Isospin transfer modes in exotic nuclei

Elena Litvinova

Western Michigan University

MICHIGAN STATE UNIVERSITY

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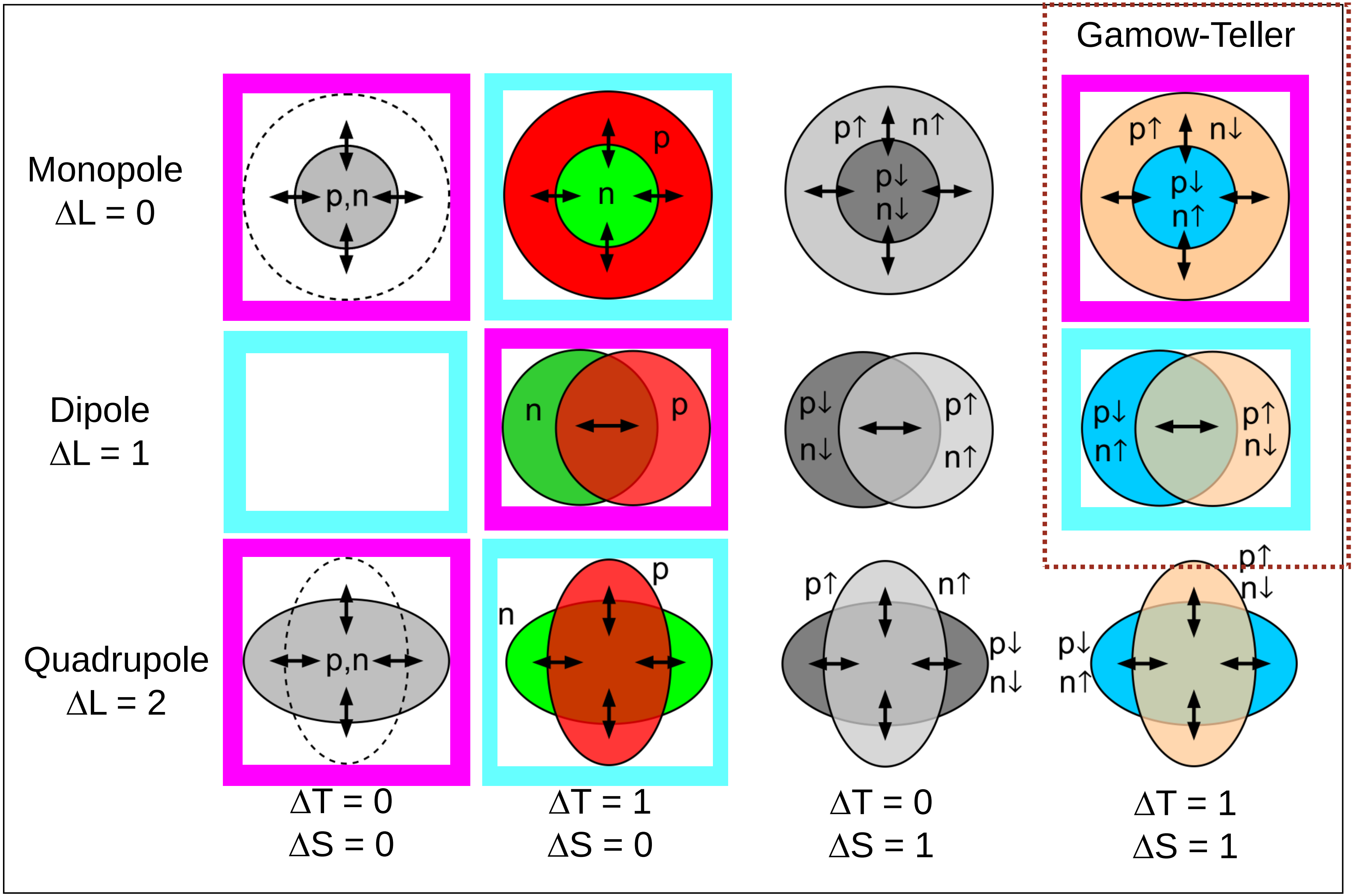
Outline

- Introduction: modes of nuclear excitations; isospin transfer modes
- Theory: building blocks
- Covariant nuclear field theory (NFT):
  response theory with non-local (in space & time) effective interaction
- Applications to nuclear spin-isospin response:

    Gamow-Teller resonance
    spin-dipole resonance

- Summary and outlook

Nuclear vibrational motion



* M. N. Harakeh and A. van der Woude: Giant Resonances

Building blocks of nuclear structure models

- ❖ Degrees of freedom

at ~1-50 MeV excitation energies:
single-particle & collective (vibrational, rotational)
NO complete separation of the scales!
-Coupling between single-particle and collective:
-Coupling to continuum
as nuclei are open quantum systems

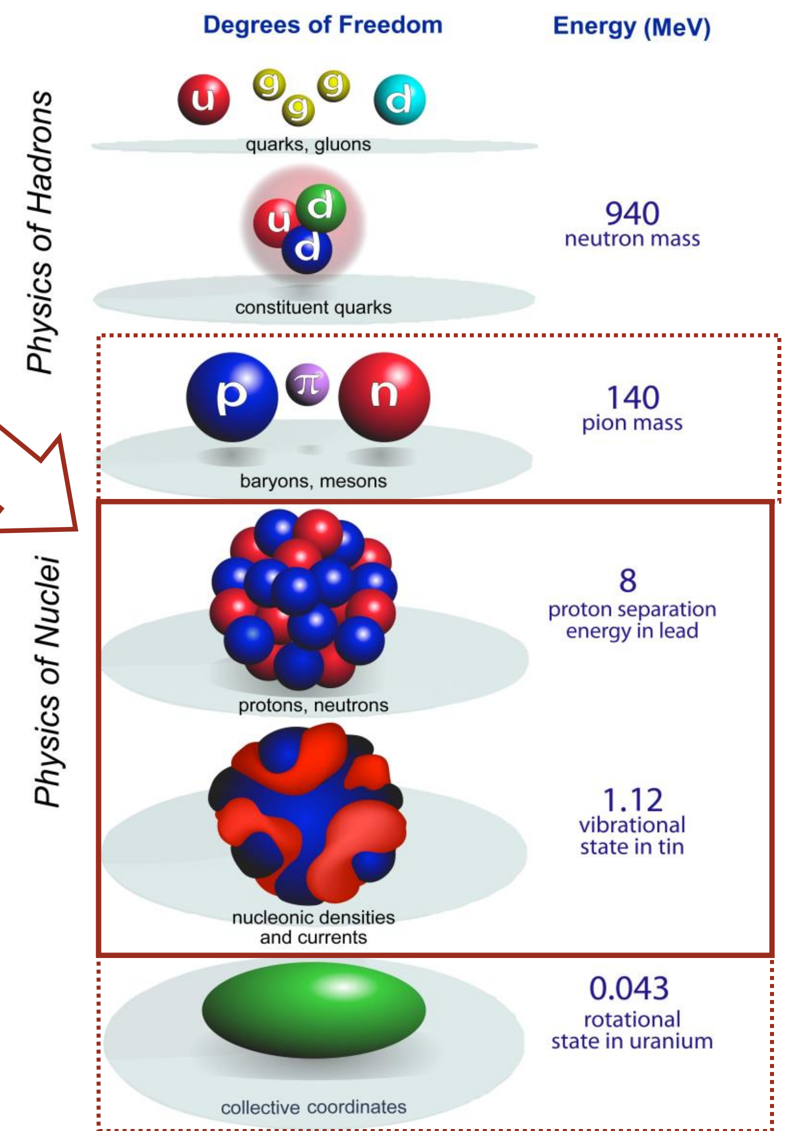
- ❖ Symmetries -> Eqs. of motion

Galilean inv. -> Schrödinger Eq.
Lorentz inv. -> Dirac & Klein-Gordon Eqs.

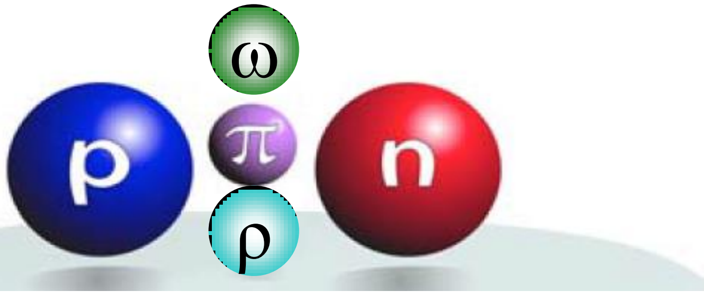
- ❖ Interaction V_{NN} : 3 basic concepts

Ab initio: from vacuum V_{NN} -> in-medium V_{NN}
Density functional: an ansatz for in-medium V_{NN}
Configuration interaction: matrix elements for in-medium V_{NN}

Separation of the scales

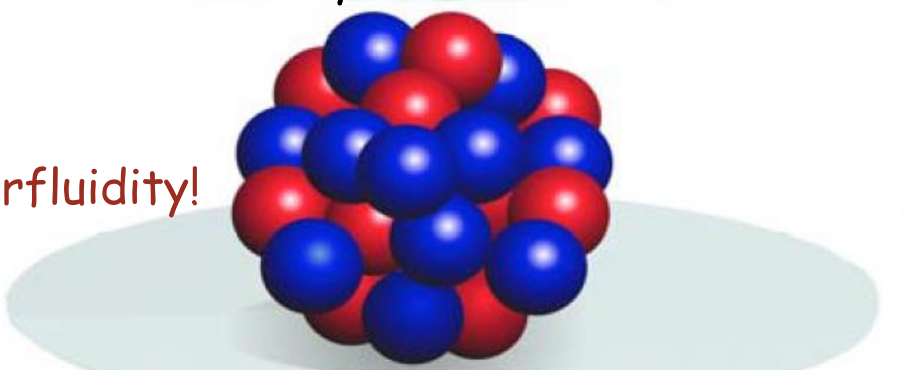


Nucleons, mesons, phonons



m_π ~140 MeV, m_ρ ~770 MeV, m_ω ~783 MeV

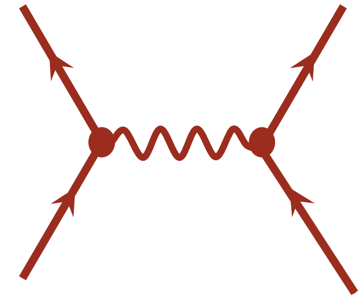
+ superfluidity!



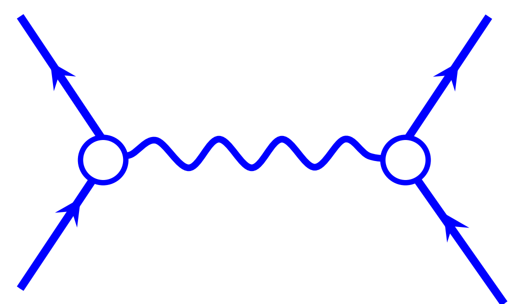
Nucleon separation energies: ~1-10 MeV

Emerging collective phonons: ~1-10 MeV

Short range:
Mean-field approximation



Strong coupling:
non-perturbative techniques

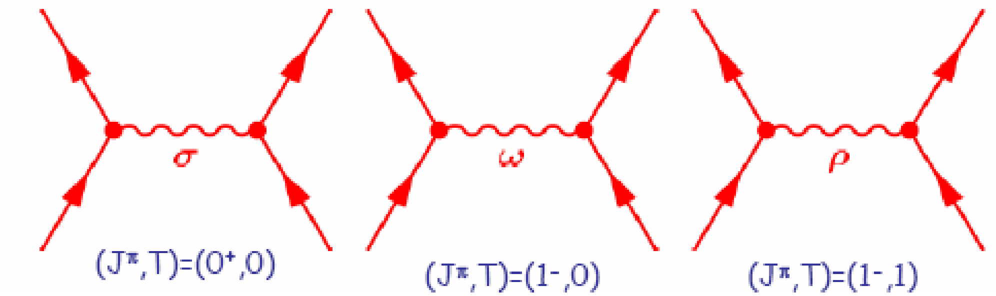


Long range:
Time blocking

Covariant density functional theory

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

Walecka model
+ later modifications
(P. Ring et al.)



Lorentz symmetry

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

Sigma-meson:
attractive scalar field

Omega-meson:
short-range repulsive

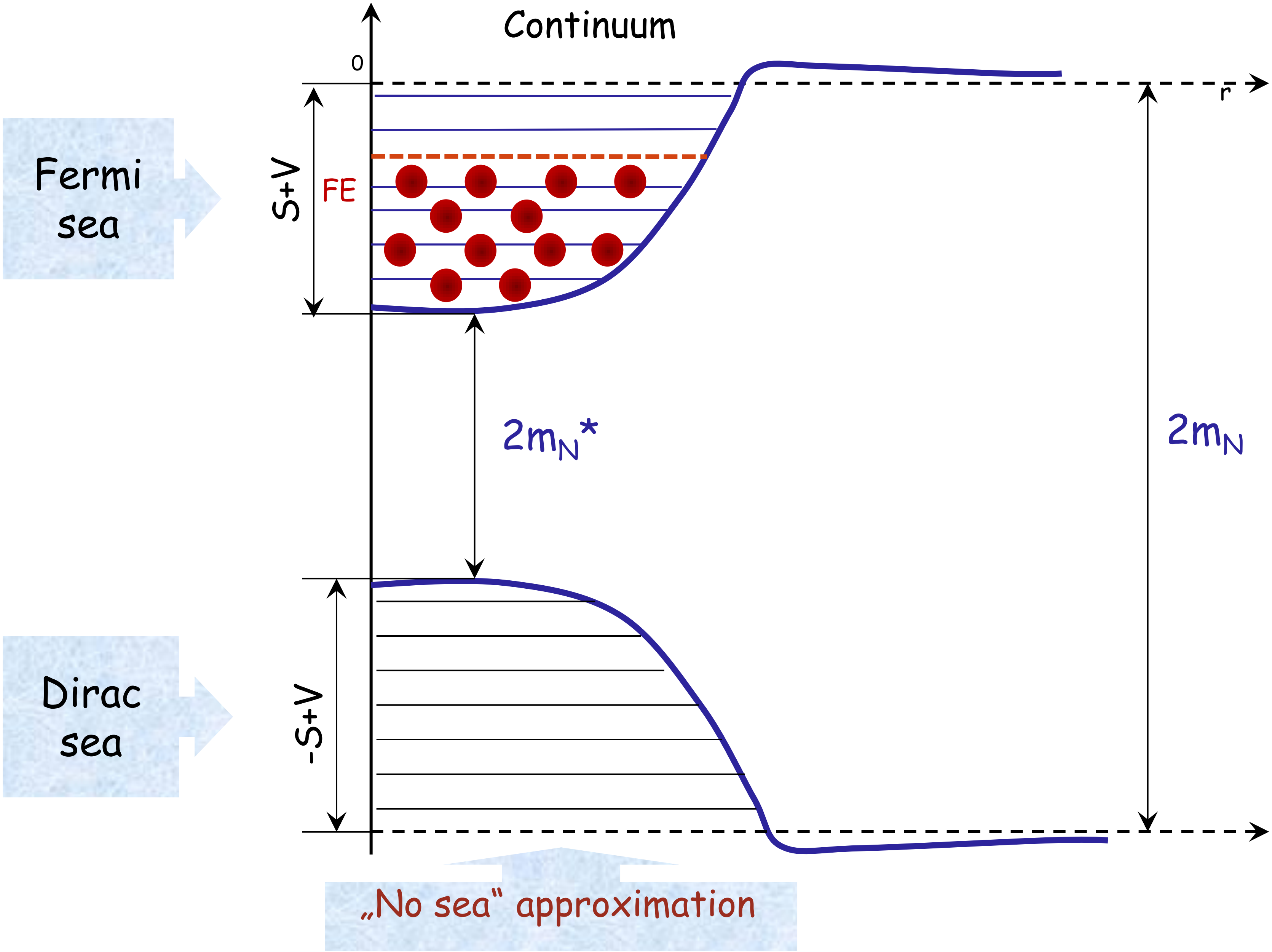
Rho-meson:
isovector field

$$\boxed{E_{RHB}[\hat{\rho}, \hat{\varkappa}, \hat{\varkappa}^*, \phi] = E_{RMF}[\hat{\rho}, \phi] + E_{pair}[\hat{\varkappa}, \hat{\varkappa}^*]}$$

