRC 79, 054312 (2009)

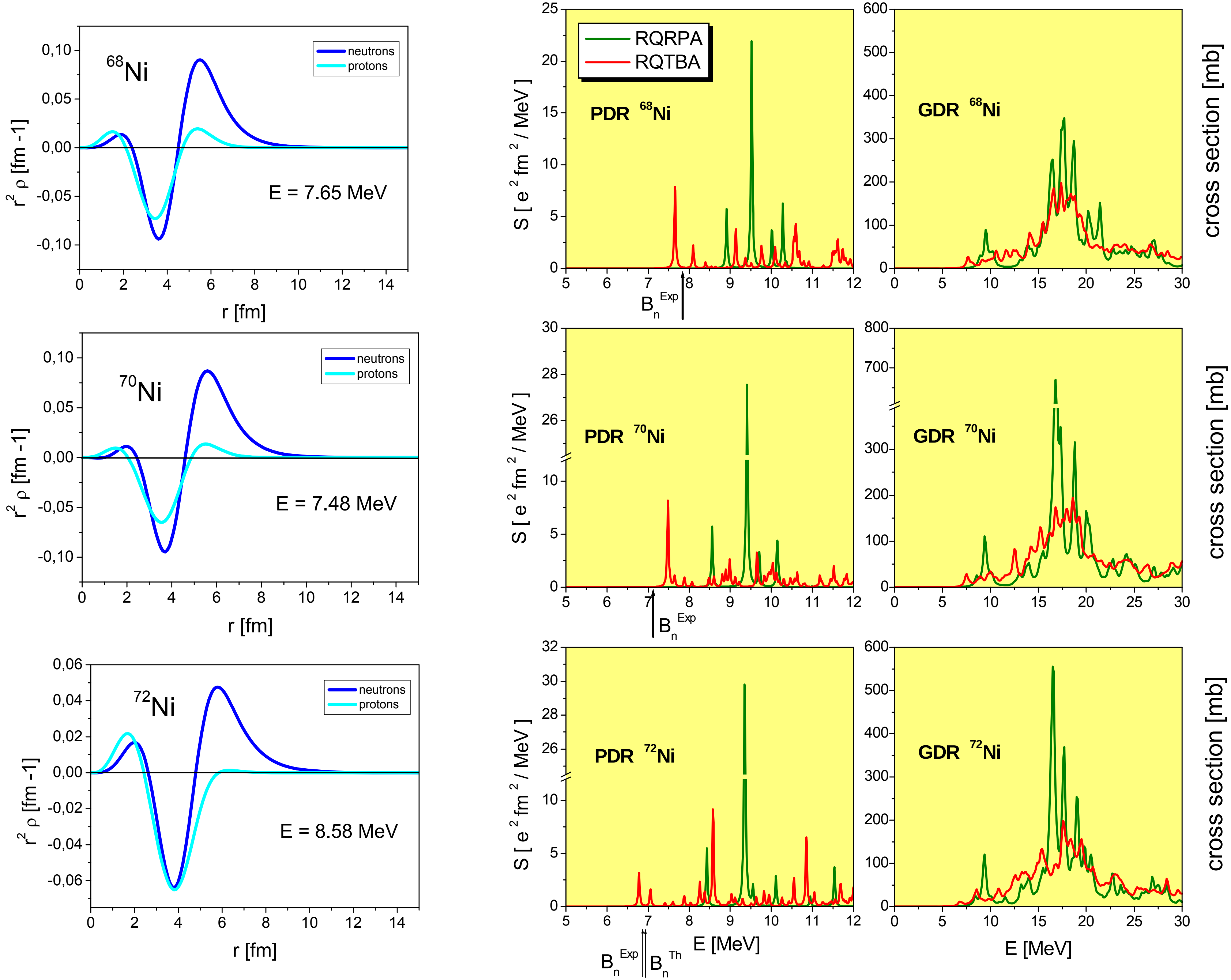


Dipole strength in Sn isotopes

E.L. et al, PRC 79, 054312 (2009)



Dipole excitations in neutron-rich Ni isotopes



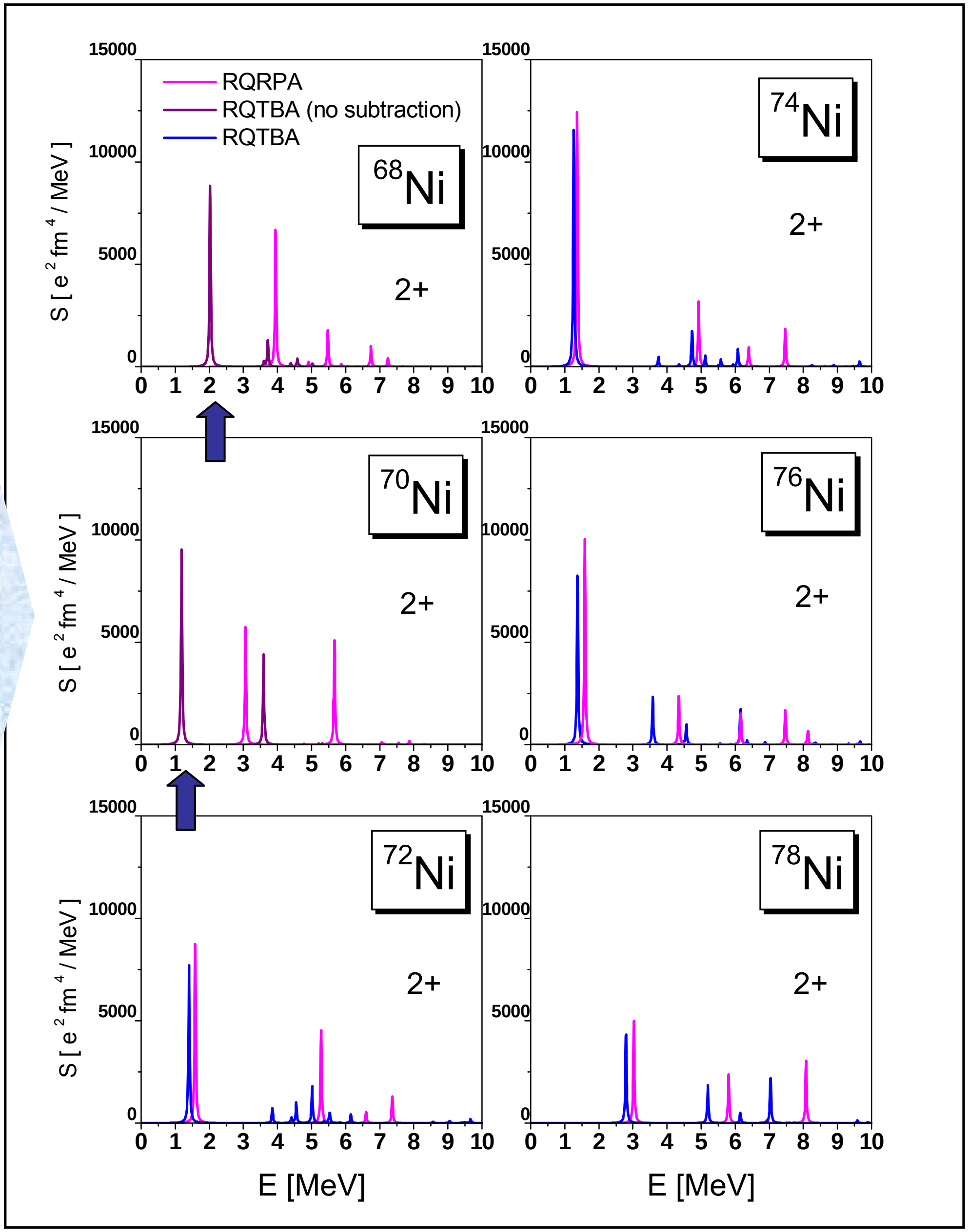
Low-lying quadrupole spectra in ^{68}Ni – ^{78}Ni

Strongly fragmented single-quasiparticle states are observed in ^{69}Ni

Coupling to phonons should strongly modify the g.s. as compared to RHB (RH-BCS)

No substraction of '2q+phonon' static contribution in RQTBA phonons

Extension of the model: E1 calculations with 'dressed' (RQTBA) phonon vertices are needed (in progress)