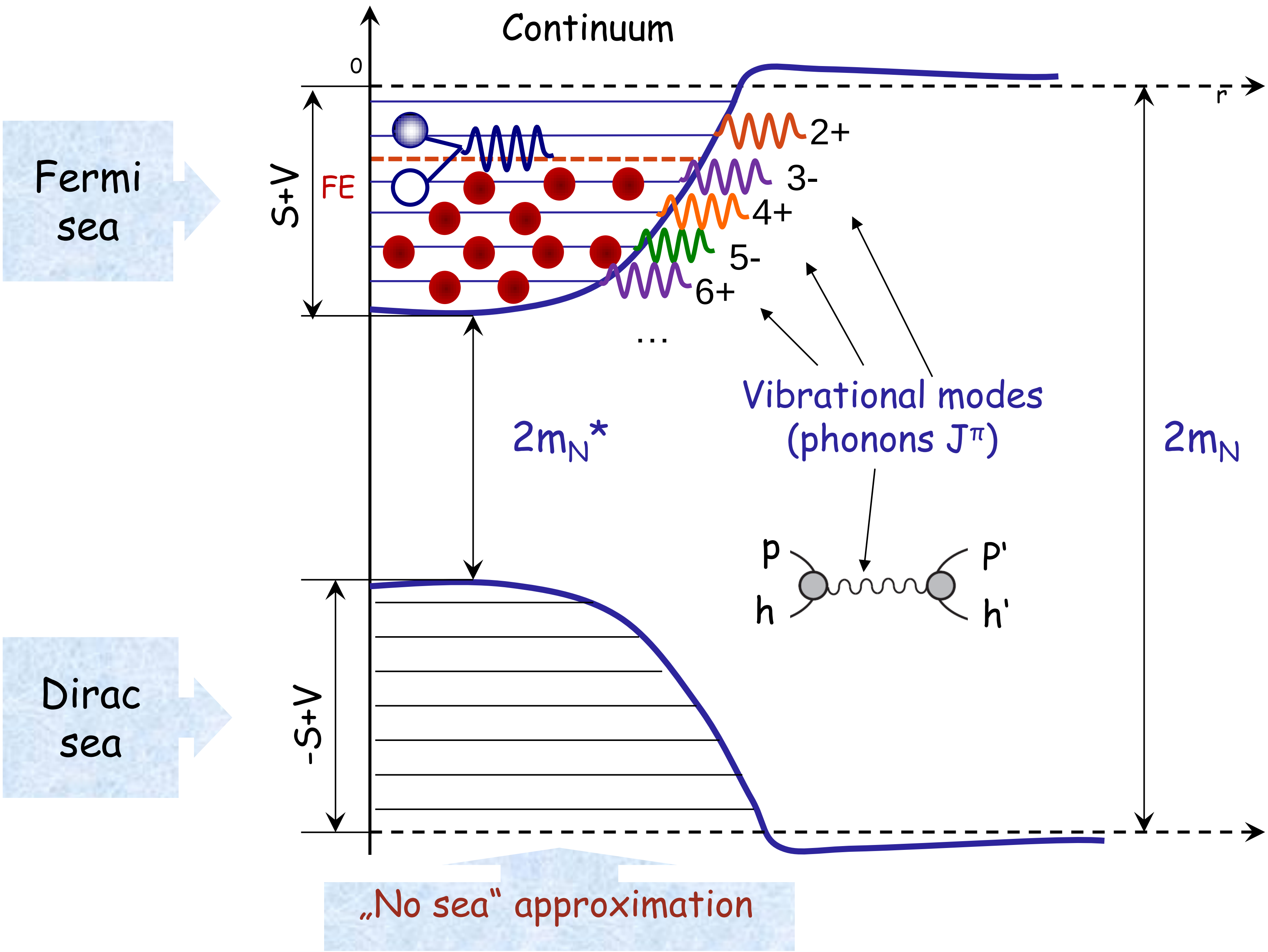
$$E_{RMF}[\hat{\rho}, \phi] = Tr[(\boldsymbol{\alpha}\mathbf{p} + \beta m)\hat{\rho}] + \sum_m \left\{ Tr[(\beta\Gamma_m \phi_m)\hat{\rho}] \mp \int \left[\frac{1}{2}(\boldsymbol{\nabla}\phi_m)^2 + U(\phi_m)\right] d^3r \right\}$$

nucleons　　interaction　　mesons (as classical fields)

Uncorrelated ground state as the zero approximation: Relativistic Mean Field (RMF)

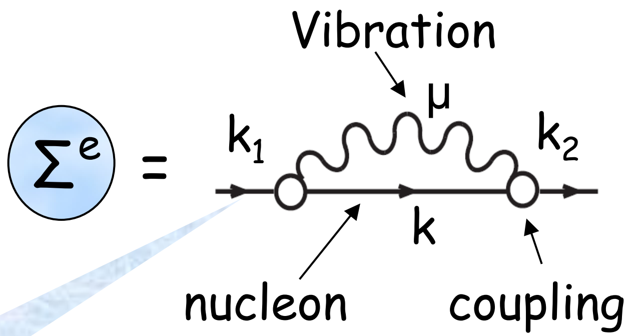


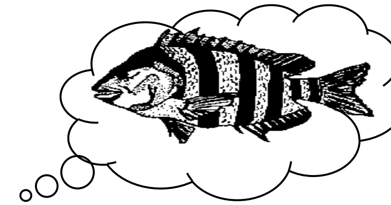
Small perturbation =>
Coherent oscillations of the mean nuclear potential



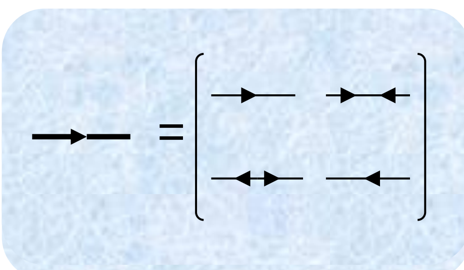
First step beyond relativistic mean field: quasiparticles coupled to vibrations

Additional "potential"
= "self-energy" =
= "mass operator"
with energy dependence





"Fish" diagram

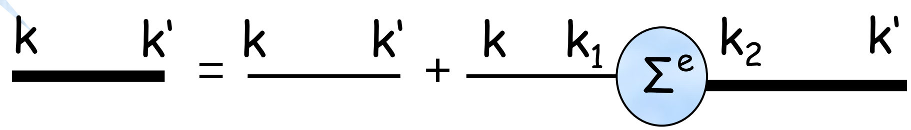


Nambu-Gor'kov
2 x 2 matrices:

One-body propagator G:
Dyson's equation

$$\left(\varepsilon - \hat{\mathcal{H}}_{RHB} - \hat{\Sigma}^{(e)}(\varepsilon)\right)\hat{G}(\varepsilon) = 1$$

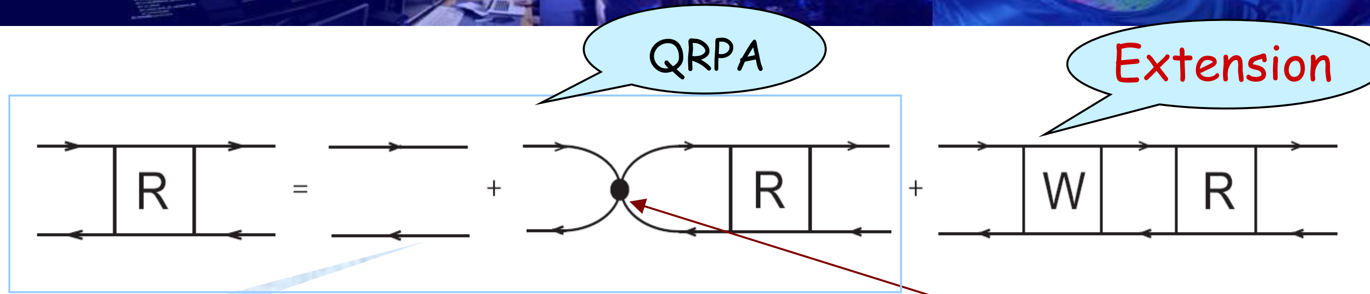
Energy dependence

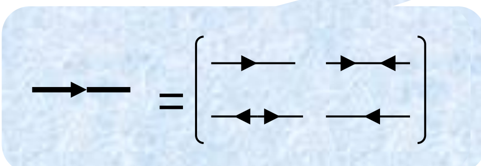


$$G \quad = \quad G_0 \quad + \quad G_0 \quad \Sigma^e \quad G$$

Excited states: linear response function

Bethe-Salpeter Equation (BSE):





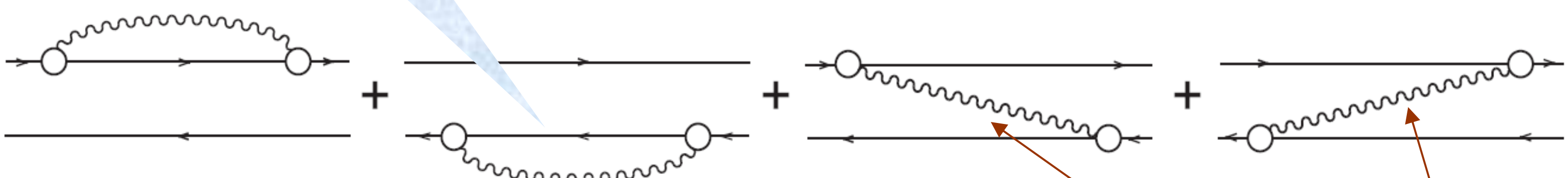
$$R(\omega) = A(\omega) + A(\omega)\left[V + W(\omega)\right] R(\omega)$$

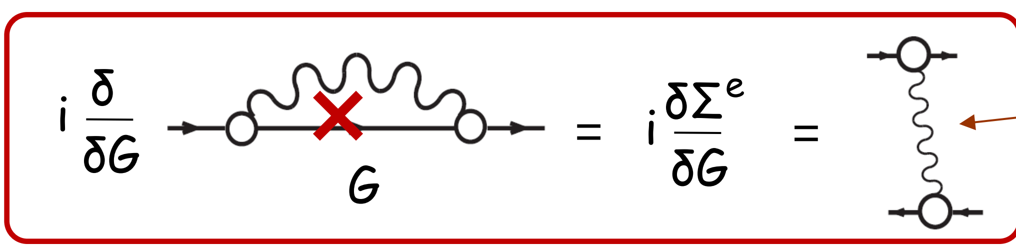
$$V = \frac{\delta\Sigma^{RMF}}{\delta\rho}$$

Self-consistency

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

$\Phi =$





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

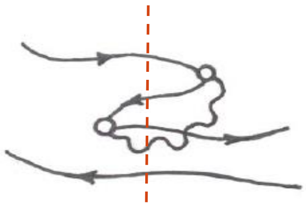
Consistency on 2p2h-level

Time blocking

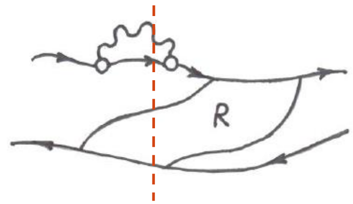
Problem:

'Melting' diagrams

3p3h



NpNh



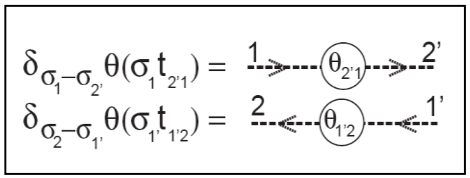
Time

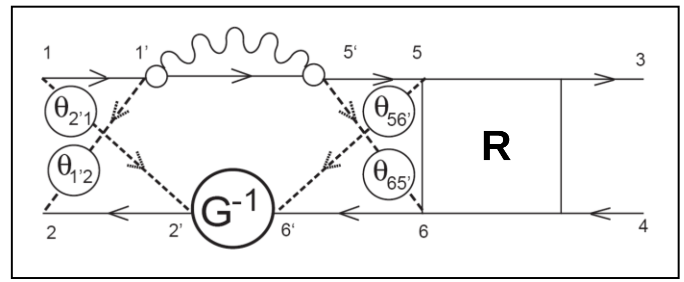
Approx. schemes

Unphysical result: negative cross sections

Solution:

Time-projection operator:

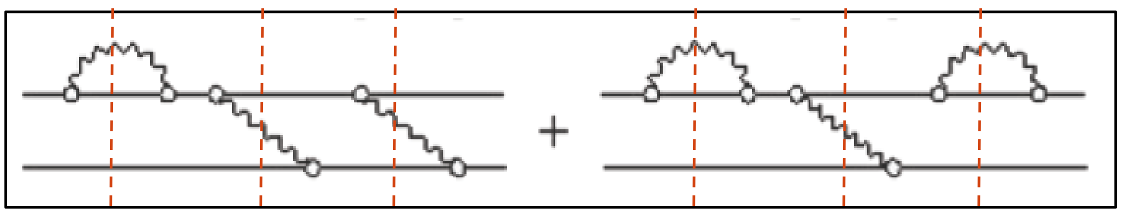




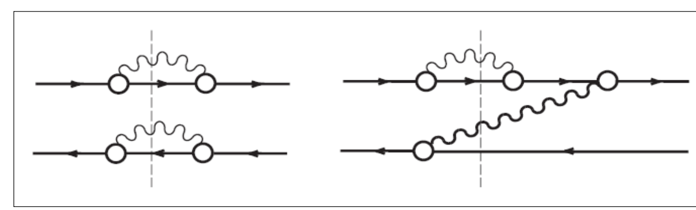
Partially fixed

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 a simple-pole structure (spectral representation)
  »» Strength function is positive definite!

Spin-isospin response function

response

$$R(\omega) = \tilde{R}^0(\omega) + \tilde{R}^0(\omega)\overline{W}(\omega)R(\omega)$$

interaction

$$\overline{W}(\omega) = V_\rho + V_\pi + V_{\delta\pi} + \Phi(\omega) - \Phi(0)$$

Subtraction to avoid double counting

Static: RRPA

$$V_\rho(1,2) = g_\rho^2 \vec{\tau}_1\vec{\tau}_2(\beta\gamma^\mu)_1(\beta\gamma_\mu)_2 D_\rho(\mathbf{r}_1,\mathbf{r}_2)$$

$$V_\pi(1,2) = -\left(\frac{f_\pi}{m_\pi}\right)^2 \vec{\tau}_1\vec{\tau}_2(\mathbf{\Sigma}_1\nabla_1)(\mathbf{\Sigma}_2\nabla_2)D_\pi(\mathbf{r}_1,\mathbf{r}_2),$$

$$V_{\delta\pi}(1,2) = g'\left(\frac{f_\pi}{m_\pi}\right)^2 \vec{\tau}_1\vec{\tau}_2\mathbf{\Sigma}_1\mathbf{\Sigma}_2\delta(\mathbf{r}_1 - \mathbf{r}_2)$$

Dynamic:

particle-vibration coupling

in time blocking approximation

$$\Phi^\eta_{k_1k_4,k_2k_3}(\omega) =$$

$$= \sum_{\mu\xi}\delta_{\eta\xi}\Bigg[\delta_{k_1k_3}\sum_{k_6}\frac{\gamma^{\eta;-\xi}_{\mu;k_6k_2}\gamma^{\eta;-\xi*}_{\mu;k_6k_4}}{\eta\omega - E_{k_1} - E_{k_6} - \Omega_\mu} + \delta_{k_2k_4}\sum_{k_5}\frac{\gamma^{\eta;\xi}_{\mu;k_1k_5}\gamma^{\eta;\xi*}_{\mu;k_3k_5}}{\eta\omega - E_{k_5} - E_{k_2} - \Omega_\mu}$$

$$-\left(\frac{\gamma^{\eta;\xi}_{\mu;k_1k_3}\gamma^{\eta;-\xi*}_{\mu;k_2k_4}}{\eta\omega - E_{k_3} - E_{k_2} - \Omega_\mu} + \frac{\gamma^{\eta;\xi*}_{\mu;k_3k_1}\gamma^{\eta;-\xi}_{\mu;k_4k_2}}{\eta\omega - E_{k_1} - E_{k_4} - \Omega_\mu}\right)\Bigg]$$

Response to an external field: strength function

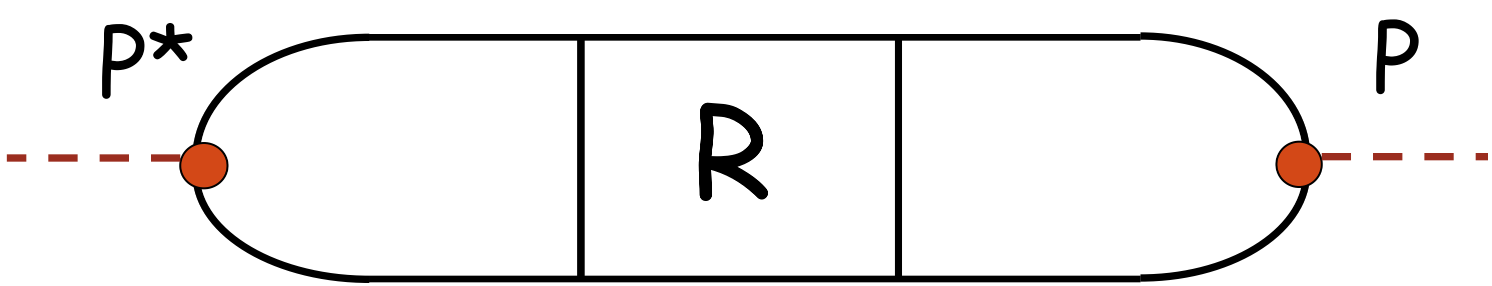
Strength function:

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

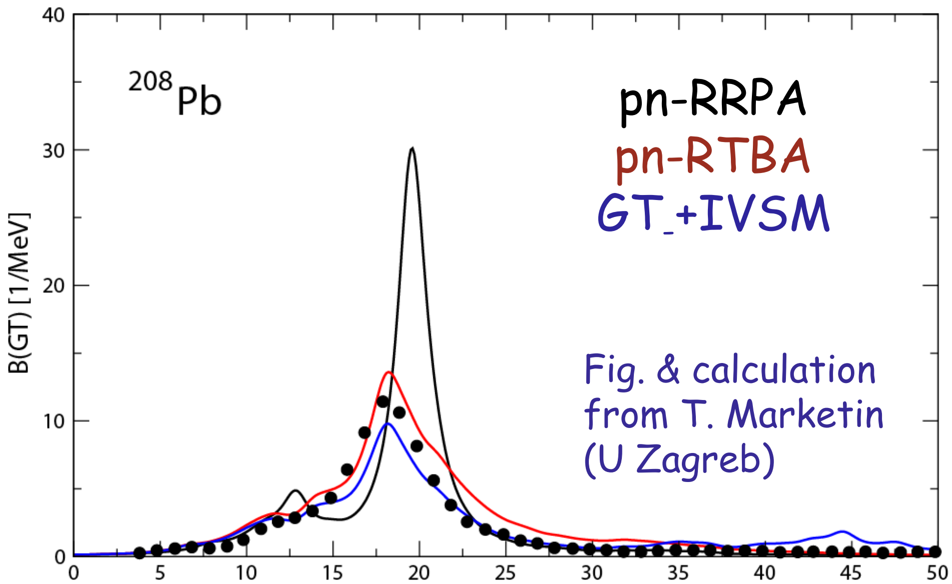
Polarizability:

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

External field

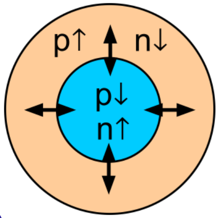


Gamow-Teller Resonance with finite momentum transfer



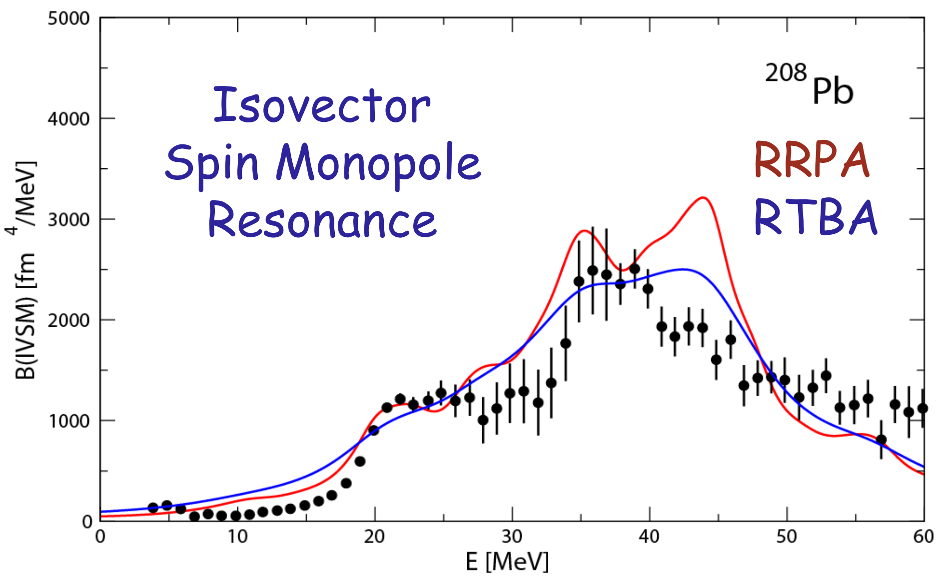
$$P = \sum_i \sigma^{(i)} \tau_{\pm}^{(i)}$$

Finite q:
a correction for
Isovector spin monopole
resonance
(IVSMR) – overtone of GTR



$$j_0(qr) \approx 1 - \frac{q^2r^2}{6} + \cdots$$

ΔL = 0
ΔT = 1
ΔS = 1



„Microscopic" quenching of B(GT):

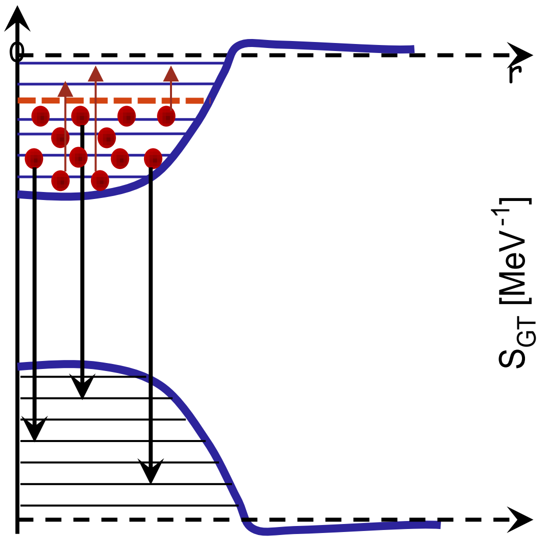
(i) relativistic effects,

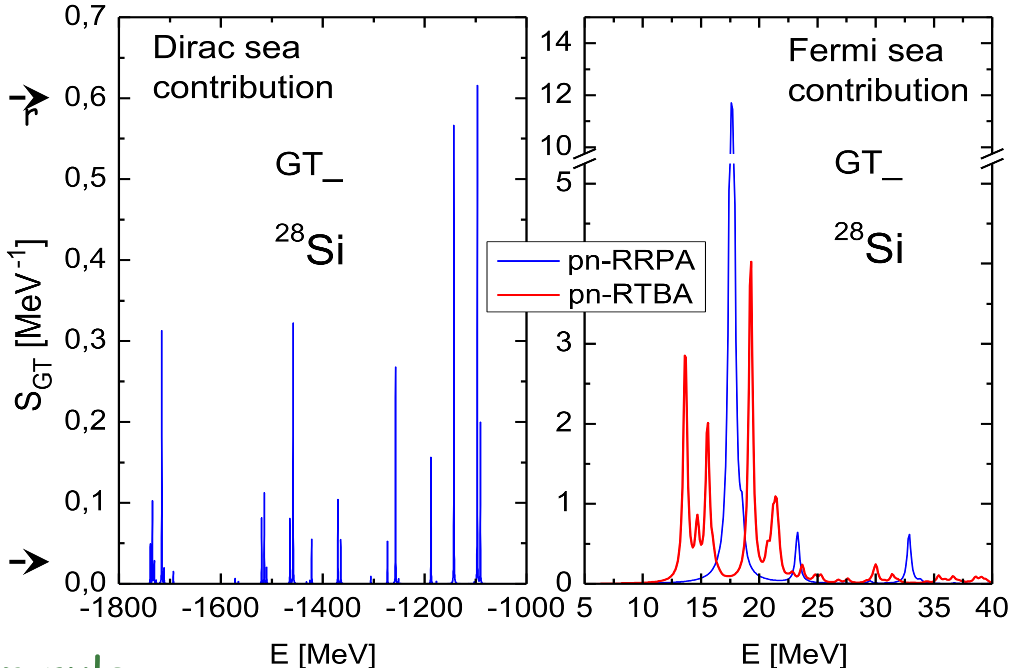
(ii) ph+phonon configurations,

(iii) finite momentum transfer

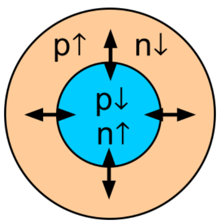
Spin-isospin response: Gamow-Teller Resonance in 28-Si

„Proton-neutron" relativistic time blocking approximation (pn-RTBA): ρ, π, phonons





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

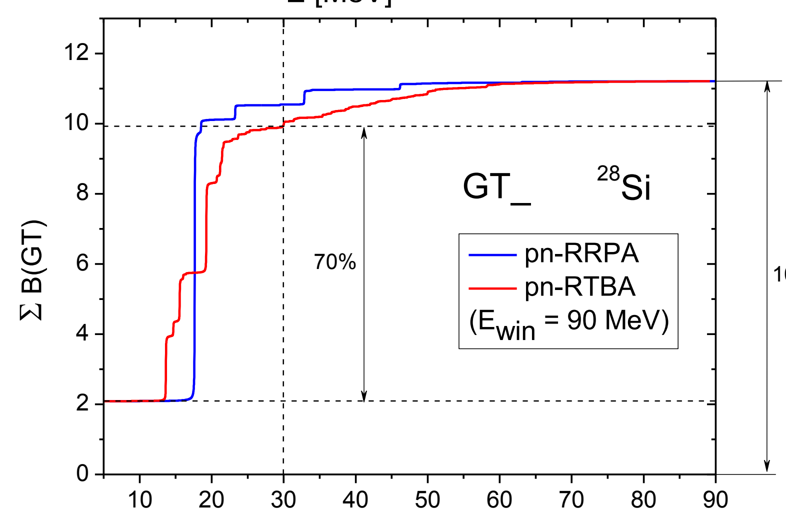


ΔL = 0
ΔT = 1
ΔS = 1

Ikeda Sum rule
(model independent):

$S_- - S_+ = 3(N - Z)$,
$S\pm = \sum B(GT \pm)$

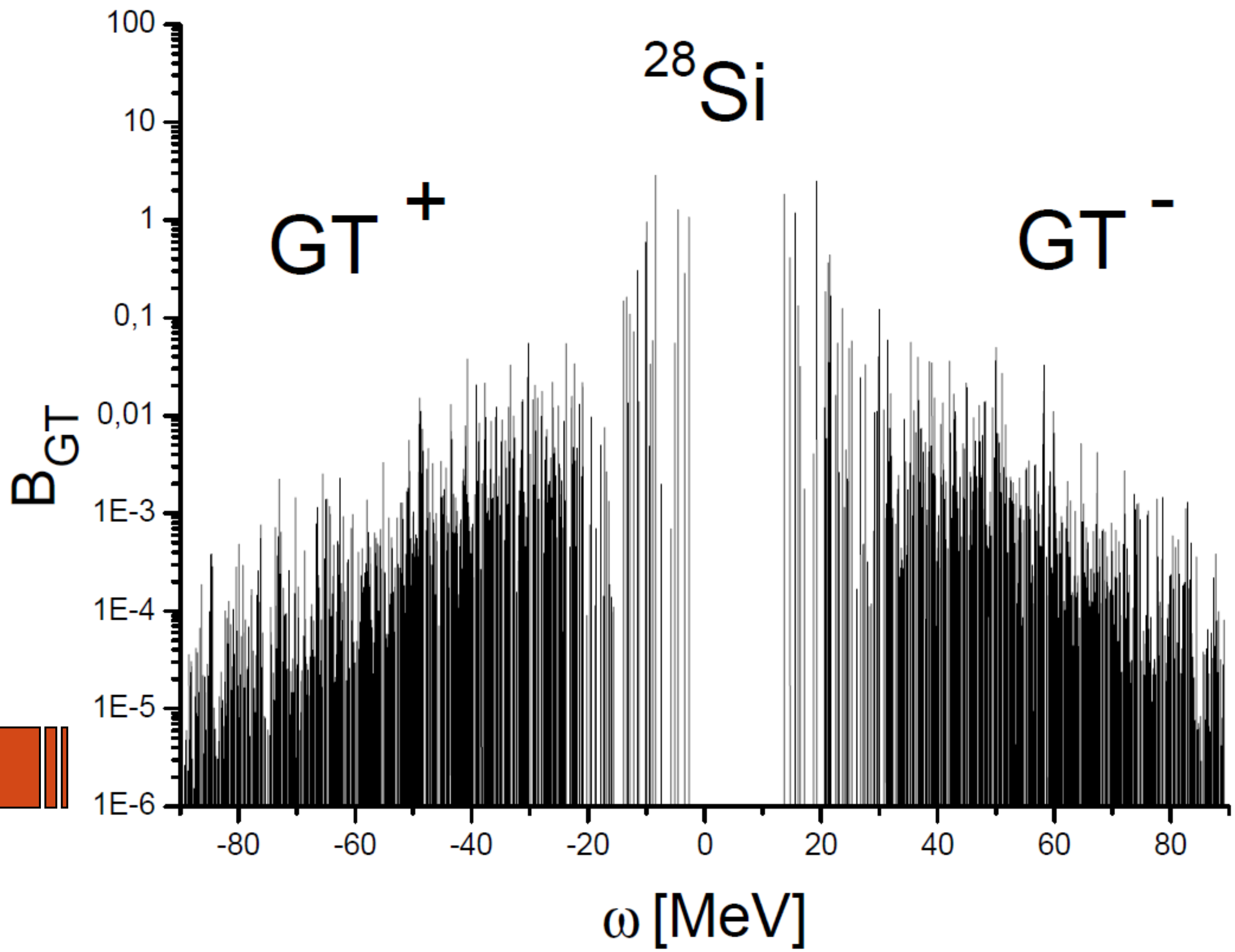
„Microscopic" quenching of B(GT):
(i) relativistic effects,
(ii) ph+phonon configurations,

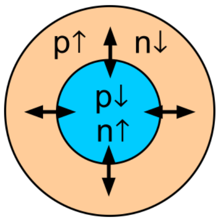


(?)

^{28}Si: N=Z

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





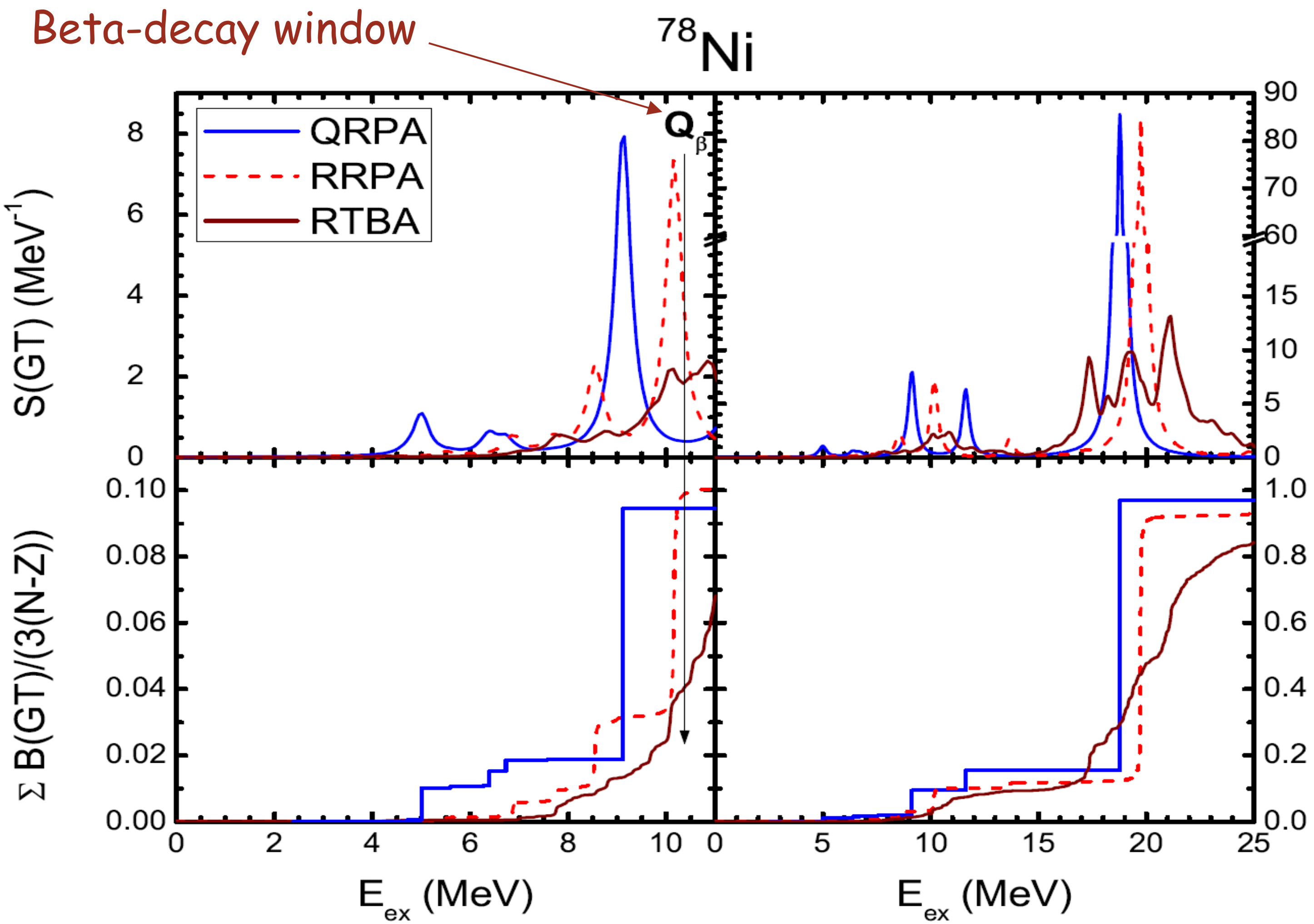
ΔL = 0
ΔT = 1
ΔS = 1

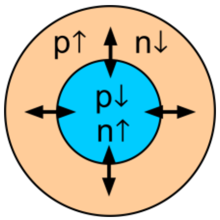
?

?

Problem: finite basis

GTR in 78-Ni: G-matrix+QRPA, RRPA and RTBA





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

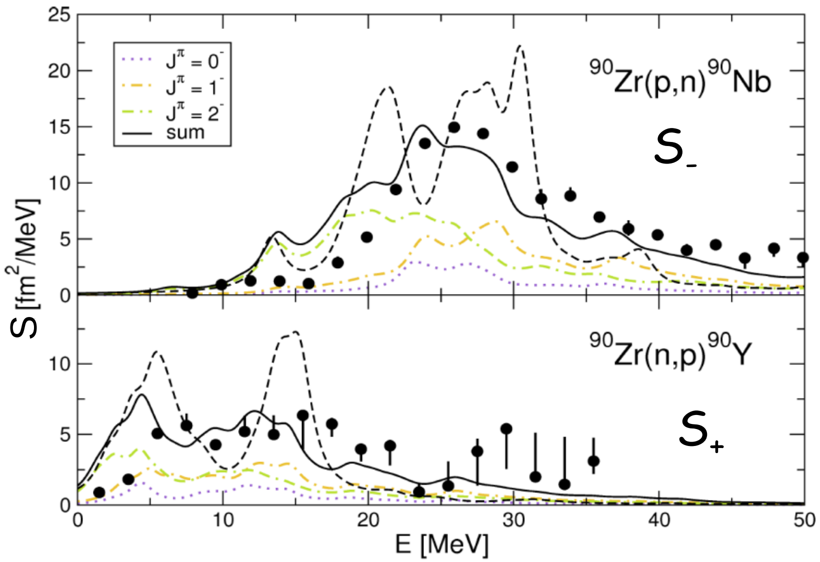
G-matrix+QRPA based on Skyrme DFT with m* = 1 (D.-L. Fang & A. Fässler & B.A. Brown)

RTBA: Relativistic RPA + phonon coupling (T. Marketin & E.L.)