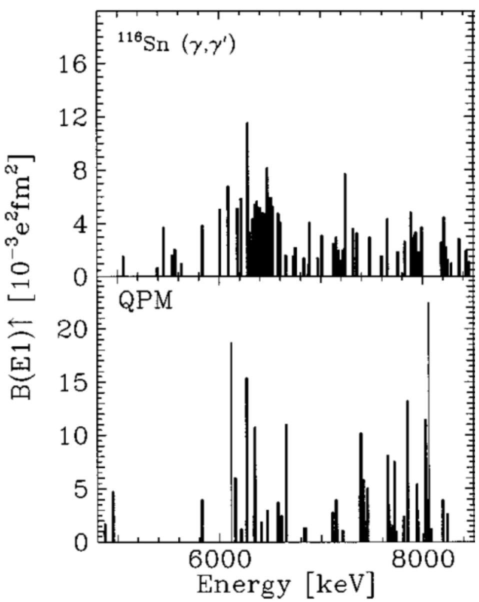


Fragmentation of pygmy dipole resonanse

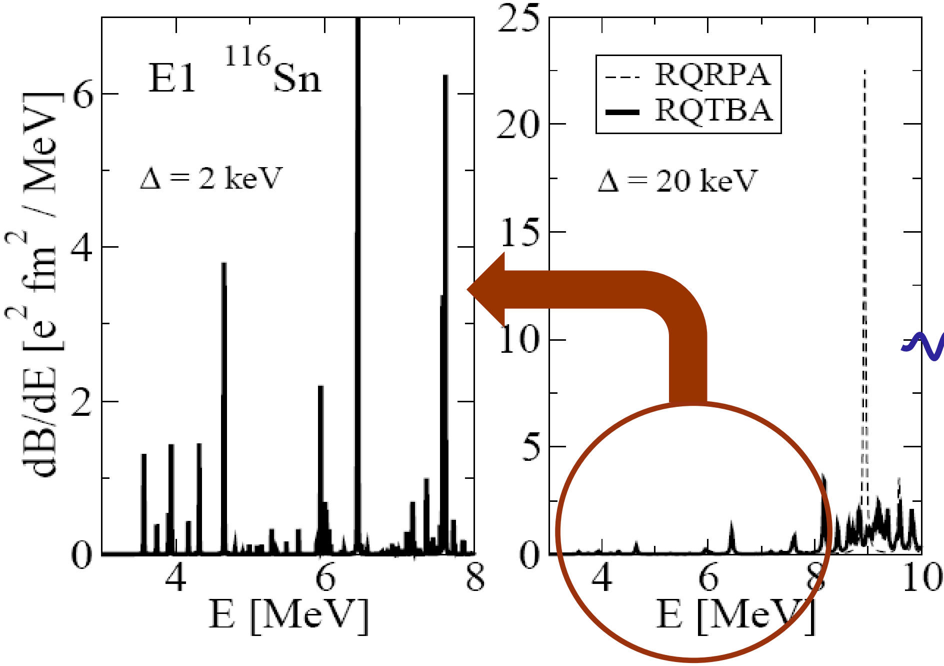
E. L., P. Ring, and V. Tselyaev,   Phys. Rev. C 78, 014312 (2008)

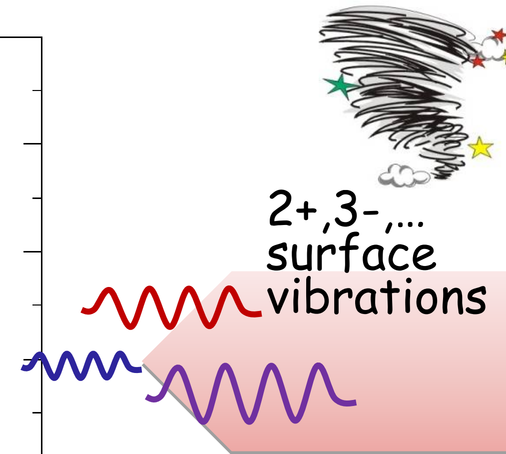
Low-lying dipole strength in ^{116}Sn

Experiment*



Fine structure   Gross structure





QPM up to 3p3h
(V.Yu. Ponomarev)

* K. Govaert et al.,
PRC 57, 2229 (1998)

RQTBA 2p2h

RQRPA 1p1h vs
RQTBA 2p2h

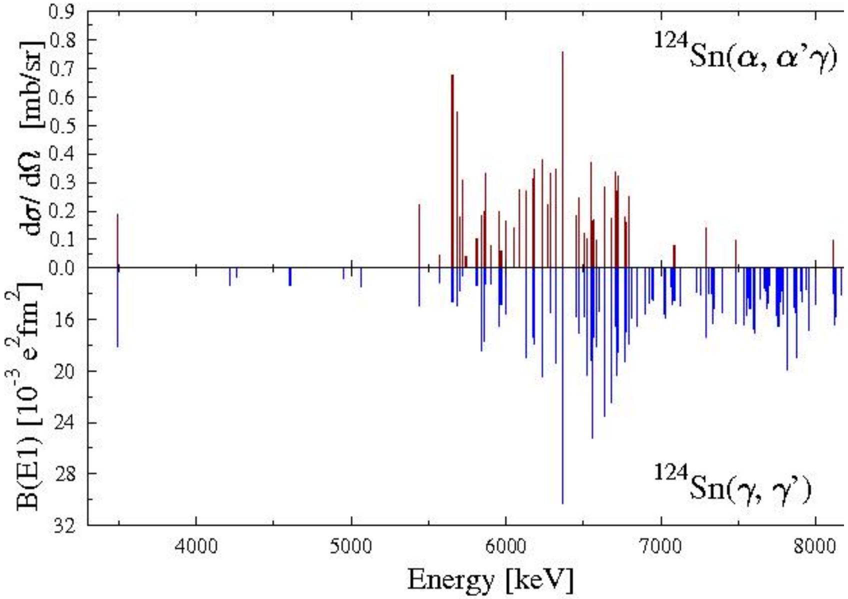
Integral
5-8 MeV:
ΣB(E1)↑ [$e^2 fm^2$]

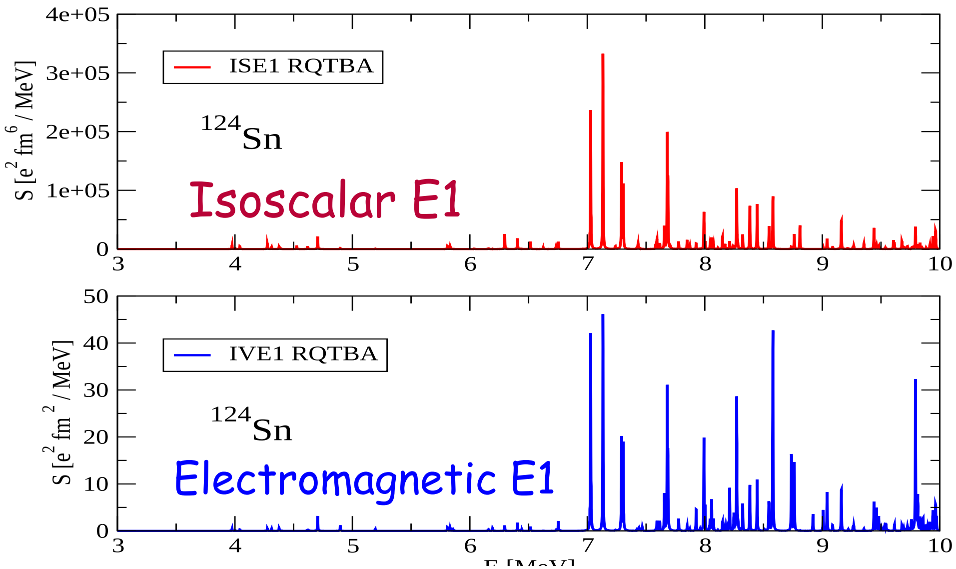
Exp.	0.204(25)
QPM	0.216
RQTBA	0.27

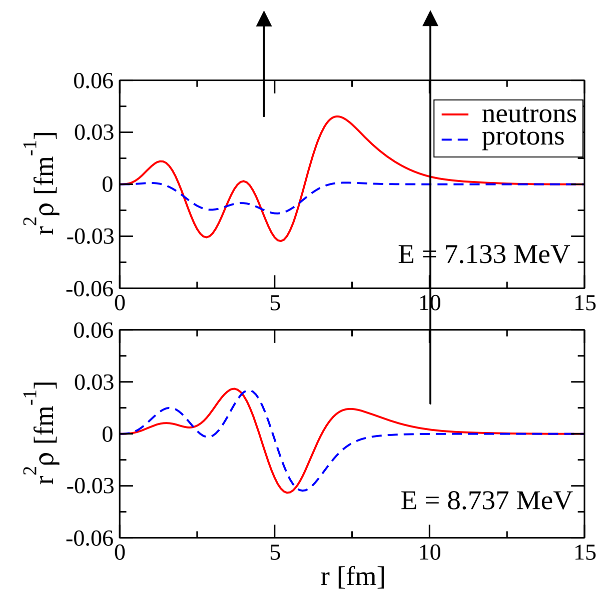
Isospin structure of the pygmy dipole resonance in ^{124}Sn

Experiment (J. Endres, D. Savran, A. Zilges et al.)

Theory: RQTBA







$$P_{IS} = e\sum_{i=1}^{A} \gamma_0 \left(r_i^3 - \frac{5}{3} < r^2 >_0 r_i \right) Y_{1M}(\hat{r}_i) \quad \Rightarrow \quad B_{IS} \sim \rho^{(n)} + \rho^{(p)}$$

$$P_{EM} = e\sum_{i=1}^{A} \left(\tau_z^{(i)} - \frac{N-Z}{2A} \right) r_i Y_{1M}(\hat{r}_i) \quad \Rightarrow \quad B_{EM} \sim Z\rho^{(n)} - N\rho^{(p)}$$

J. Endres, E. L., D. Savran et al., PRL 105, 212503 (2010)

Fine structure of spectra: next-order correlations from "2q+phonon" to "2 phonons"

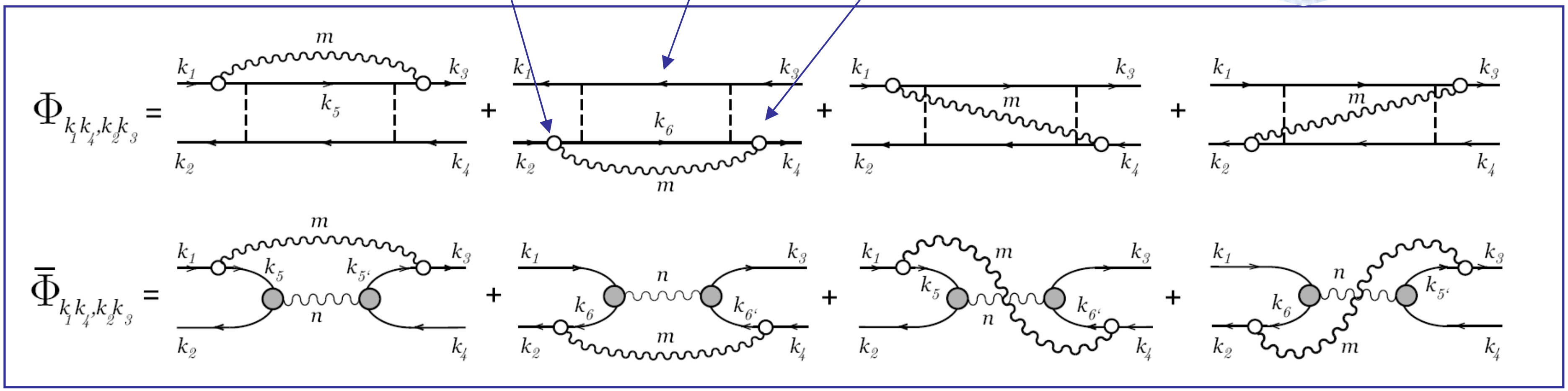
P. Schuck, Z. Phys. A 279, 31 (1976)
V.I. Tselyaev, PRC 75, 024306 (2007)