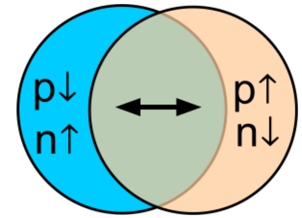
E.L., B.A. Brown, D.-L. Fang, T. Marketin, R.G.T. Zegers, PLB 730, 307 (2014)

Spin-dipole resonance: beta-decay, electron capture

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



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



- - - - - -	RQRPA
———	RQTBA

ΔL = 1

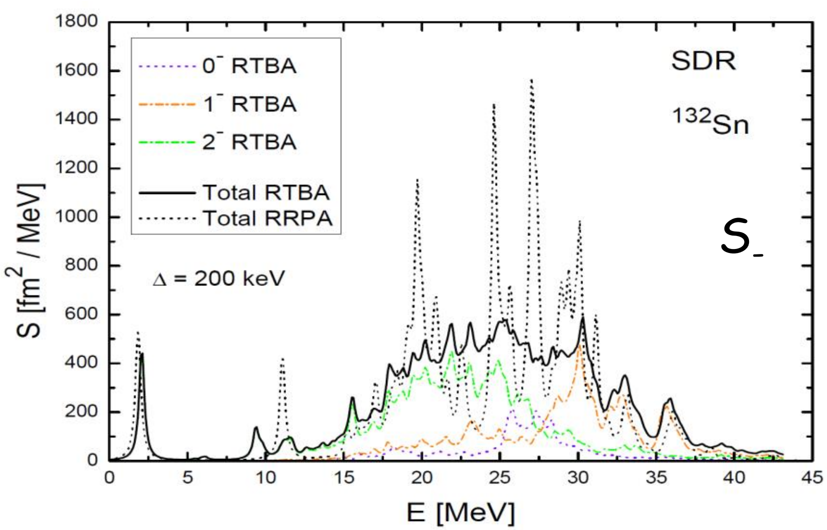
ΔT = 1 λ = 0,1,2

ΔS = 1

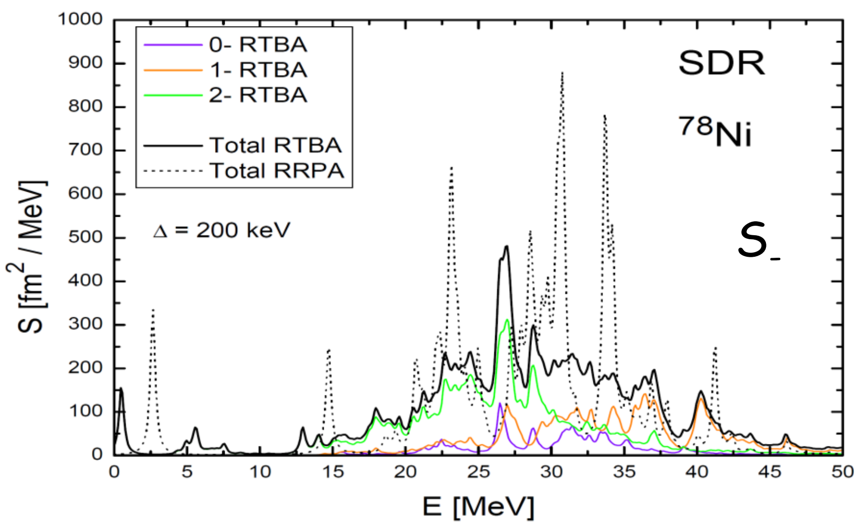
Skin thickness: $\delta_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p}$

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

Measured recently at RIKEN:



To be measured in the future (?)



Summary and outlook

Conclusions:

- Fully self-consistent and covariant response theory (pn-RTBA) is formulated and applied to spin-isospin excitations in ordinary and exotic nuclei

- The approach is tested and benchmarked by comparison to data and to other existing approaches (non-rel. QRPA & shell-model)

- The pn-RTBA has a great potential to describe simultaneously the overall strength distribution up to high excitation energy, fine structure and quenching of spin-isospin strength

- Applications to beta-decay, double beta-decay, r-process etc.

Perspectives:

- Extension to superfluid systems (underway)

- Implementation of higher-order correlations, two-body currents

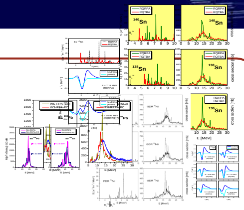
- Understanding the role of 2- states in the phonon basis, connecting QVC and tensor forces

- Solution for the finite-basis problem, …

Outlook

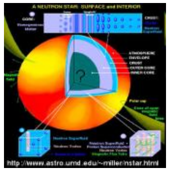
New

Consistent input for r-process nucleosynthesis



Applications

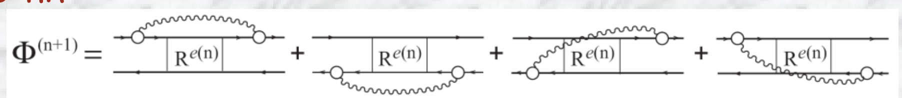
Nuclear matter, Neutron stars, …



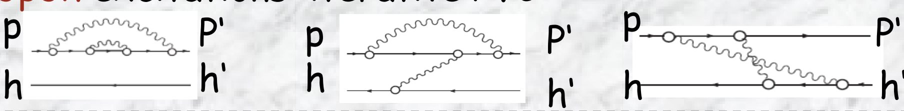
Data => Constraints from RIB facilities

np-nh

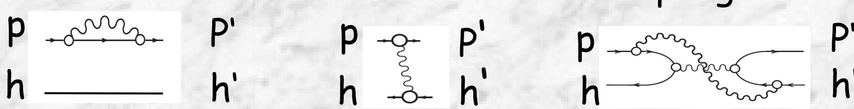
$\Phi^{(n+1)} =$



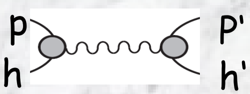
3p3h excitations: iterative PVC



2p2h excitations: Particle-Vibration Coupling



1p1h excitations: RQRPA

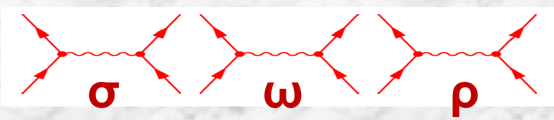


Self-consistency

$$V = \frac{\delta^2 E[R]}{\delta R^2}$$

Time-dependent CEDFT ???

Ground state: Covariant EDFT



E[R]

Generalized CEDFT ???

DD-MEδ CEDFT:
Ab initio Brückner +
4 adjustable parameters
PRC 84, 054309 (2011)

Toward „ab initio“

UNEDF:
DFT from EFT
…

Data => Constraints from RIB facilities

Many thanks for collaboration:

Theory & computing:

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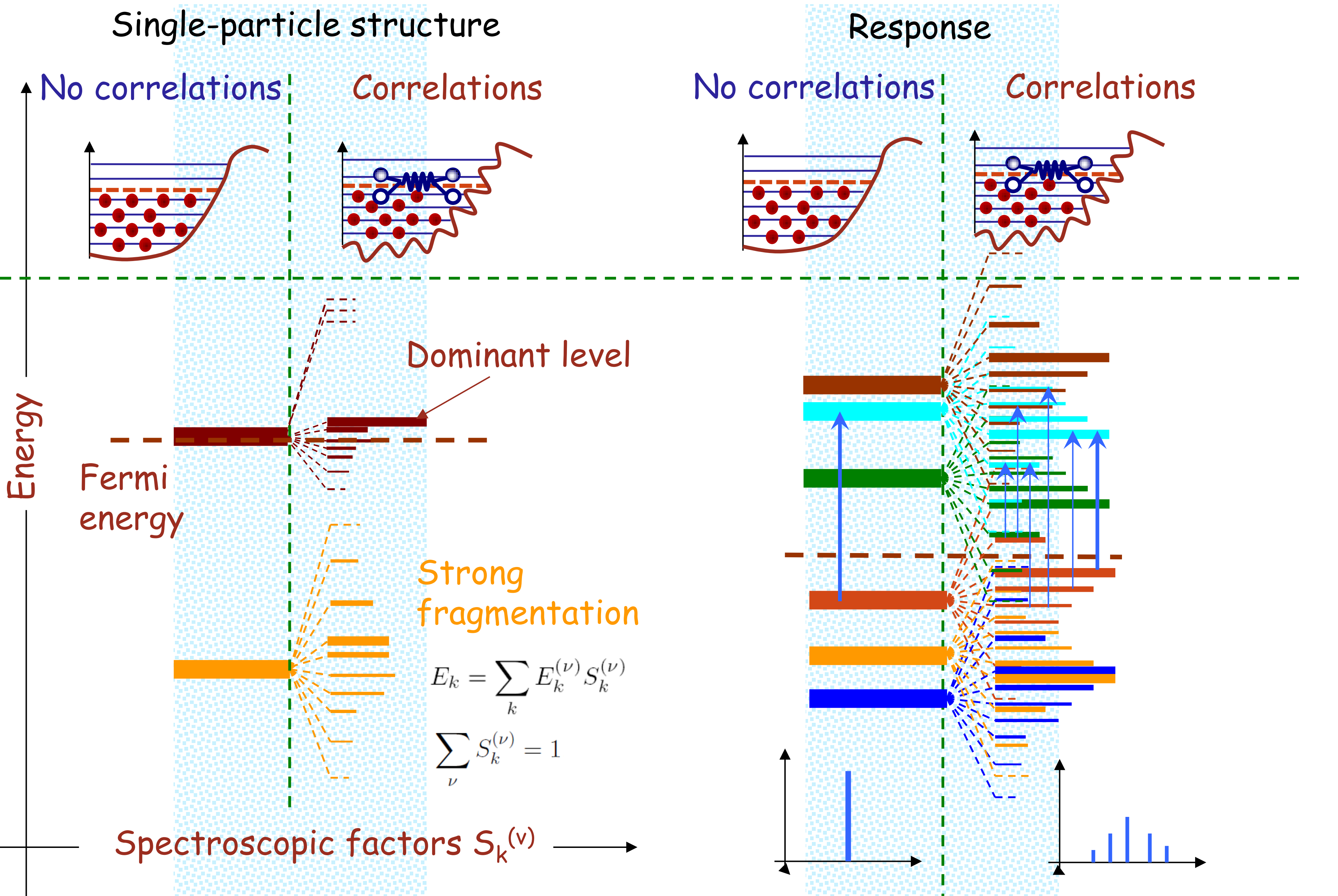
Victor Tselyaev (St. Petersburg State University)
Tomislav Marketin (U Zagreb)

Applications:

B.A. Brown (NSCL),
D.-L. Fang (NSCL)
R.G.T. Zegers (NSCL)
V. G. Zelevinsky (NSCL)

This work supported by NSCL @ Michigan State University and by US-NSF Grants PHY-1204486, PHY-1404343

Fragmentation of states in odd and even systems (schematic)

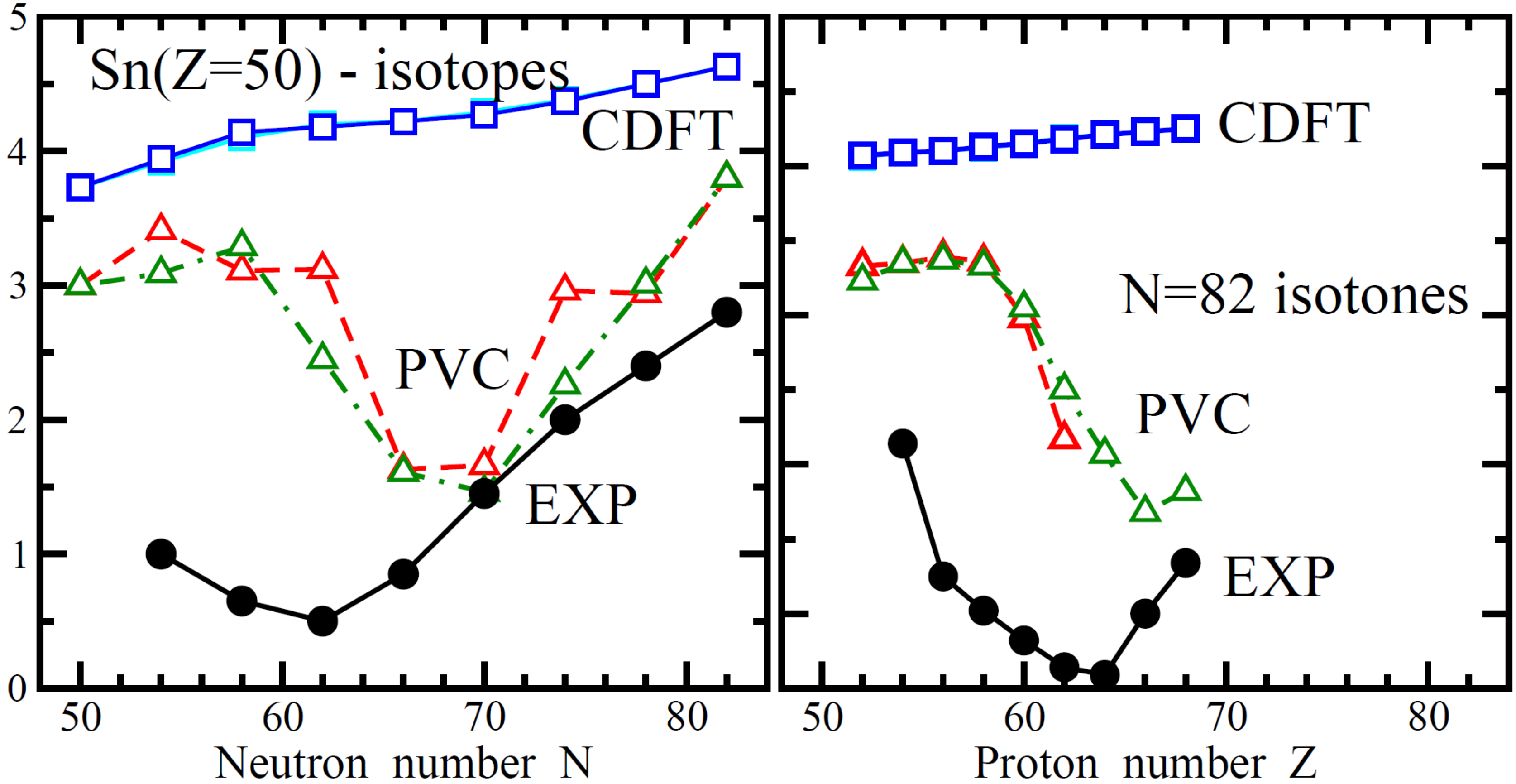


Properties of single-particle states in Z=50 and N=82 nuclei

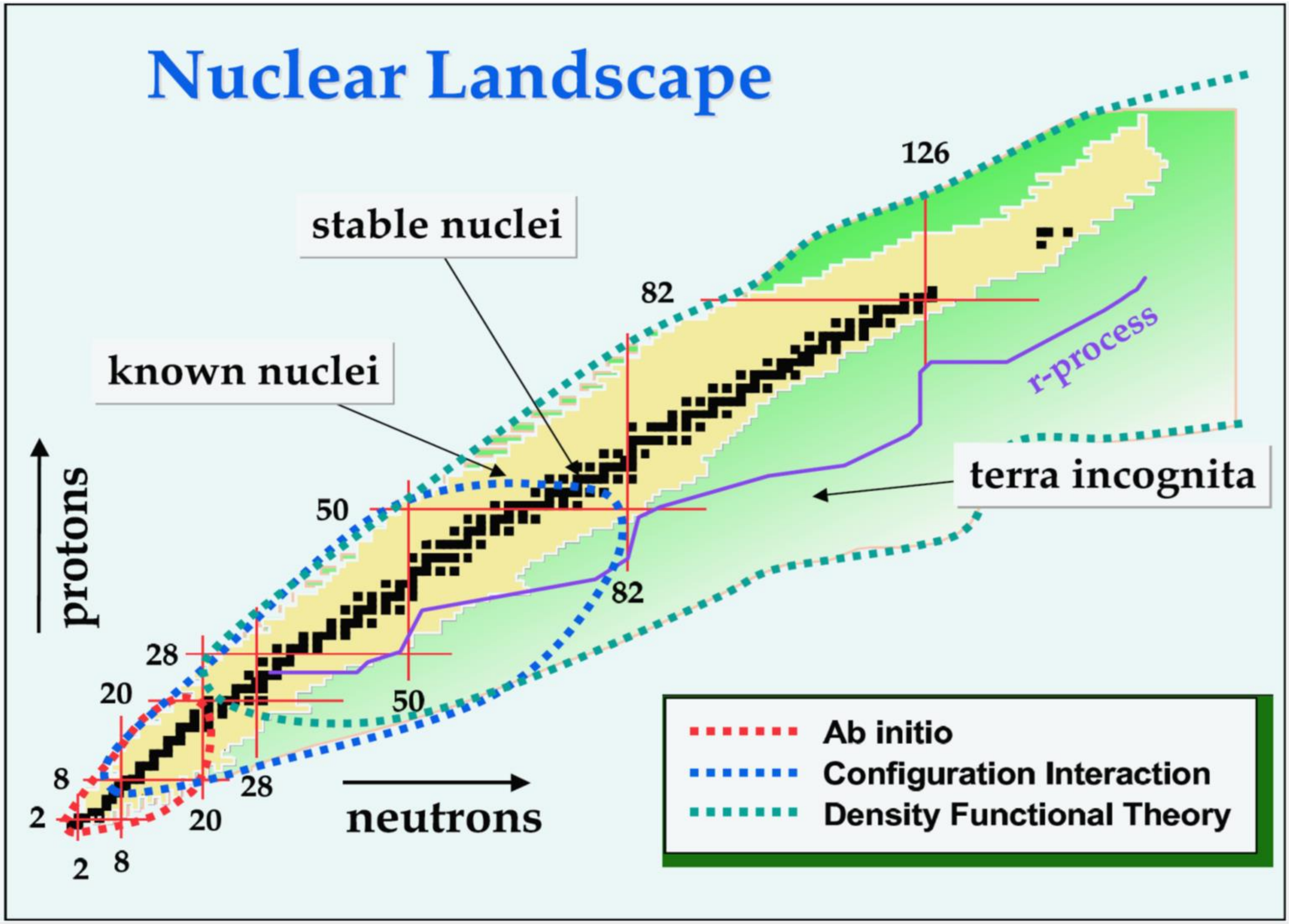
Particle-vibration coupling improves the description of the single-particle states considerably and if the low-lying phonons are described well the single-particle states are reproduced as well.