&

Mode Coupling Theory
Time Blocking

$$\Phi_{12,34}(\omega) = -\sum_{5678,\eta,m} \gamma_{12}^{m56(\eta)} A^{(\eta)}_{56,78}(\omega - \eta\,\omega_m)\, \gamma_{34}^{m78(\eta)*}$$

Replacement of the uncorrelated propagator inside the Φ amplitude by QRPA response



Nuclear response:

$$R = A + A\,(V + \bar{\Phi} - \bar{\Phi}_0)\,R$$

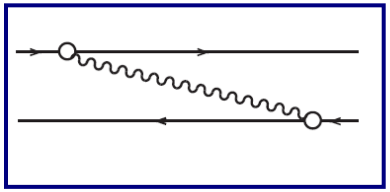
Poles may appear at lower energies:

'2q+phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu k}\, \alpha_{ijk\mu}/(\omega - E_{i'} - E_k - \Omega_\mu)$

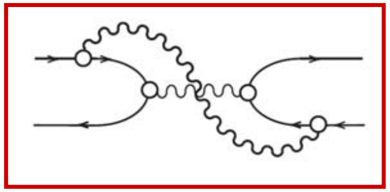
'2 phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu\nu}\, \alpha_{iji'j'}/(\omega - \Omega_\nu - \Omega_\mu)$

Fine features of dipole spectra: two-phonon effects

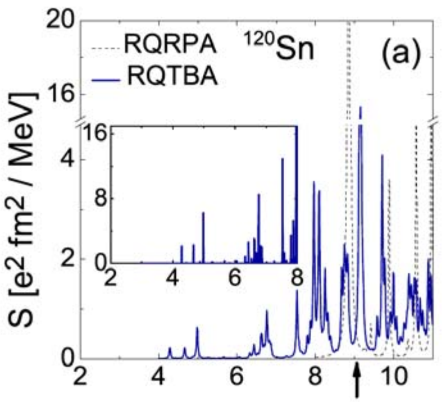
2q+phonon

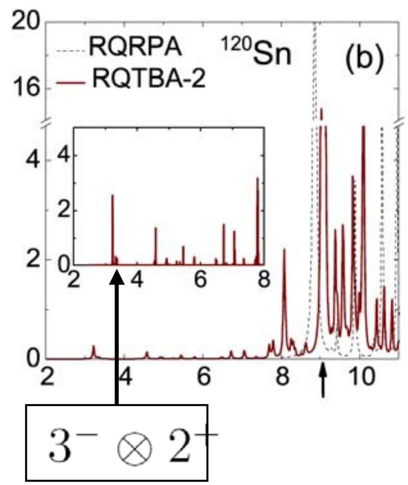


2 phonon



^{120}Sn

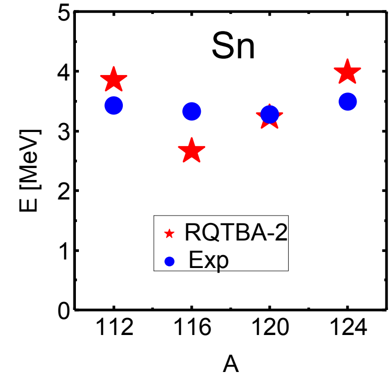


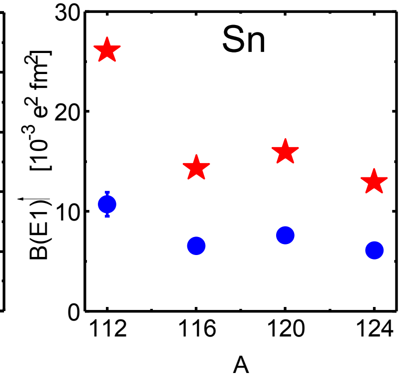


E.L., P.Ring, V.Tselyaev, PRL 105, 02252 (2010)

First two-phonon state 1^-_1 : $3^- \otimes 2^+$

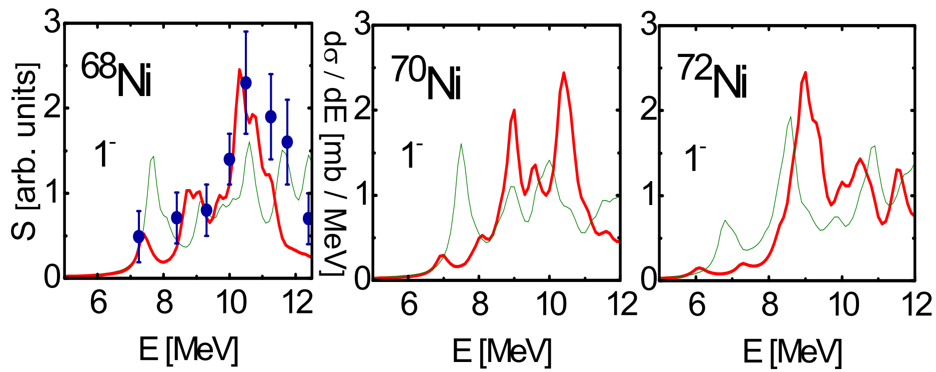
$E(1^-_1)$ $B(E1)\uparrow$





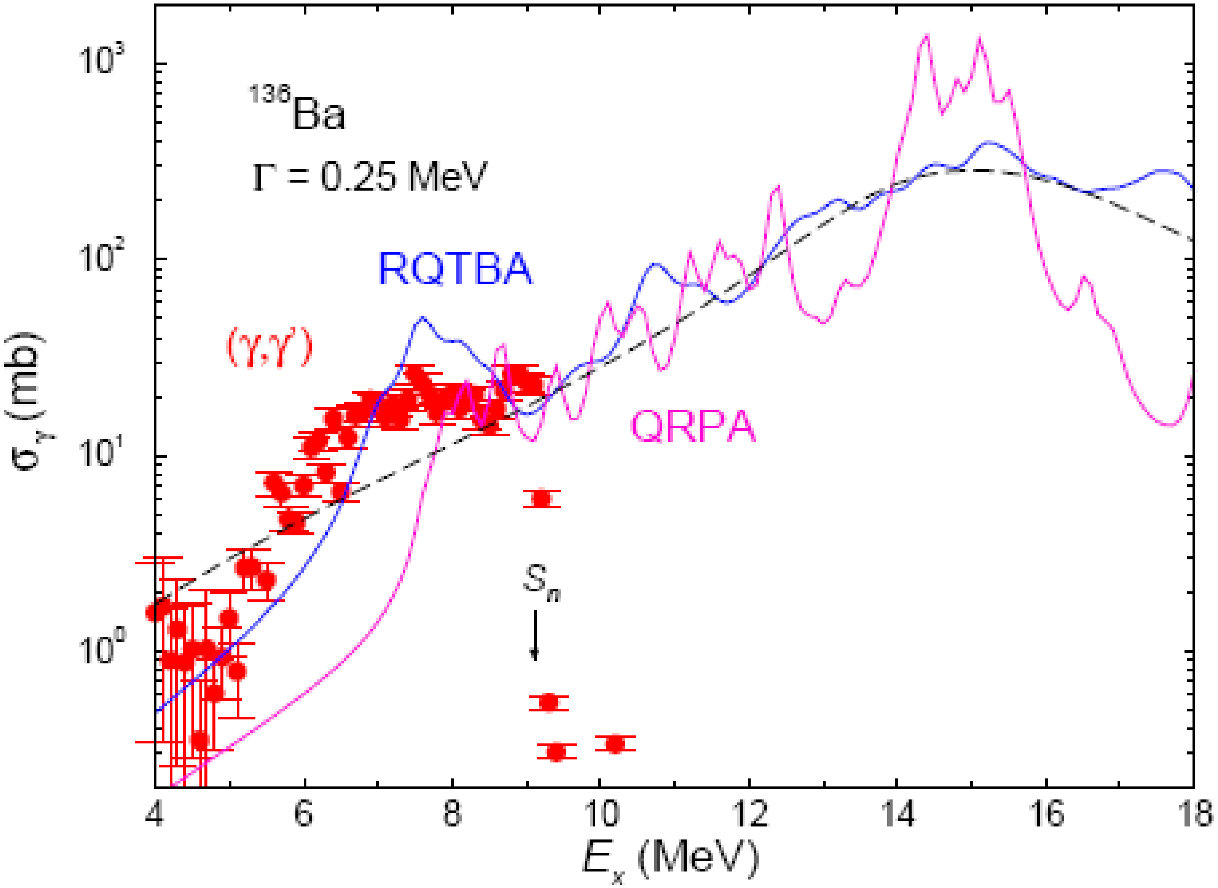
Data: I.Pysmenetska et al., PRC73 (2006) 017302

Pygmy dipole resonance in neutron-rich Ni:
2q+phonon vs 2 phonon



Data: O. Wieland et al., PRL 102, 092502 (2009)

Absorption cross section in ^{136}Ba



Present (γ, γ) data

Three-Lorentz model (TLO)

A.R. Junghans et al.,

PLB 670, 200 (2008)

QRPA

Calculations by F. Dönau

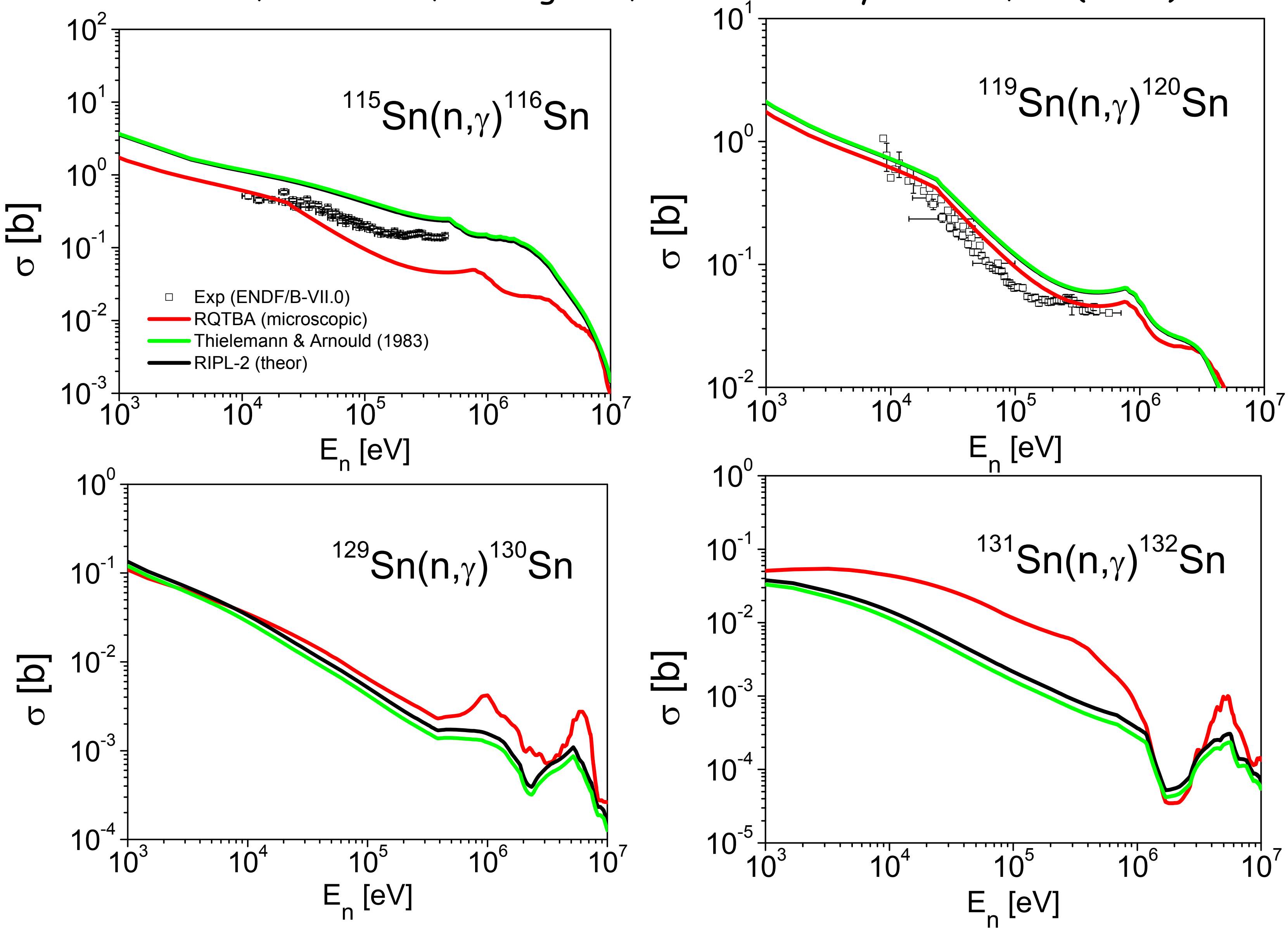
RQTBA

Calculations by E. Litvinova

R. Massarczyk et al. PRC 86, 014319 (2012)

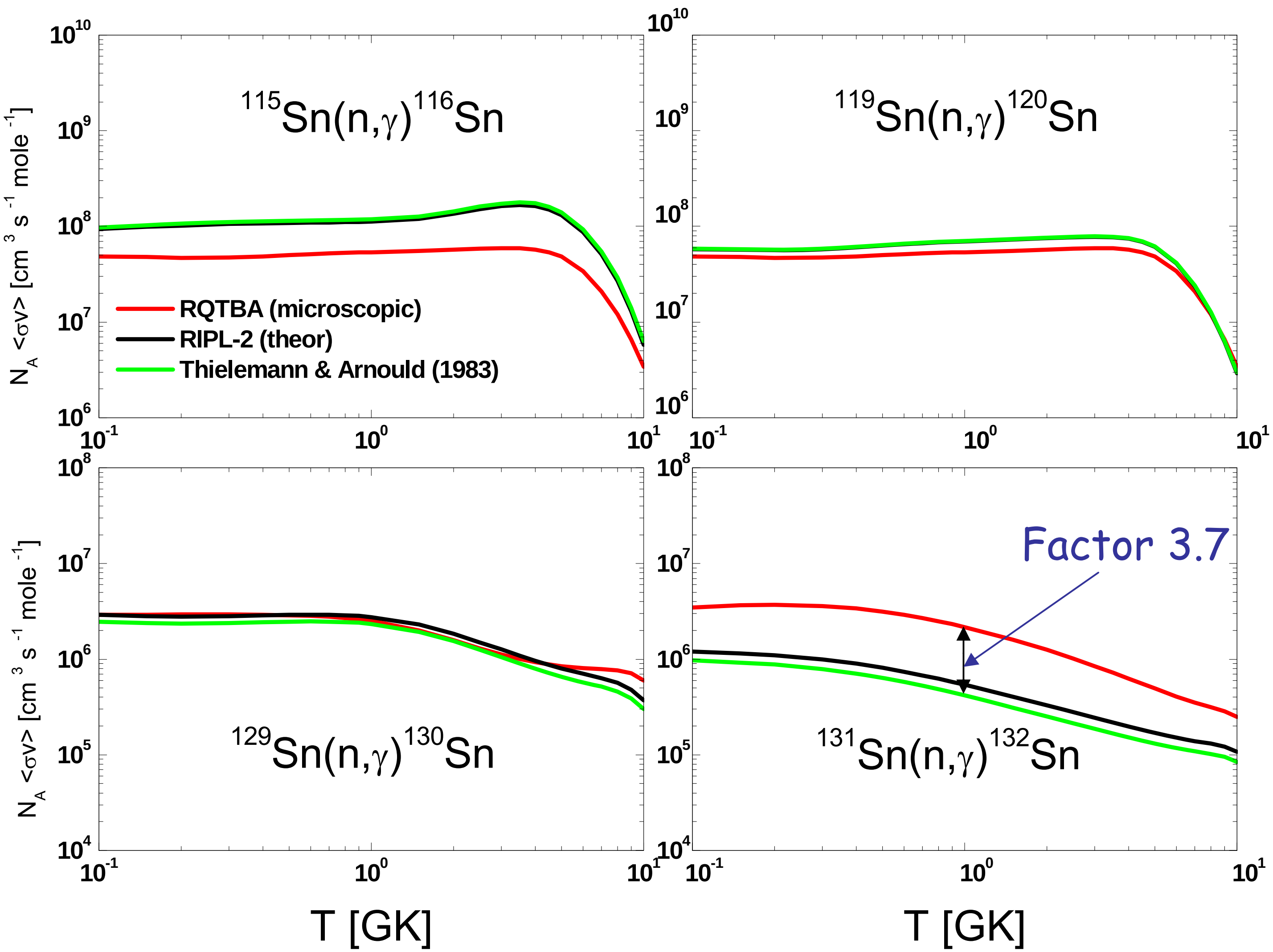
Radiative neutron capture in the Hauser-Feshbach model: standard Lorentzians and microscopic structure