$E(h_{11/2})-E(g_{7/2})$ protons

$E(i_{13/2})-E(h_{9/2})$ neutrons



Nuclear models



DFT: major part of the nuclear chart => input for astrophysical modeling

Figure from: G.F. Bertsch, J. Phys.: Conf. Ser. 78, 012005 (2007)

Single-quasiparticle Green's function

Doubled quasiparticle space: $\eta = \pm 1$

$$G_k^{\eta}(\varepsilon) = \sum_{\nu,\eta'} \frac{\tilde{S}_k^{\eta'(\nu)}}{\varepsilon - \eta\eta' E_k^{(\nu)}}$$

Spectroscopic factors

Energies

One-body Green's function in N-body system (Lehmann):

$$G(\xi,\xi';\varepsilon) = \sum_n \frac{(\Psi(\xi))_{0n}(\Psi^\dagger(\xi'))_{n0}}{\varepsilon - (E_n^{(N+1)} - E_0^{(N)}) + i\delta} + \\ + \sum_m \frac{(\Psi^\dagger(\xi'))_{0m}(\Psi(\xi))_{m0}}{\varepsilon + (E_m^{(N-1)} - E_0^{(N)}) - i\delta},$$

Model dependence of S!

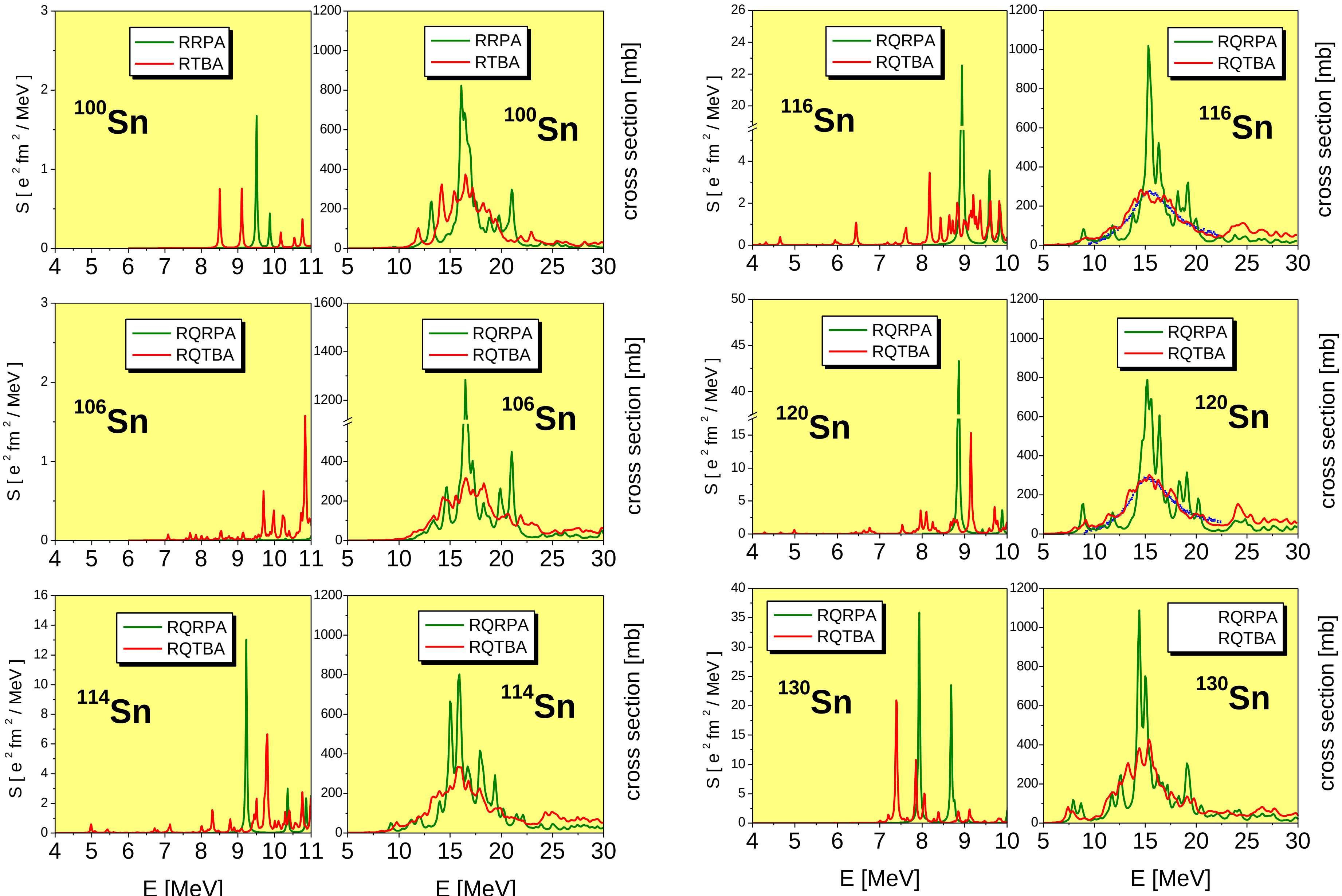
Excited state (N+1)

$$\begin{aligned}(\Psi^\dagger(\xi))_{n0} &= \langle \Phi_n^{(N+1)} | \Psi^\dagger(\xi) | \Phi_0^{(N)} \rangle, \\ (\Psi(\xi))_{n0} &= \langle \Phi_n^{(N-1)} | \Psi(\xi) | \Phi_0^{(N)} \rangle,\end{aligned}$$

Ground state (N)

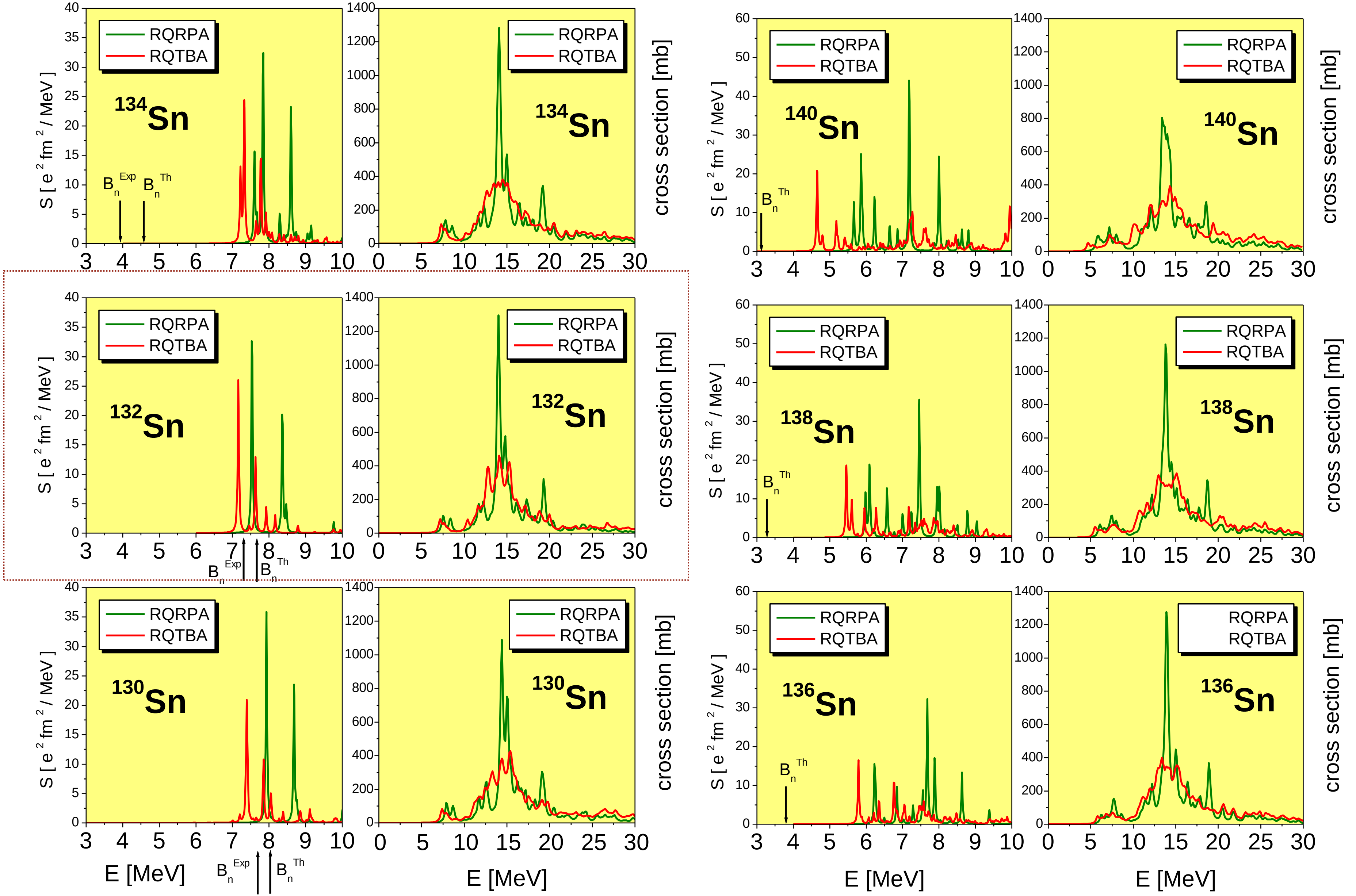
Dipole strength in Sn isotopes

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

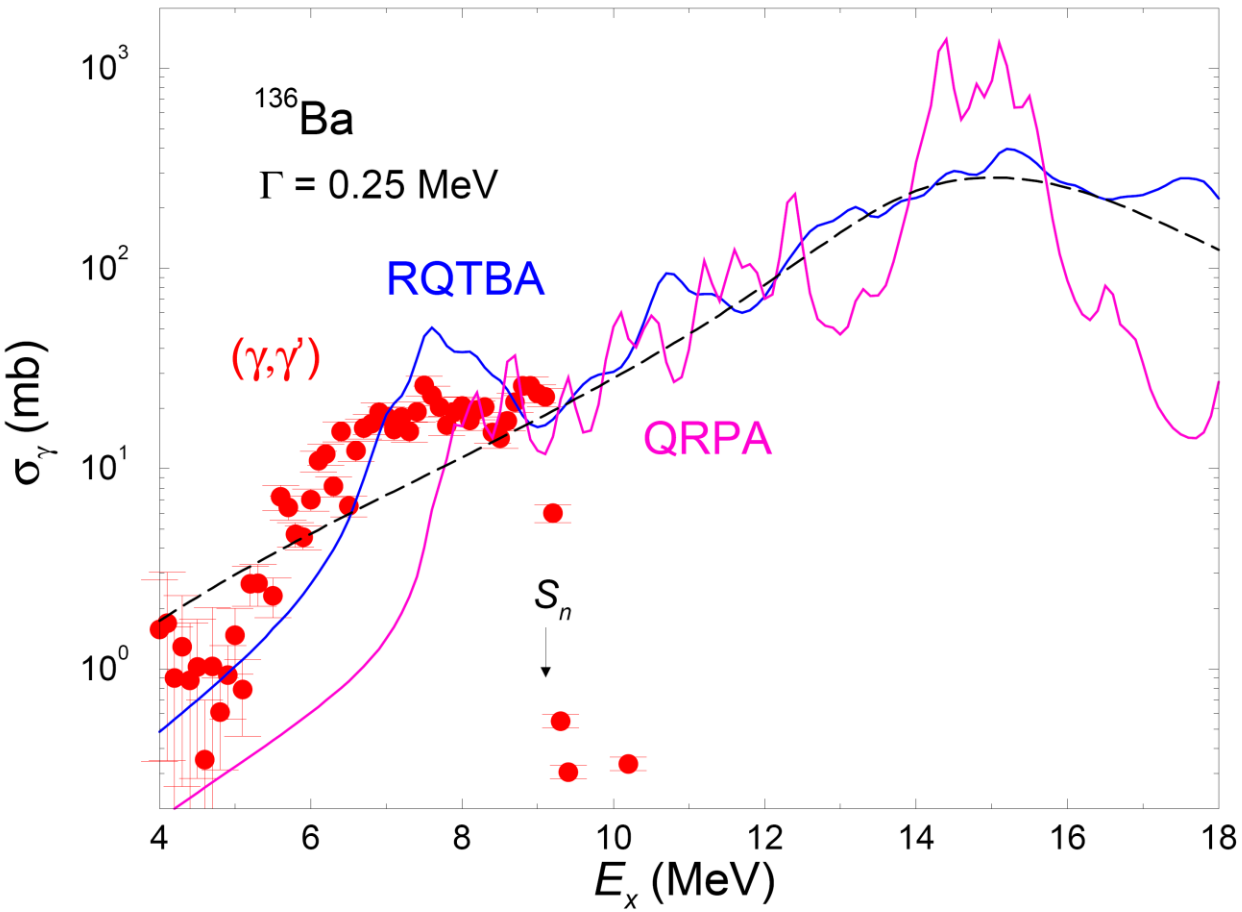


Dipole strength in Sn isotopes

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



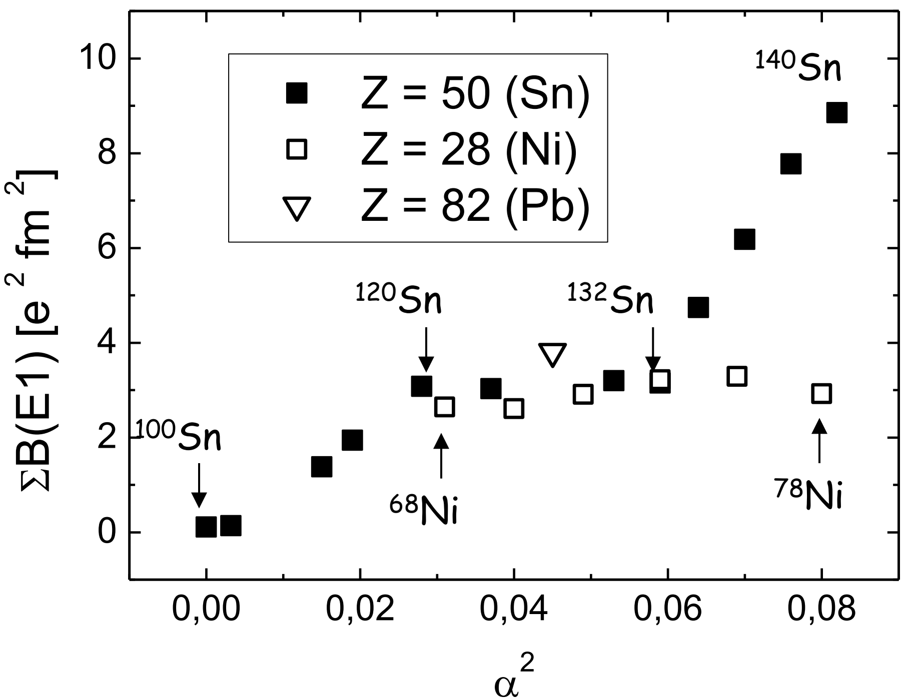
Low-lying dipole strength in 136-Ba



R. Massarczyk, R. Schwengner, F. Doenau, E. Litvinova, G. Rusev et al., Phys. Rev. C 86, 014319 (2012)

RQTBA systematics for PDR:

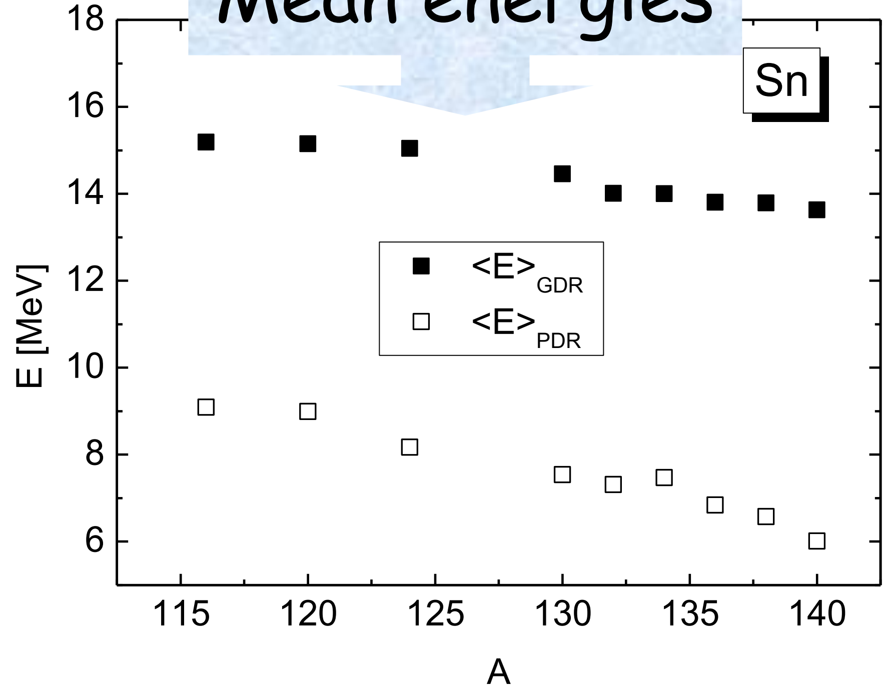
A proper definition of Pygmy Dipole Resonance is important!
PDR = all states with the "isoscalar" underlying structure!



Strength vs α^2

$\alpha = (N - Z)/A$
(Asymmetry parameter)

Mean energies



^{120}Sn → ^{132}Sn: 1h11/2 (n)
^{68}Ni → ^{78}Ni: 1g9/2 (n)

Intruder orbits !

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

Elimination of the spurious state

$$\delta\rho(x;\omega,T) = \frac{\zeta(x;T)}{\omega-\omega_0} + \delta\rho^{reg}(x;\omega,T), \qquad \omega_0 \to 0$$

Condition 1

$$F(x,x') = F^{LM}(x,x') + F^{rest}(x,x')$$

$$F^{LM}(x,x') = C_0\Big[f(x) + f'(x)\boldsymbol{\tau\tau}' + (g(x) + g'(x)\boldsymbol{\tau\tau}')\boldsymbol{\sigma\sigma}'\Big]\delta(\mathbf{r}-\mathbf{r}'),$$

$$f(x) = f_{ex} + (f_{in} - f_{ex})\frac{\rho_0(x)}{\rho_0(0)}$$

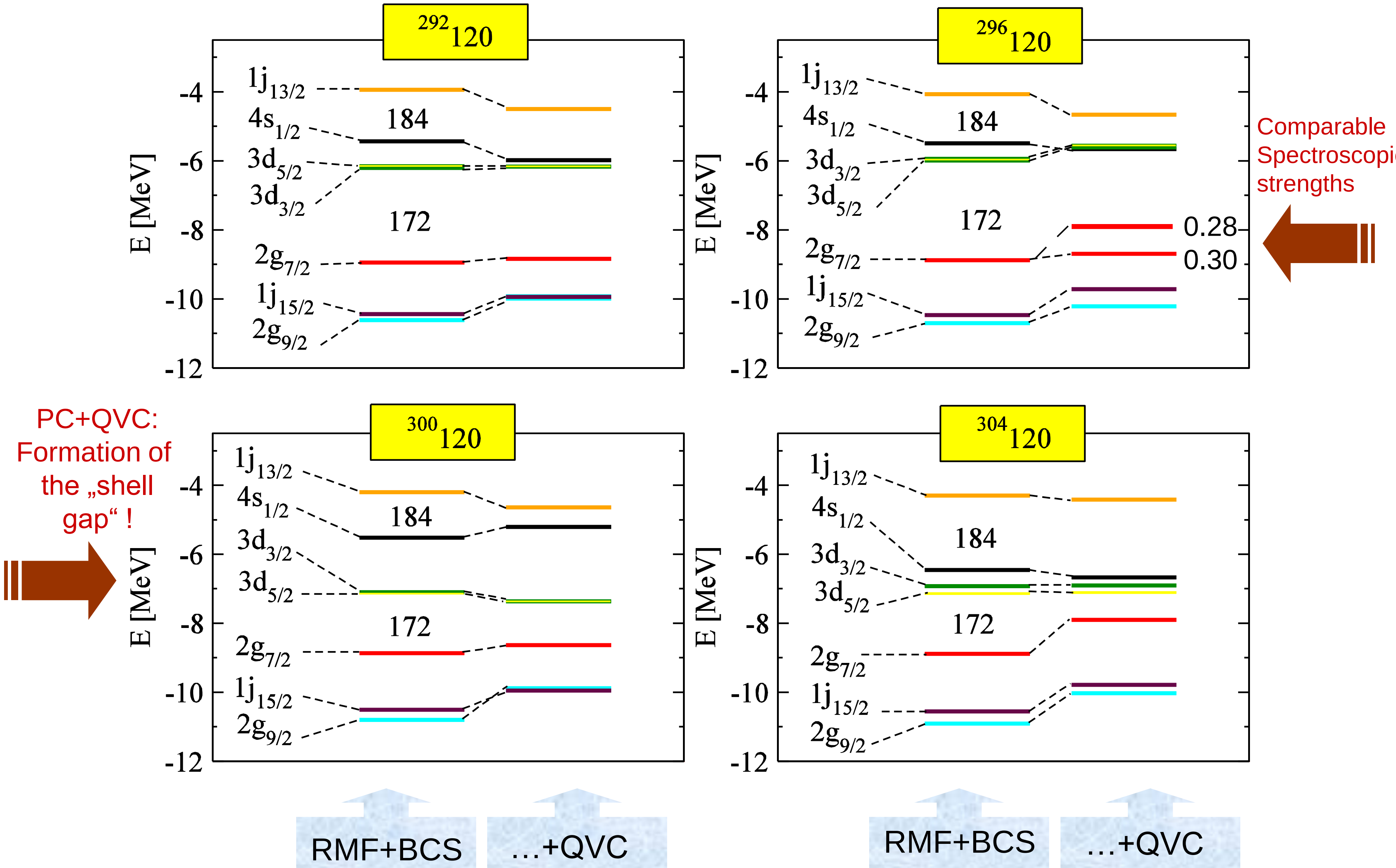
$$F^{rest}(r,r') = \sum_{k=1,2} \kappa_k f_k(x) f_k(x')$$

$$B^{(0)}_{E1} = \int dx\zeta(x,T)P_{E1}(x) = 0$$

Condition 2

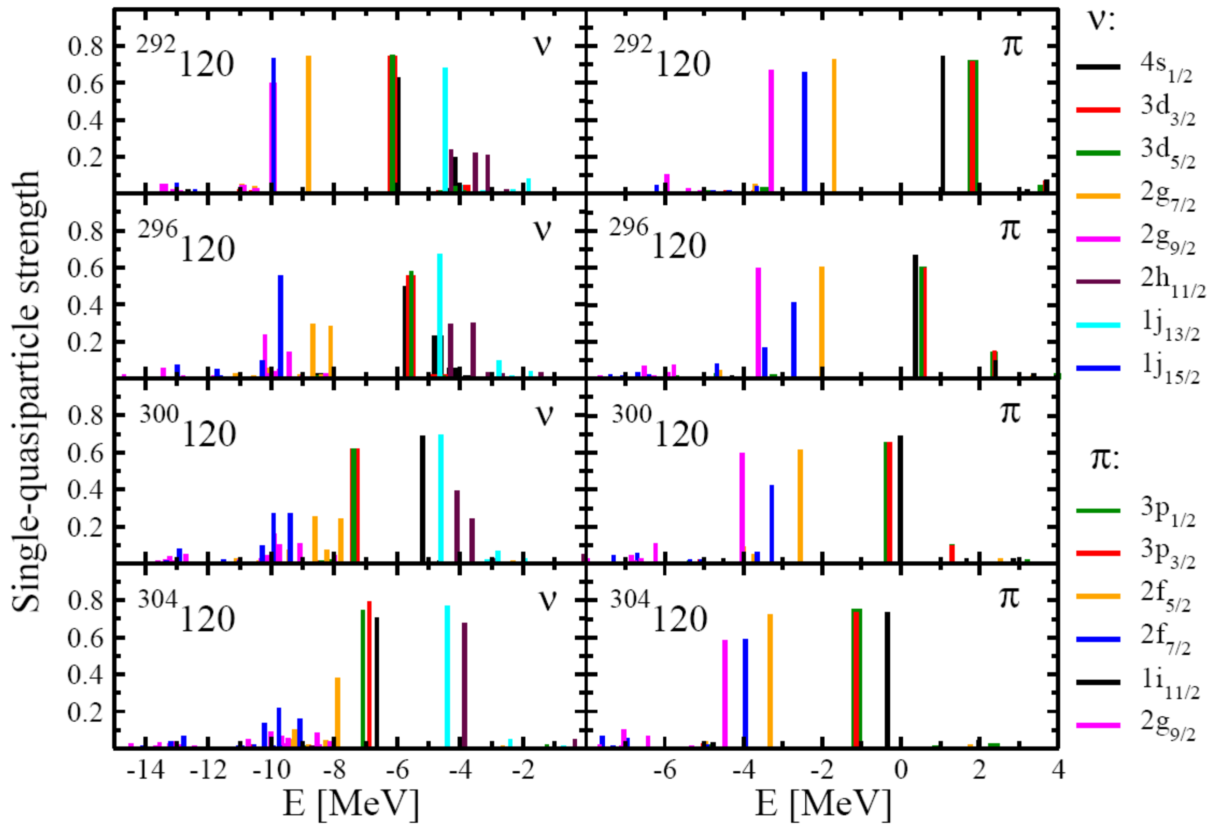
V. Tselyaev: S. Kamerdzhiev et al., PRC 58, 172 (1998)
M.I. Baznat et al., Sov. J. Nucl. Phys. 52, 627 (1990)

Dominant neutron states in Z = 120



Shell evolution in superheavy Z = 120 isotopes: Quasiparticle-vibration coupling (QVC) in a relativistic framework

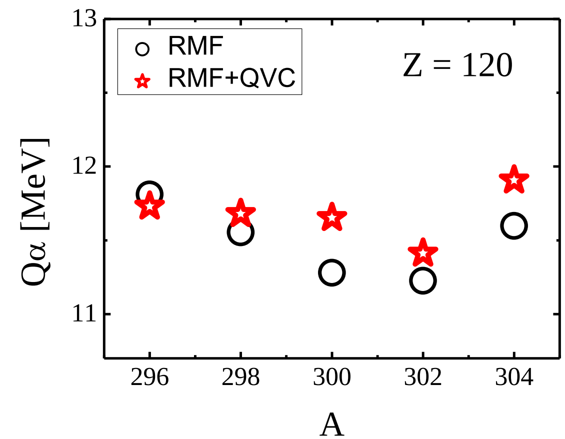
1. Relativistic Mean Field: spherical minima
2. π: collapse of pairing, clear shell gap
3. ν: survival of pairing coexisting with the shell gap
4. Very soft nuclei: large amount of low-lying collective vibrational modes (~100 phonons below 15 MeV)



Vibration corrections to binding energy (RQRPA)

$$E_{VC} = -\sum_{\mu} \Omega_{\mu} \sum_{k_1 k_2} |Y^{\mu}_{k_1 k_2}|^2$$

Vibration corrections to α-decay Q-values



Vibrational corrections:

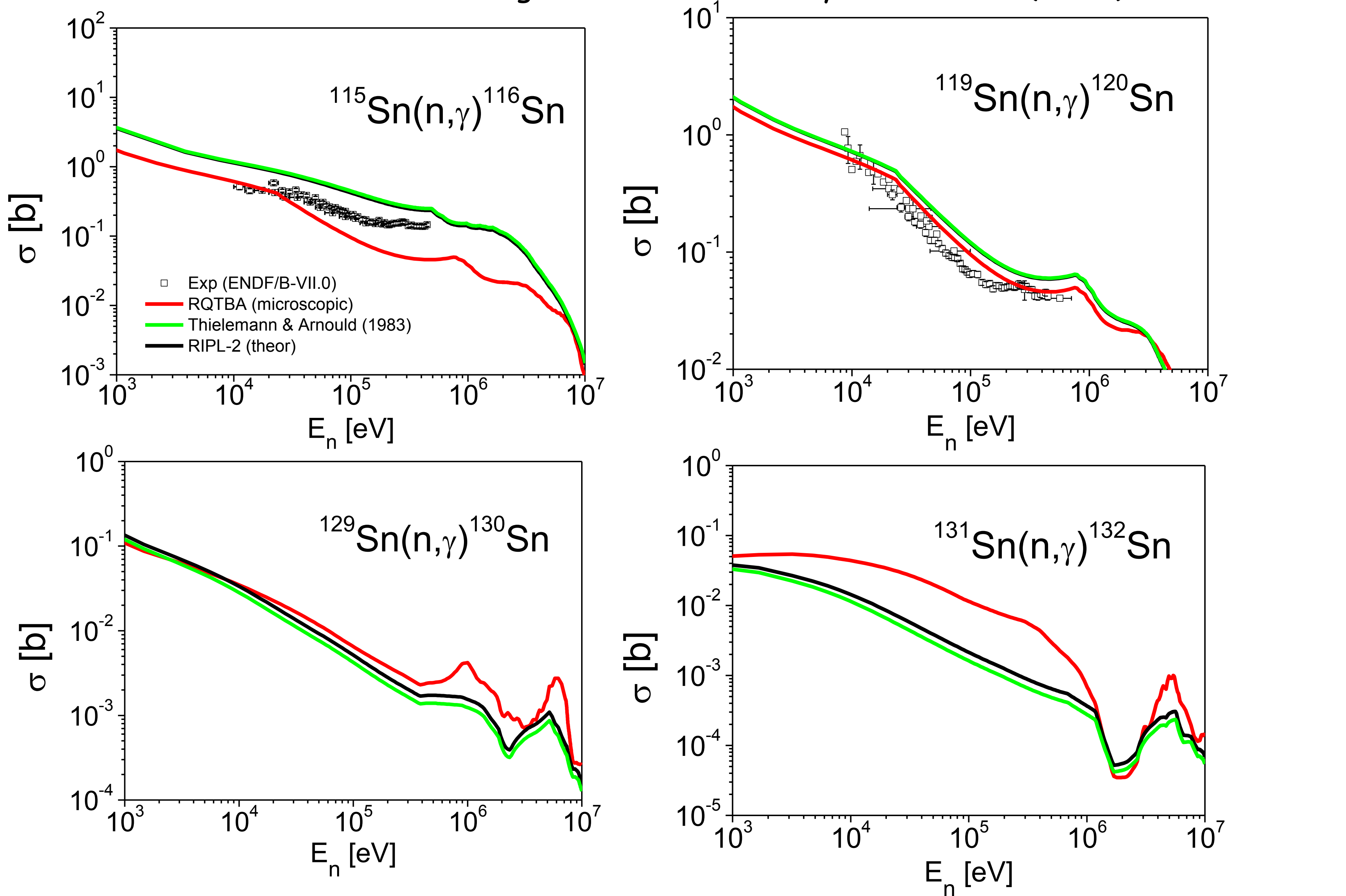
1. Impact on the shell gaps
2. Smearing out the shell effects

Shell stabilization & vibration stabilization/destabilization (?)