E. L., H.P. Loens, K. Langanke, et al. Nucl. Phys. A 823, 26 (2009).



(n,γ) stellar reaction rates

E. L., H.P. Loens, K. Langanke, et al. Nucl. Phys. A 823, 26 (2009).



PDR at neutron threshold

Gamow-Teller Resonance in 208-Pb

„Proton-Neutron" relativistic time blocking approximation: ρ, π, phonons

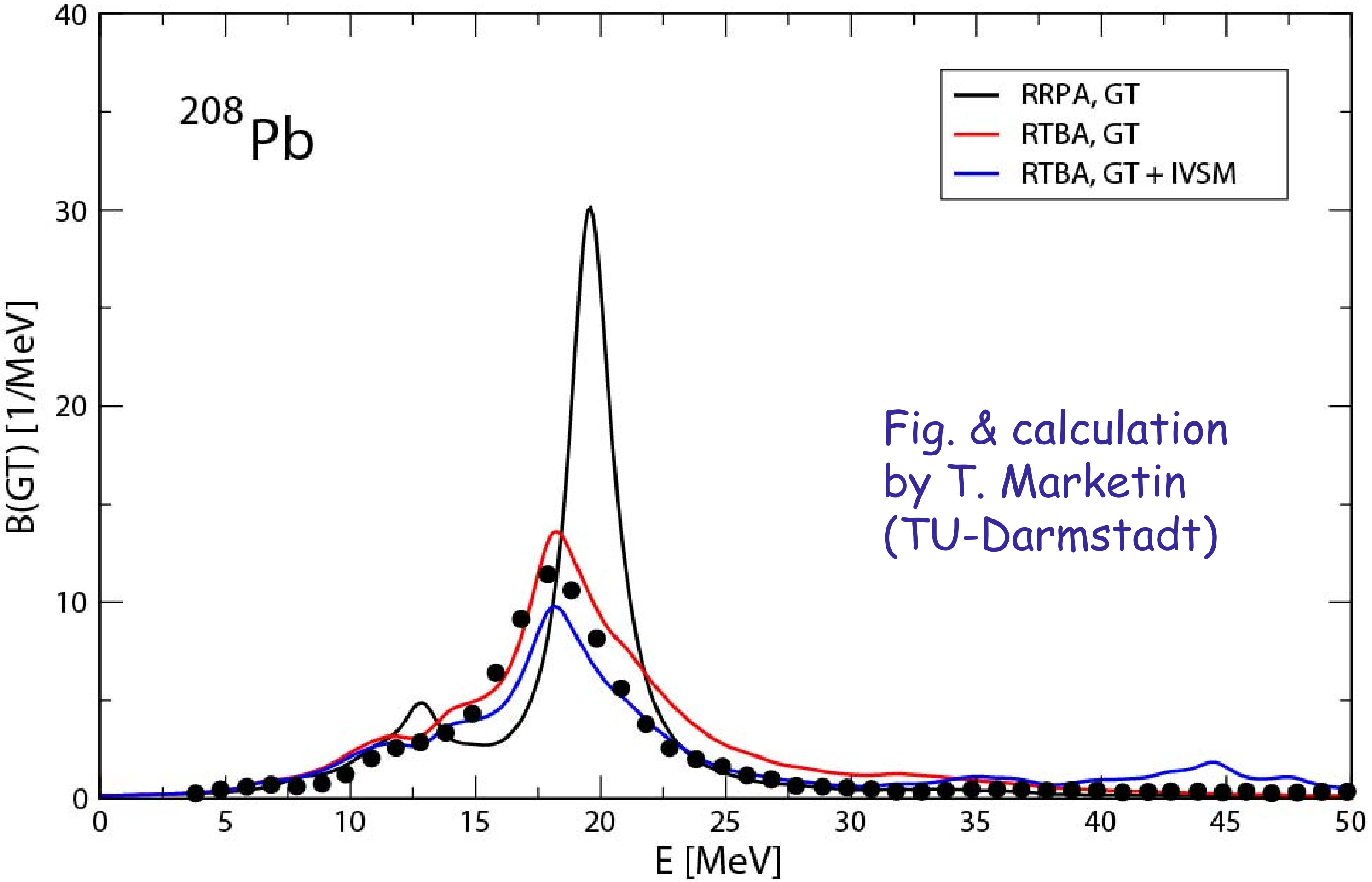
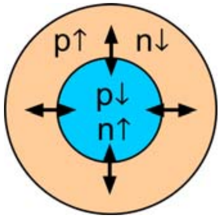


Fig. & calculation by T. Marketin (TU-Darmstadt)

$$P = \sum_i \sigma^{(i)} \tau_{\pm}^{(i)}$$



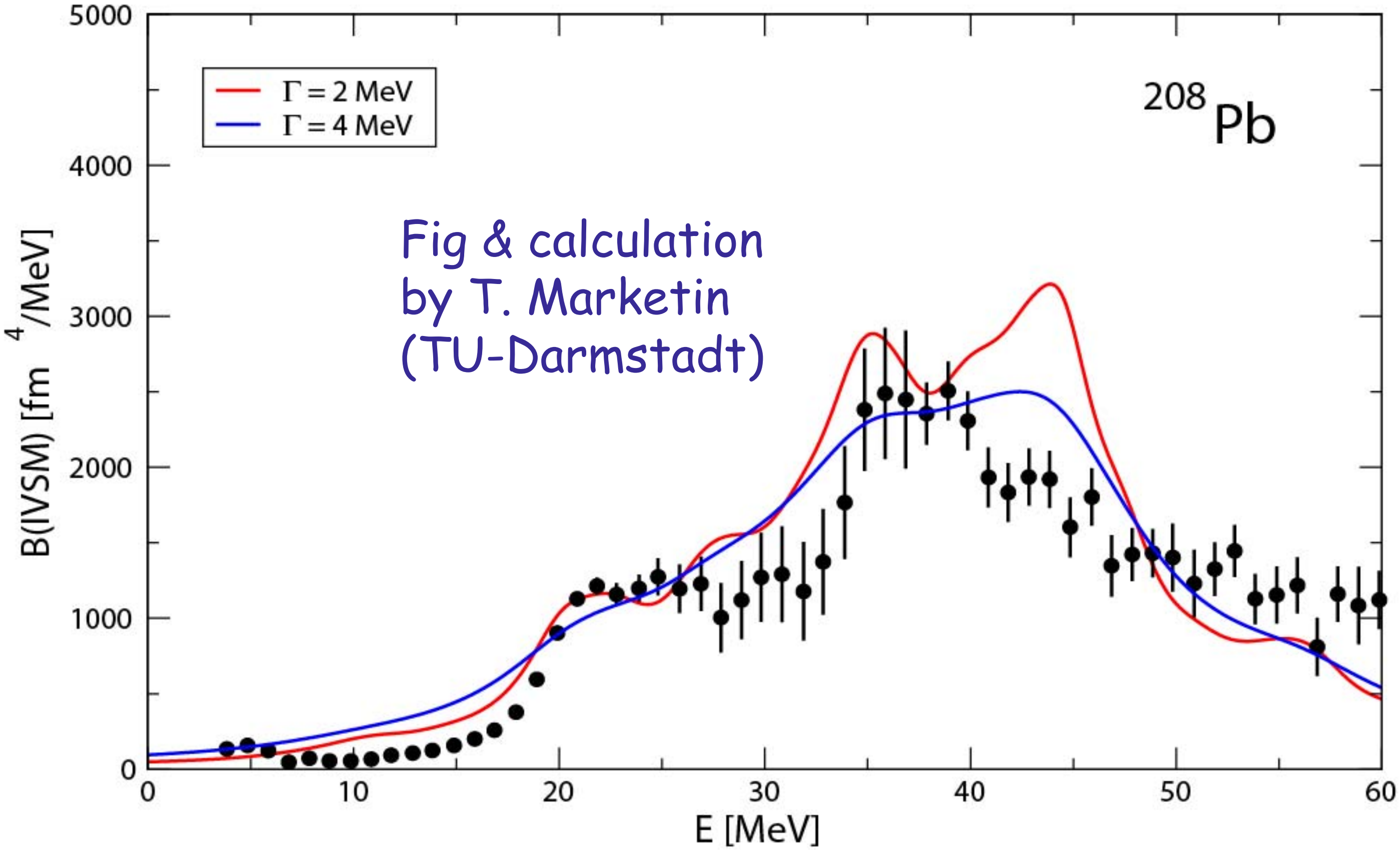
ΔL = 0
ΔT = 1
ΔS = 1

Quenching of S^- due to ph+phonon configurations

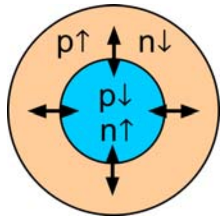
Isovector spin-monopole resonance in 208-Pb

„Proton-Neutron" relativistic time blocking approximation: ρ, π, phonons

IVSMR – overtone of GTR



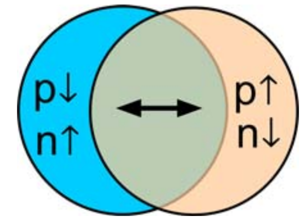
$$P = \sum_i \sigma^{(i)} \tau_{\pm}^{(i)}$$