E.L., PRC 85, 021303(R) (2012)

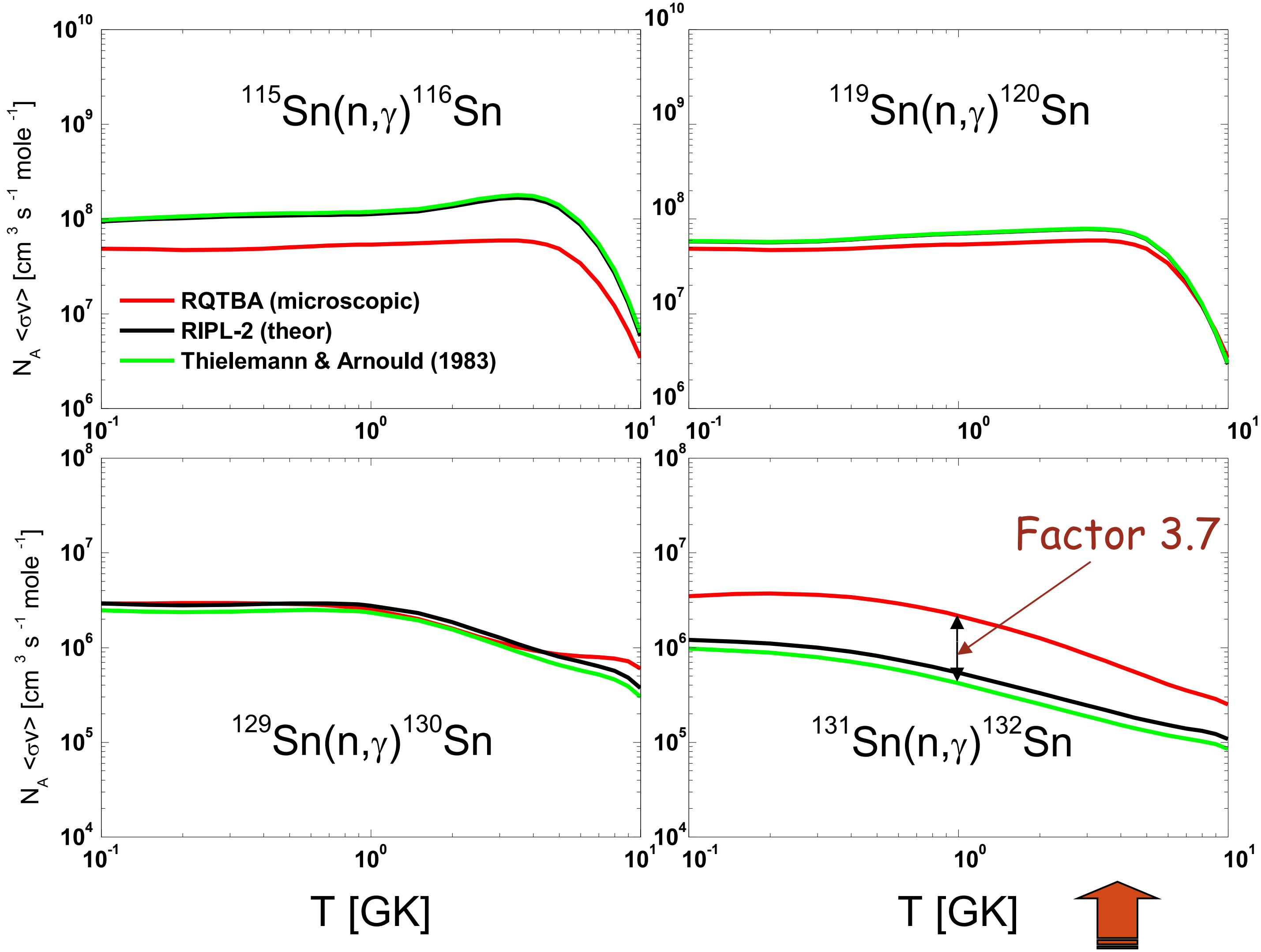
Radiative neutron capture in the Hauser-Feshbach model: standard Lorentzians and microscopic structure

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



(n,γ) stellar reaction rates

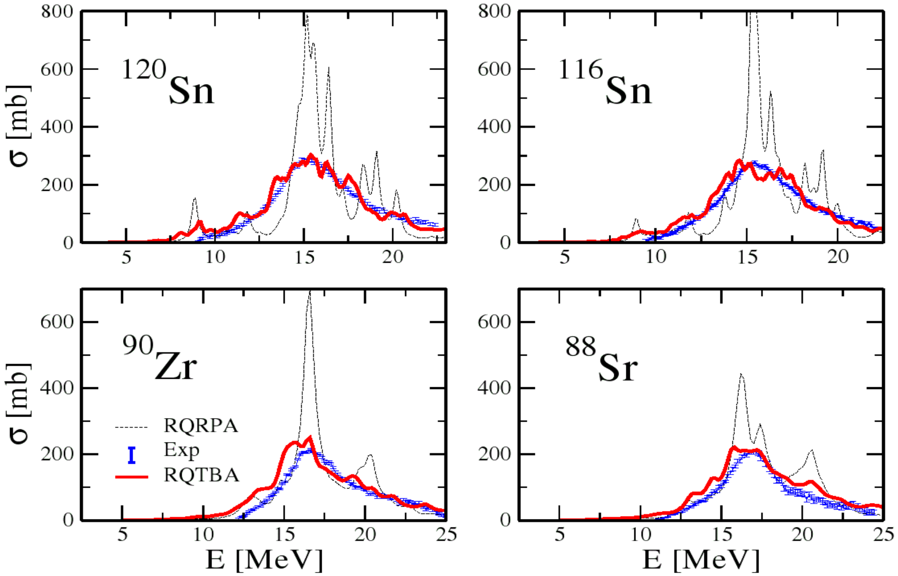
E. L., H.P. Loens, K. Langanke, et al. Nucl. Phys. A 823, 26 (2009).



Microscopic structure is important, e.g. PDR at the neutron threshold

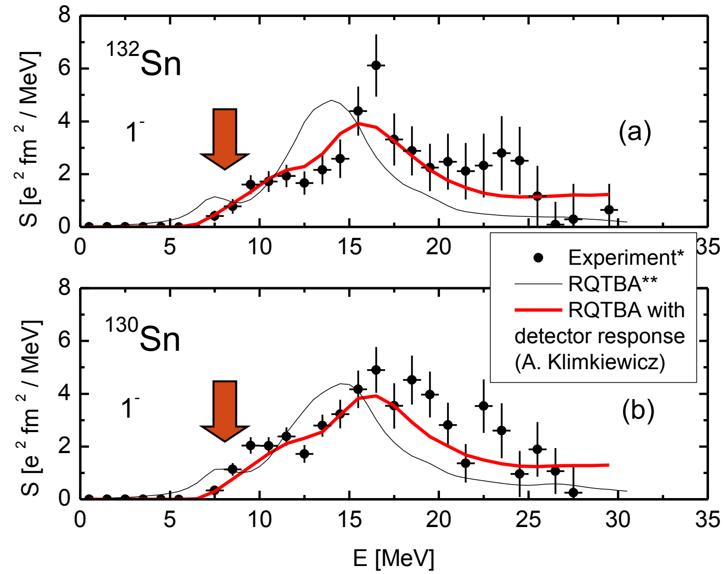
Dipole strength in neutron-rich nuclei within Relativistic Quasiparticle Time Blocking Approximation (RQTBA)

Test case: E1 (IVGDR) stable nuclei



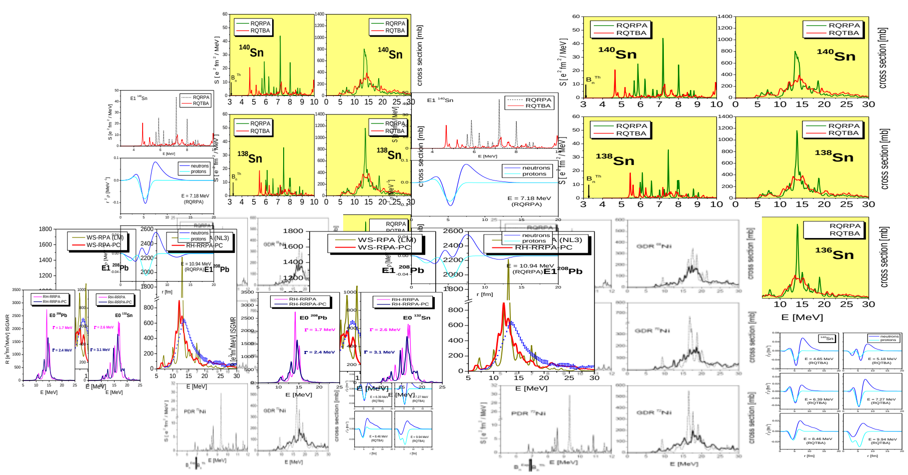
*E. L., P. Ring, and V. Tselyaev, Phys. Rev. C 78, 014312 (2008)

Neutron-rich Sn



* P. Adrich, A. Klimkiewicz, M. Fallot et al., PRL 95, 132501 (2005)

**E. L., P. Ring, V. Tselyaev, K. Langanke PRC 79, 054312 (2009)



Input for r-process nucleosynthesis: (n,γ) cross sections and reaction rates

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

Nuclear response at finite temperature

Density matrix variation at T > 0:

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

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

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

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

Radiative strength function (RSF):

$$f_{E1}(E_\gamma,T) = -\frac{8e^2}{27(\hbar c)^3}\mathrm{Im}\int dx P_{E1}^\dagger(x)\delta\mathcal{R}(x;\omega,T)$$

$$\omega = E_\gamma + i\Delta, \Delta \to 0$$

Exp. energy resolution

Structure of the propagator in ph-channel

$$\mathcal{A}^{\mathrm{cont}L}_{LS,LS'}(r,r';\omega;T)$$
$$= -\sum_1 \boxed{v_1^2(T)(1-n_1(T))} R_1(r)R_1(r')\sum_{l_2j_2} T_{12}^{LSS'}$$
$$\times\Big[\mathcal{G}_{l_2j_2}(r,r';\mu(T)-E_1(T)+\omega)$$
$$+(-1)^{S+S'}\mathcal{G}_{l_2j_2}(r,r';\mu(T)-E_1(T)-\omega)\Big]$$
$$-\sum_1 \boxed{u_1^2(T)n_1(T)} R_1(r)R_1(r')\sum_{l_2j_2} T_{12}^{LSS'}$$
$$\times\Big[\mathcal{G}_{l_2j_2}(r,r';\mu(T)+E_1(T)+\omega)$$
$$+(-1)^{S+S'}\mathcal{G}_{l_2j_2}(r,r';\mu(T)+E_1(T)-\omega)\Big],$$

$$\mathcal{A}^{\mathrm{disc}L}_{LS,LS'}(r,r';\omega;T)$$
$$=\sum_{12}^{\mathrm{disc}} R_1(r)R_2(r')R_1(r')R_2(r)T_{21}^{LSS'}$$
$$\times\Bigg[\mathcal{L}_{12}(\omega,T)+\frac{v_2^2(T)(1-n_2(T))}{\omega+\mu(T)-\epsilon_1-E_2(T)}$$
$$-\frac{v_1^2(T)(1-n_1(T))}{\omega-\mu(T)+\epsilon_2+E_1(T)}$$
$$+\frac{u_2^2(T)n_2(T)}{\omega+\mu(T)-\epsilon_1+E_2(T)}$$
$$-\frac{u_1^2(T)n_1(T)}{\omega-\mu(T)+\epsilon_2-E_1(T)}+(-1)^S\mathcal{M}_{12}(\omega,T)\Bigg]$$

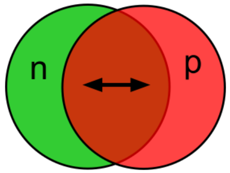
$$n_1(T)=\frac{1}{1+\exp(E_1(T)/T)},$$
$$v_1^2(T)=\frac{1}{2}\left(1-\frac{\epsilon_1-\mu(T)}{E_1(T)}\right),$$
$$E_1(T)=\sqrt{(\epsilon_1-\mu(T))^2+\Delta_1^2(T)}$$

$$u_1^2(T) = 1 - v_1^2(T)$$

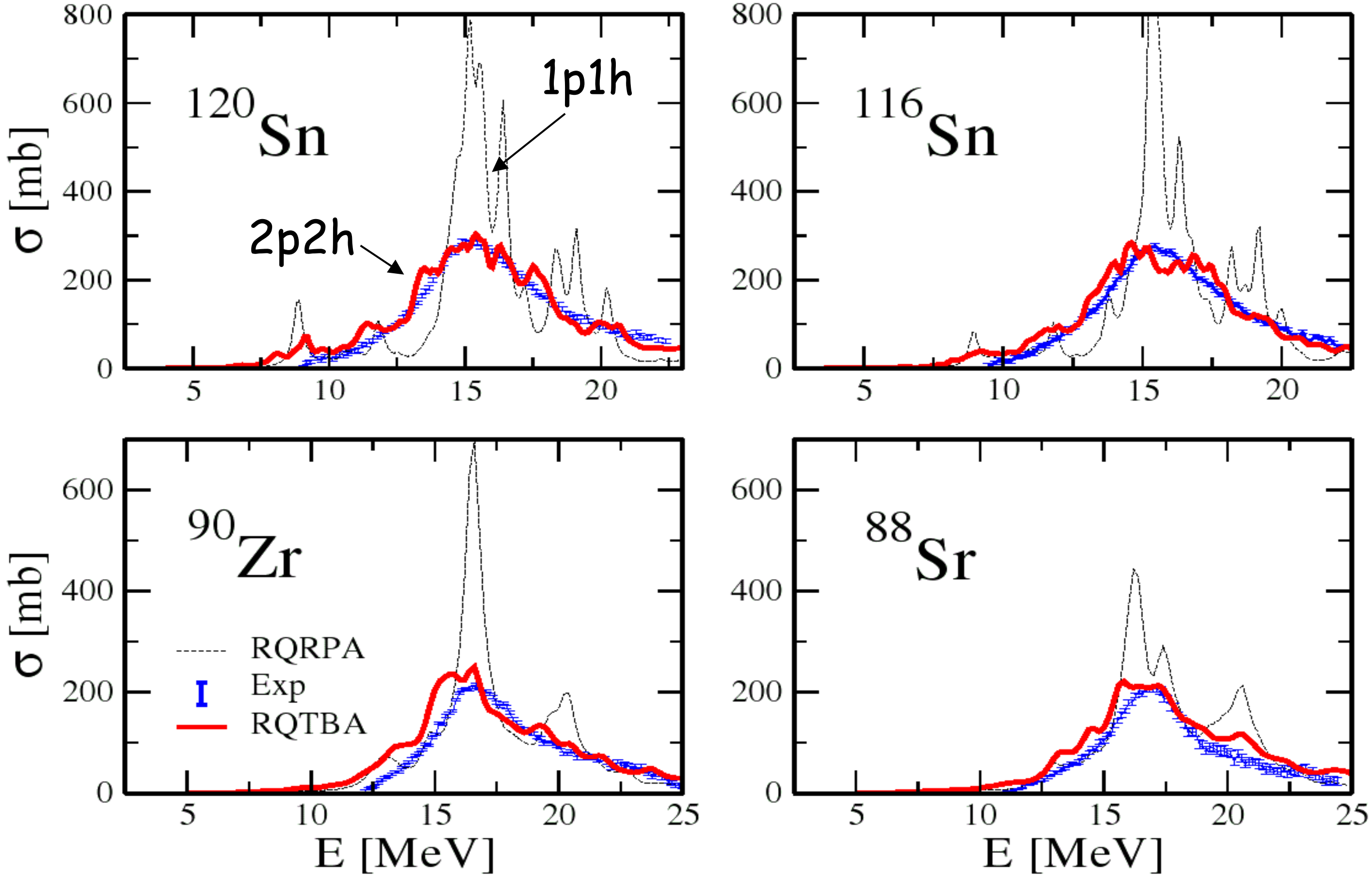
$$\mathcal{L}_{12}(\omega,T)=-A_{ph}(\omega,T)$$
$$\times\left[(u_1^2u_2^2+v_1^2v_2^2)(E_1-E_2)-(u_1^2u_2^2-v_1^2v_2^2)\omega\right]$$
$$-A_{pp}(\omega,T)\Big[-(u_1^2v_2^2+v_1^2u_2^2)(E_1+E_2)$$
$$+(u_1^2v_2^2-v_1^2u_2^2)\omega\Big],$$
$$\mathcal{M}_{12}(\omega,T)=\frac{\Delta_1\Delta_2}{2E_1E_2}\Big[A_{ph}(\omega,T)(E_1-E_2)$$
$$+A_{pp}(\omega,T)(E_1+E_2)\Big],$$
$$A_{ph}(\omega,T)=\frac{n_1(T)-n_2(T)}{(E_1-E_2)^2-\omega^2},$$
$$A_{pp}(\omega,T)=\frac{1-n_1(T)-n_2(T)}{(E_1+E_2)^2-\omega^2};$$

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

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



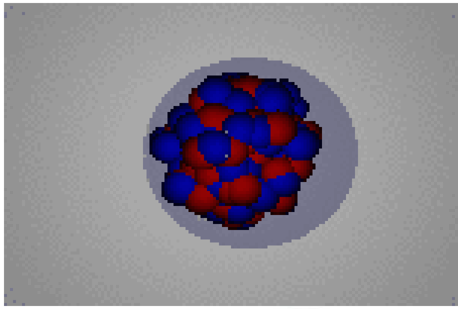
ΔL = 1
ΔT = 1
ΔS = 0



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

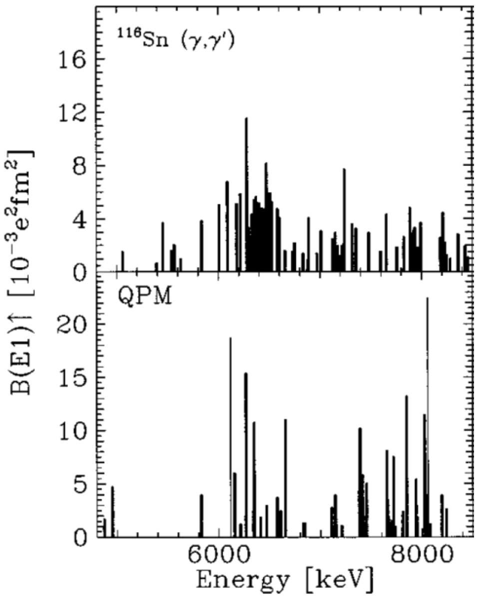
Fragmentation of pygmy dipole resonanse

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

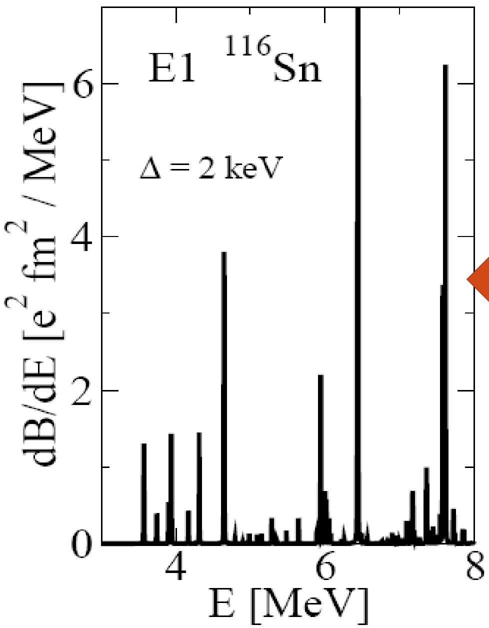


Low-lying dipole strength in ^{116}Sn

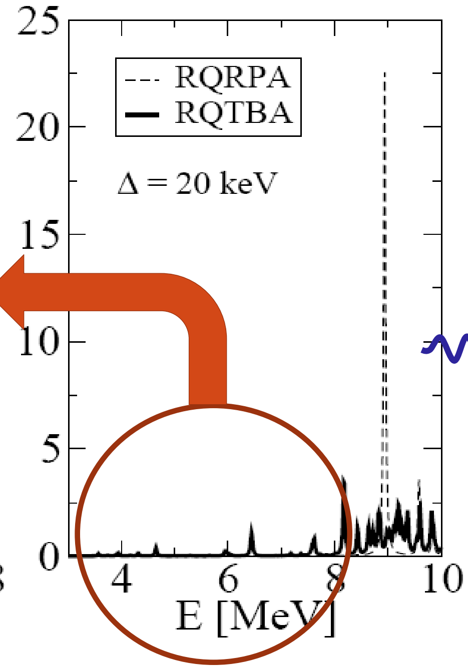
Experiment*



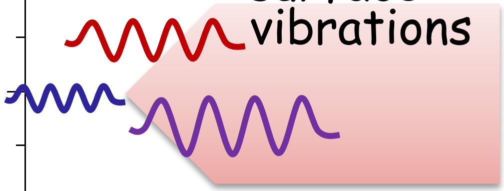
Fine structure



Gross structure



2+,3-,...
surface
vibrations



Integral
5-8 MeV:
$\Sigma B(E1)\uparrow$ [$e^2 fm^2$]