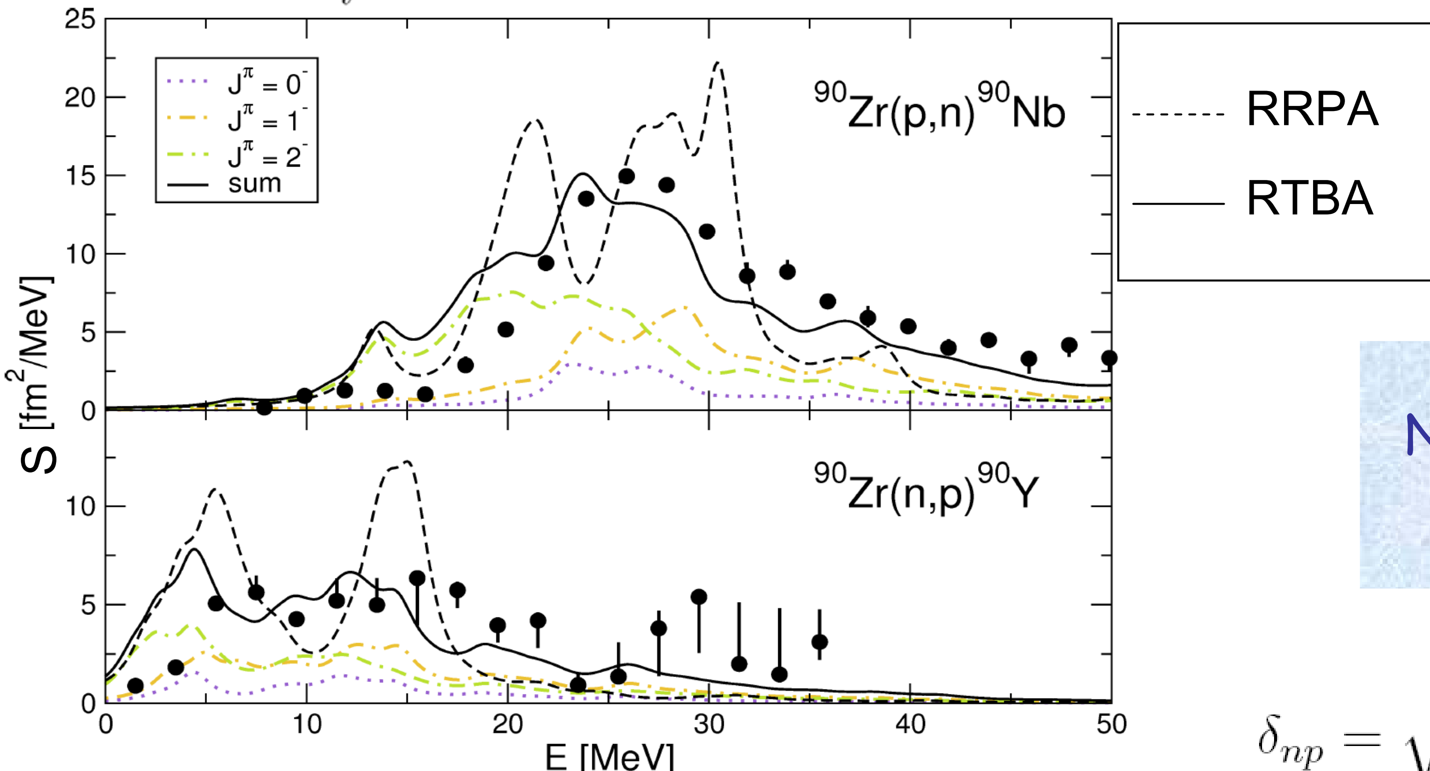


ΔL = 0
ΔT = 1
ΔS = 1

Spin & isospin-flip excitations: spin-dipole resonance

$$P_{\pm}^{\lambda} = \sum_i r_i \left[\boldsymbol{\sigma}^{(i)} \otimes Y_1(\hat{\vec{r}}_i) \right]_{\lambda} \tau_{\pm}^{(i)}$$





$\Delta L = \lambda = 0,1,2$
$\Delta T = 1$
$\Delta S = 1$

Neutron skin thickness

$$\delta_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p}$$

Sum rule:

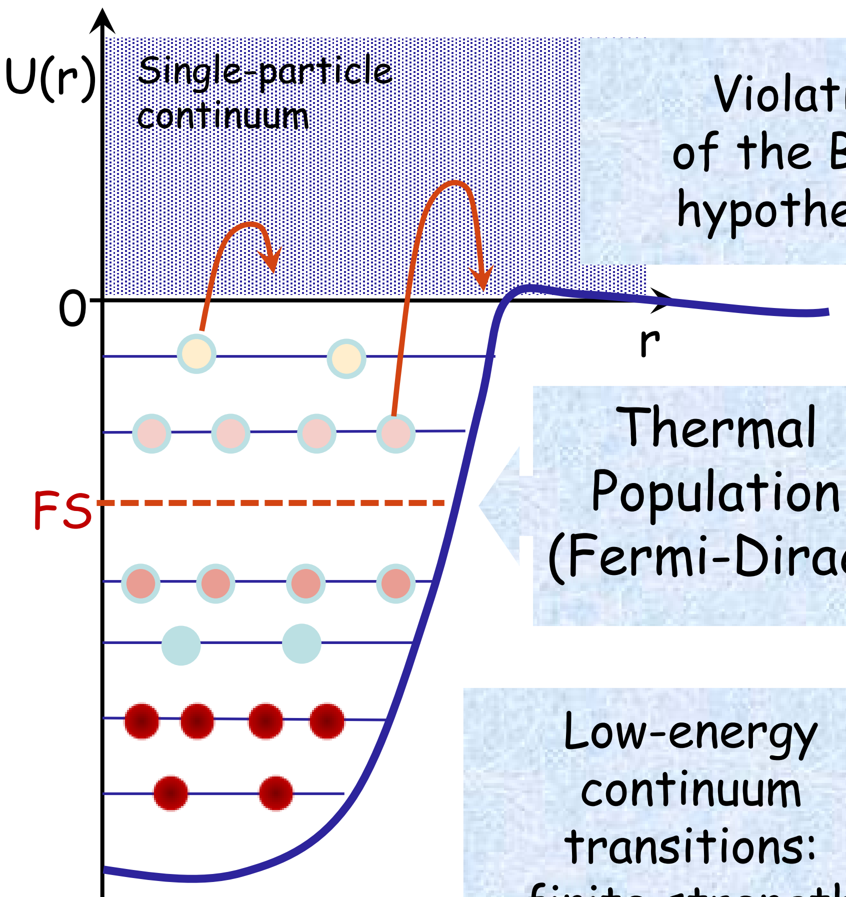
$$S_{-}^{\lambda} - S_{+}^{\lambda} = \frac{2\lambda + 1}{4\pi} \left(N \langle r^2 \rangle_n - Z \langle r^2 \rangle_p \right)$$

See talk of Tomislav Marketin for more details

T. Marketin, E.L., D. Vretenar, P. Ring, PLB 706, 477 (2012).

Temperature dependence of low-lying dipole strength: Continuum QRPA at finite temperature revisited*

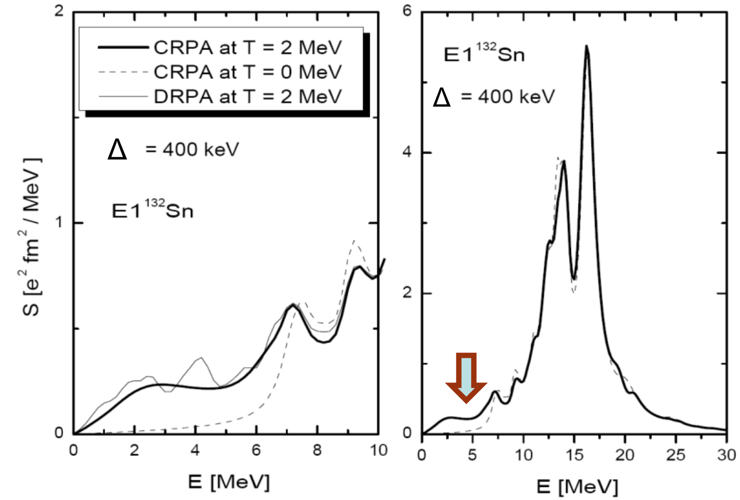
Strong continuum effects at $\varepsilon_\gamma \sim 0$

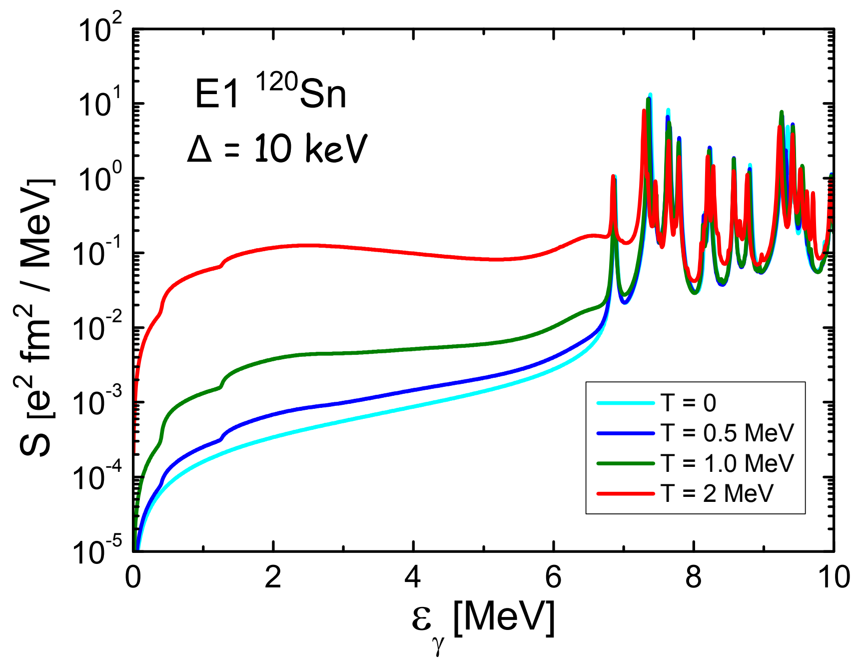


Violation of the Brink hypothesis?

Thermal Population (Fermi-Dirac)

Low-energy continuum transitions: finite strength at $\varepsilon_\gamma \to 0$





*E.L. et al., Phys. At. Nucl. 66, 558 (2003)

Finite-„temperature" CEDF

Maximum entropy principle

$\delta\Omega = 0$:

$$\Omega(\lambda, T) = E - \lambda N - TS$$

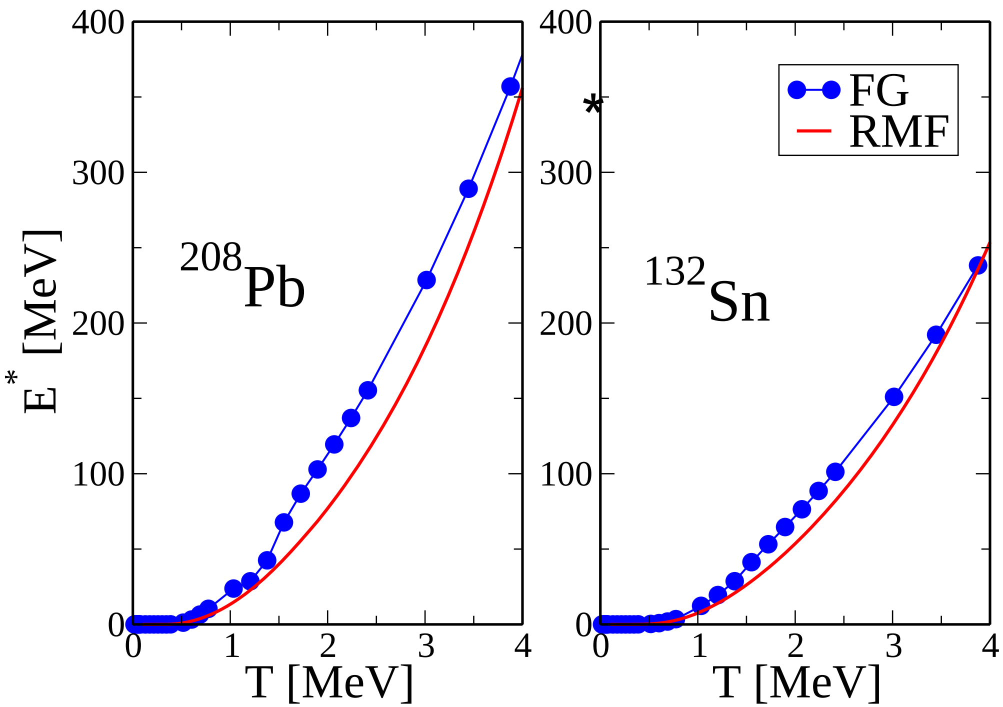
$$S[\mathcal{R}] = -Tr(\mathcal{R} \ln \mathcal{R})$$

Leads to:

$$\mathcal{R} = \frac{1}{e^{\mathcal{H}/T} + 1}$$

$$\mathcal{H} = \frac{\delta E[\mathcal{R}]}{\delta \mathcal{R}}$$

Finite-temperature CEDF E[ρ] =
= Thermal Relativistic Mean Field (TRMF)



FG = Fermi gas: $T = [\,(E-\delta)/a\,]^{1/2}$

T. Rauscher, Astrophys. J. Suppl. Ser. 147, 403 (2003).

Nuclear response at finite temperature

Density matrix variation:

$$\delta\mathcal{R}(x;\omega,T) = \delta\mathcal{R}^{(0)}(x;\omega,T) +$$
$$+ \int dx'dx''\mathcal{A}(x,x';\omega,T)F(x',x'')\delta\mathcal{R}(x'';\omega,T)$$

Thermal „mean-field + pairing“ propagator in the continuum :

E.L. et al., Phys. Atomic Nuclei 66, 558 (2003)

$$\mathcal{A}(x,x';\omega,T) = \sum_{1234} \varphi_1^*(x)\varphi_2(x)\varphi_3(x')\varphi_4^*(x') \int \frac{d\varepsilon}{2\pi i} G_{12}(\varepsilon,T)G_{34}(\varepsilon+\omega,T)$$

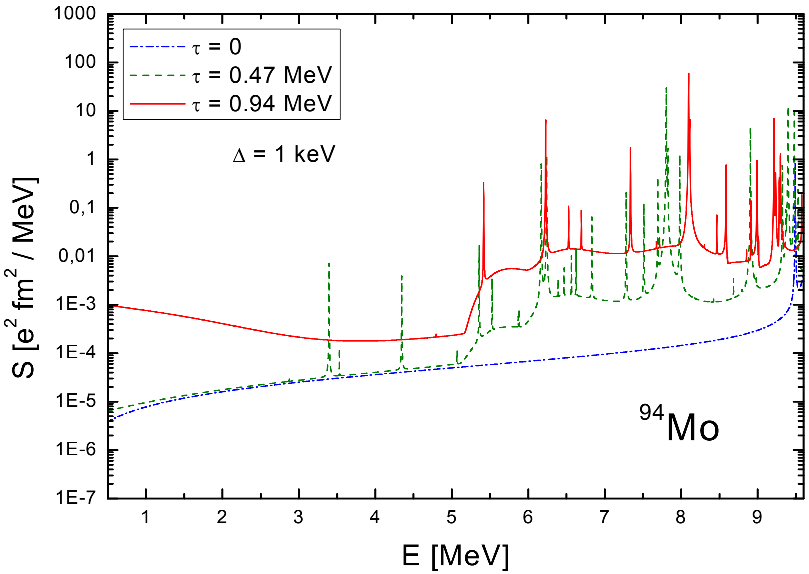
Gamma-strength function

Thermally averaged

?

$$S(E_\gamma,T) = -\frac{1}{\pi}\frac{1}{1-e^{-E_\gamma/T}}\mathrm{Im}\langle D^\dagger\delta\mathcal{R}(E_\gamma+i\Delta,T)\rangle$$

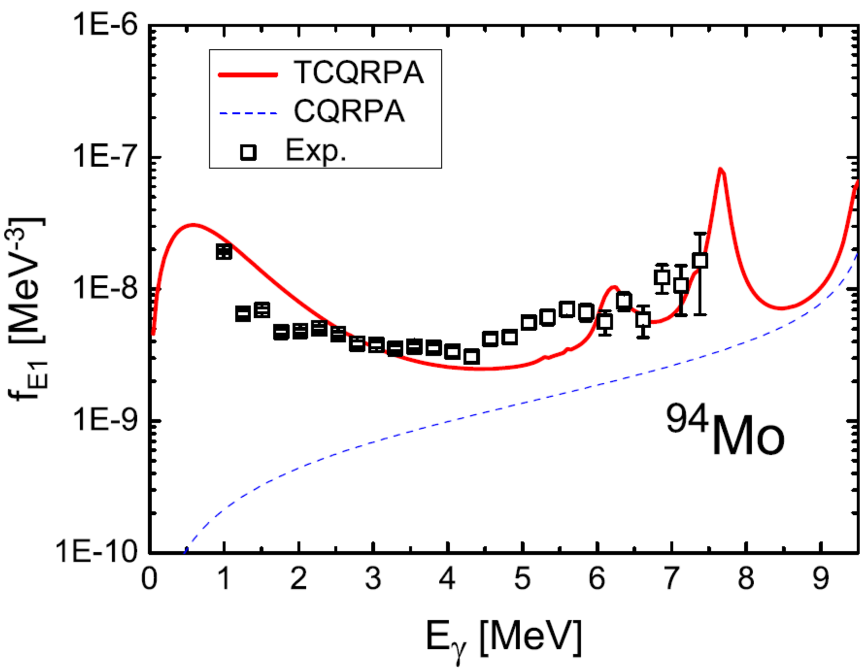
Dipole gamma-strength function (preliminary)

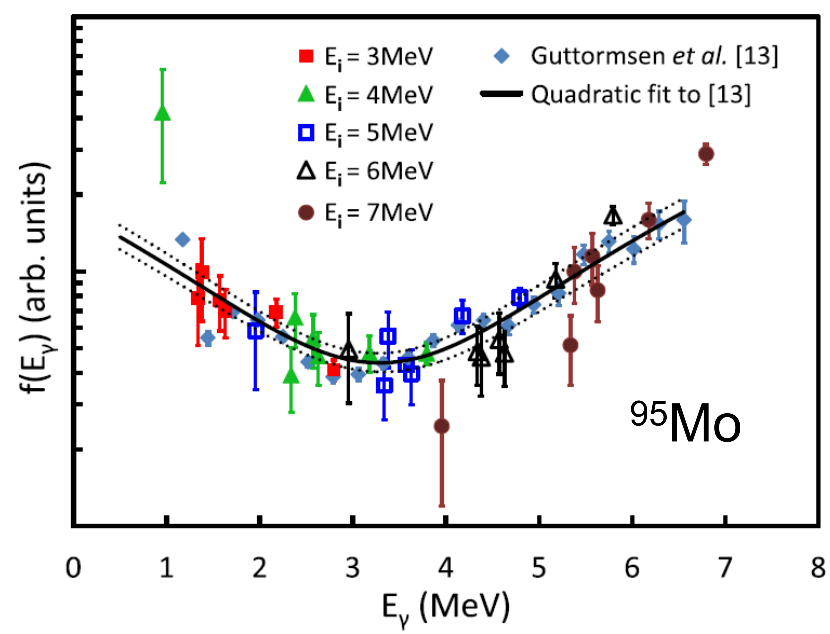


- Enhancement at lowest energies;
- Superfluid phase transition
- Violation of Brink hypothesis - ?

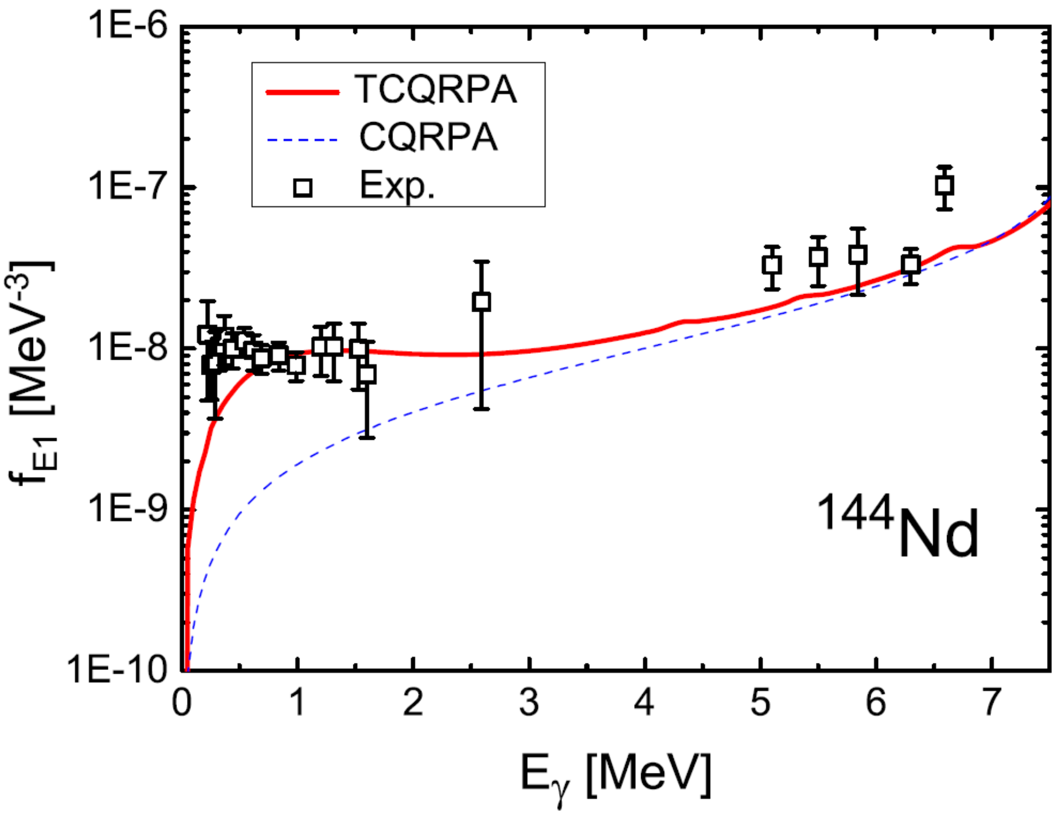
M. Guttormsen et al., PRC 71, 044307 (2005)

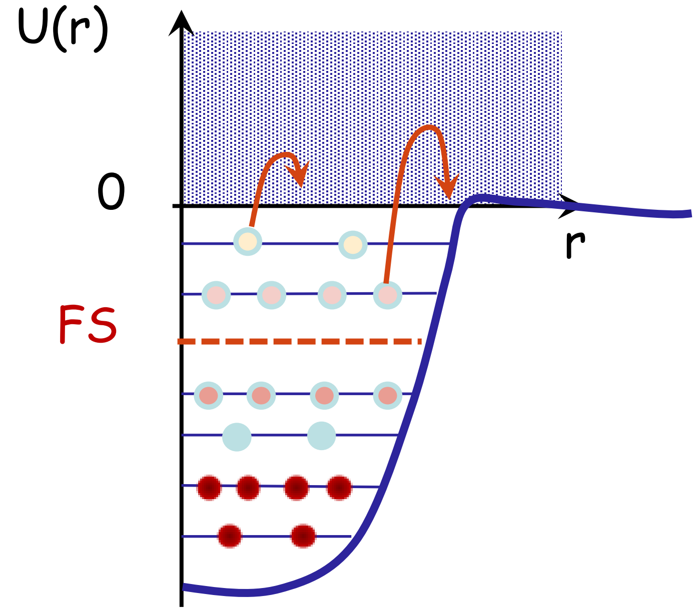
M. Wiedeking et al., PRL 108, 162503 (2012):





Dipole gamma-strength function (preliminary)





- Consequences for (n,γ) reaction rates - ?
- For electric dipole polarizability (EDP) - ???
- For EDP – neutron skin correlation - ??

QTBA Calculations with Skyrme functional

HFB from
J. Dobaczewski

Self-consistent calculations within the extended theory of finite Fermi systems

+ QTBA from
E.L., V. Tselyaev,
PRC 75, 054318 (2007)

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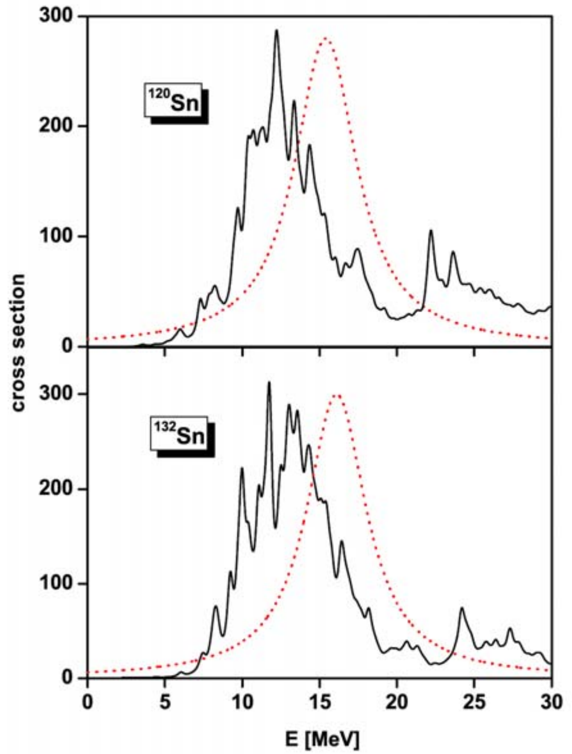
PLB 653, 196 (2007)



IG. 1: E1 photo absorption cross section for ^{120}Sn and ^{132}Sn
lculated within the present theory (full). The dotted lines
dicate the data for ^{120}Sn [32] and ^{132}Sn [33]. The smearing
rameter is $\Delta = 0.2$ MeV. The SLy4 Skyrme parametriza-
on was used.

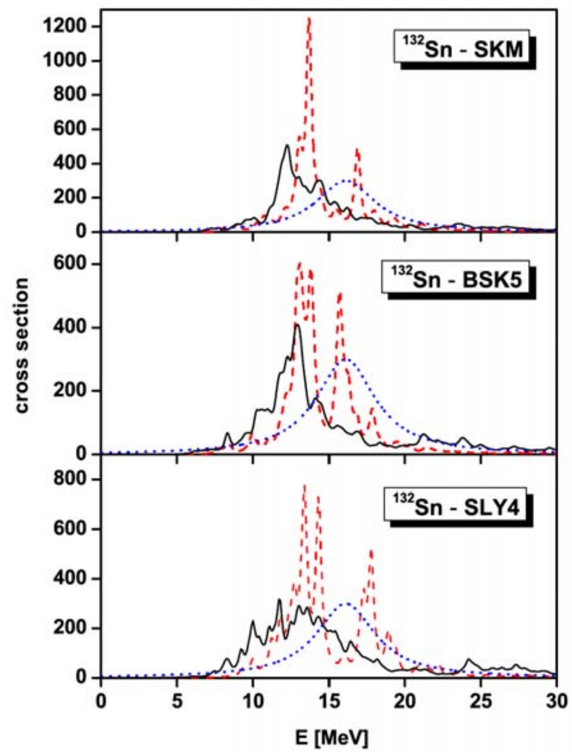


FIG. 2: E1 photo absorption cross section for ^{132}Sn calculated within the present theory with different Skyrme forces. The smearing parameter is $\Delta = 0.2$ MeV. The dotted line are the data of ref. [33].

Giant monopole resonance in "soft" tin isotopes

PHYSICAL REVIEW C **79**, 034309 (2009)

Description of the giant monopole resonance in the even-A $^{112-124}$Sn isotopes within a microscopic model including quasiparticle-phonon coupling

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(Received 6 October 2008; published 10 March 2009)

Approach: Skyrme T5 + QTBA

Phonons – from Ladau-Migdal theory

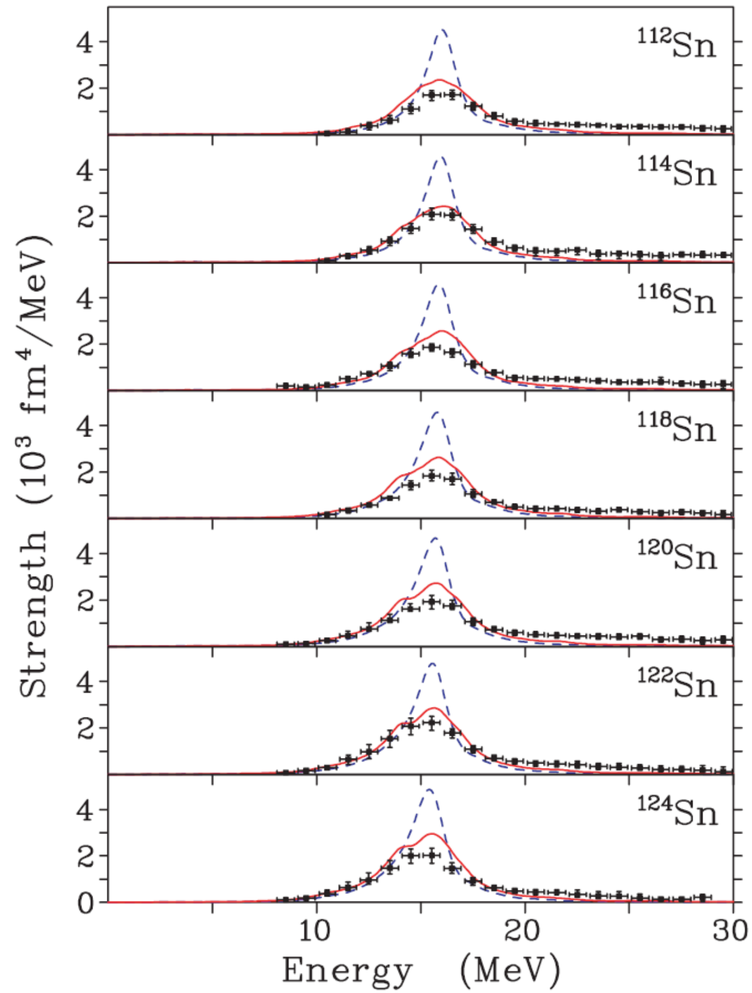

FIG. 1. (Color online) Isoscalar giant monopole resonance in the even-A $^{112-124}$Sn isotopes calculated within QRPA (dashed line) and QTBA (solid line). The results are obtained within the self-consistent HF+BCS approach based on the T5 Skyrme force. The smearing parameter Δ is equal to 500 keV. Experimental data (solid squares) are taken from Ref. [18].