Exp.	0.204(25)
QPM	0.216
RQTBA	0.27

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

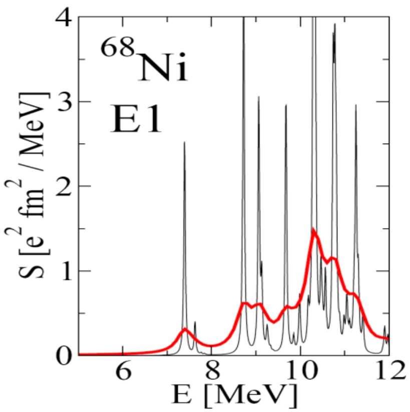
* K. Govaert et al.,
PRC 57, 2229 (1998)

RQTBA 2p2h

RQRPA 1p1h vs
RQTBA 2p2h

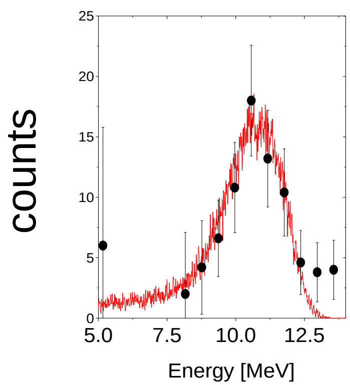
RQTBA dipole transition densities in ^{68}Ni at 10.3 MeV

Theory:

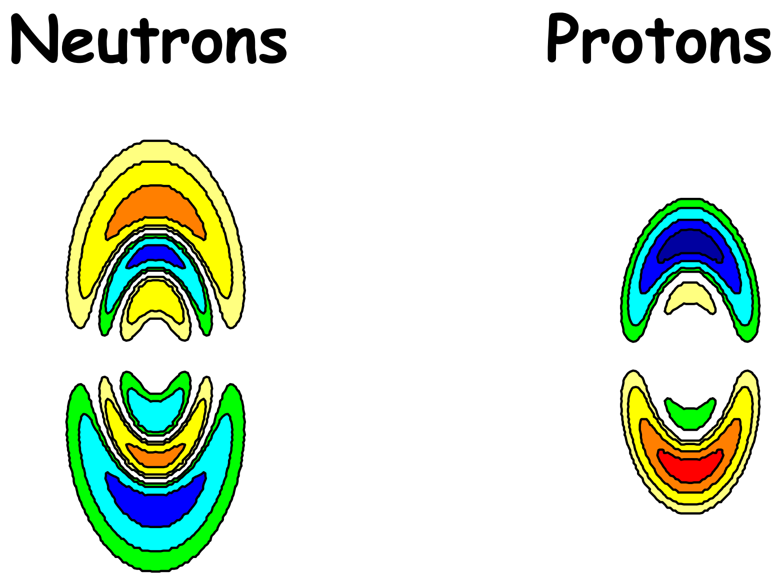


E.L., P.Ring, V.Tselyaev, PRL 105, 02252 (2010)

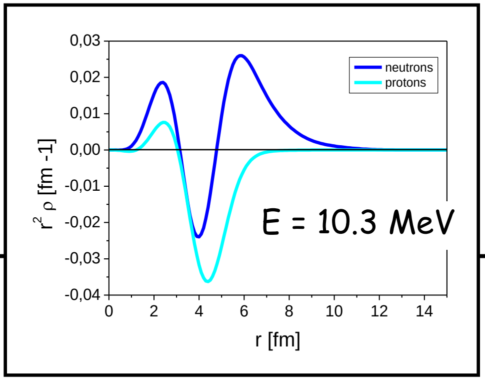
Experiment:

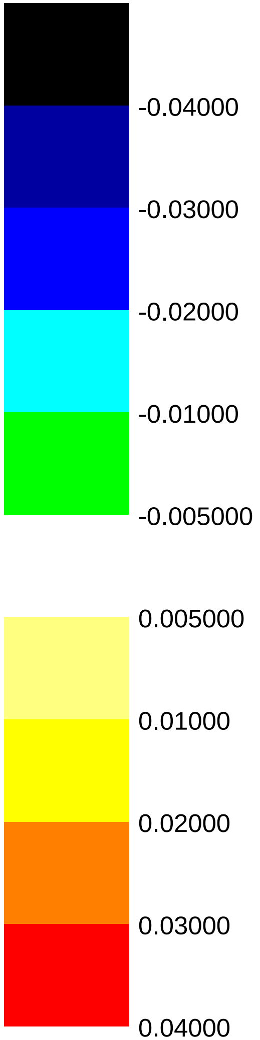


O.Wieland et al., PRL 102, 092502 (2009)



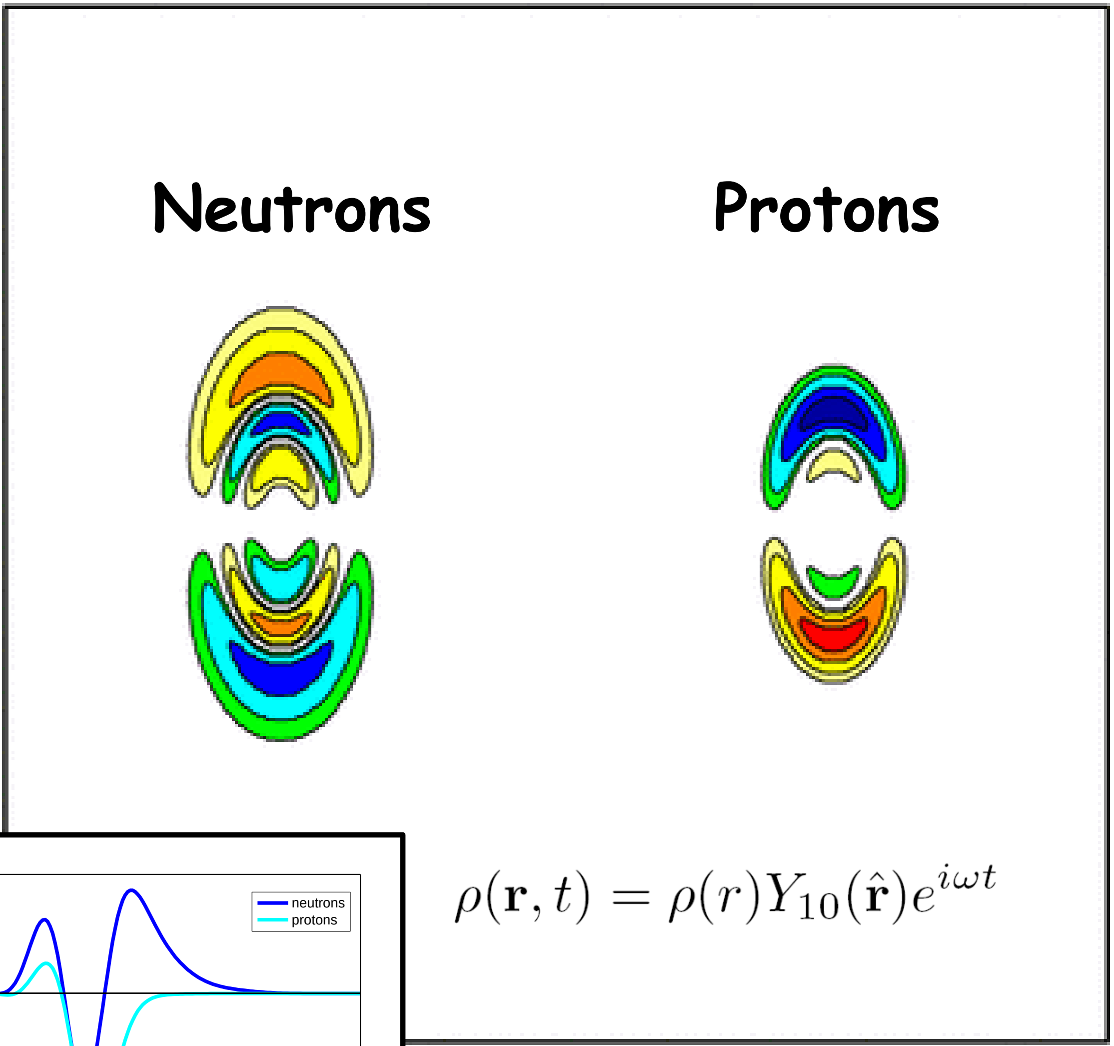
$$\rho(\mathbf{r}) = \rho(r) Y_{10}(\hat{\mathbf{r}}),$$



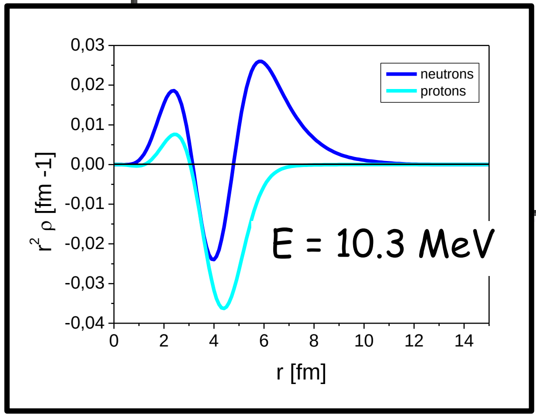


Experiment:
Coulomb excitation of ^{68}Ni at 600 AMeV

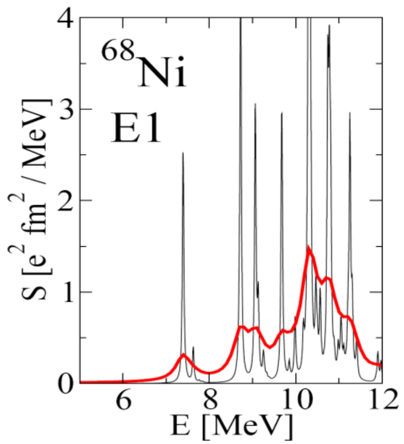
RQTBA dipole transition densities in ^{68}Ni at 10.3 MeV



$$\rho(\mathbf{r},t) = \rho(r)Y_{10}(\hat{\mathbf{r}})e^{i\omega t}$$

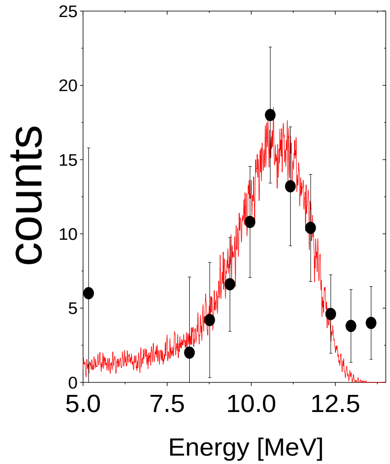


Theory: RQTBA-2



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

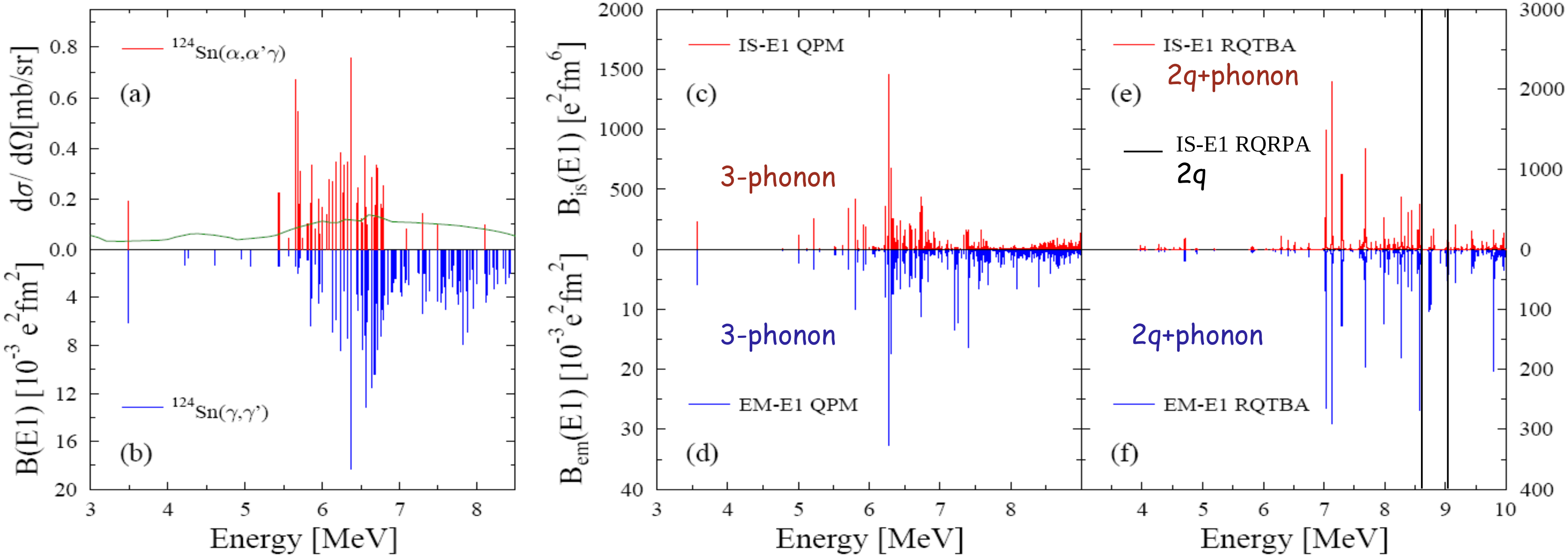
Experiment:

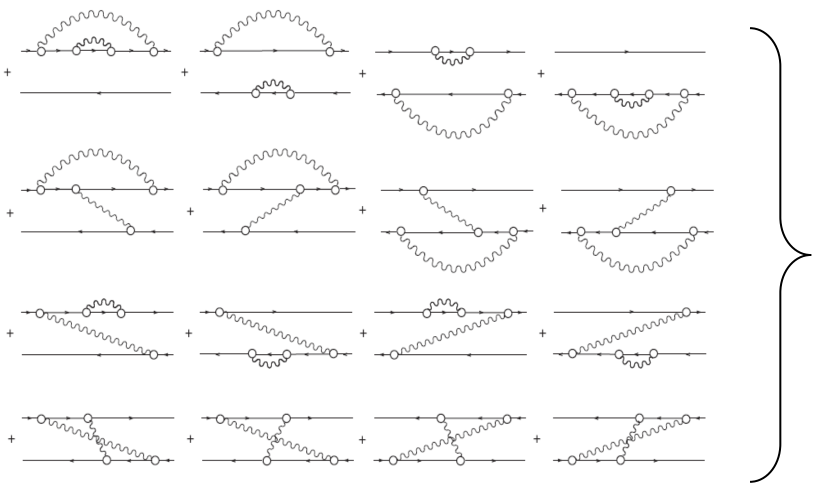


O.Wieland et al., PRL 102, 092502 (2009)

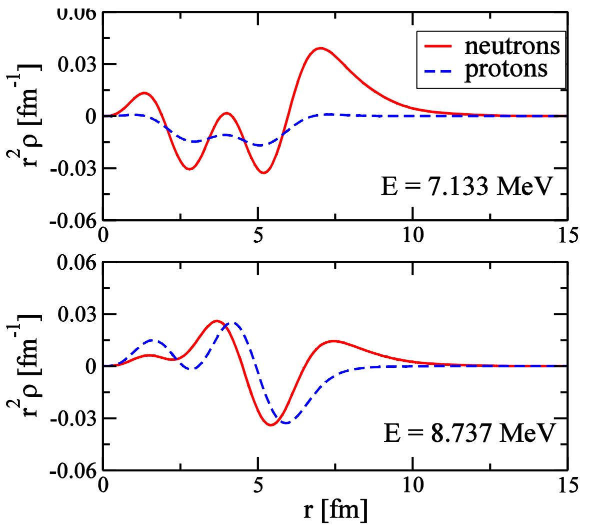
Isospin splitting of the pygmy dipole resonance in ^{124}Sn

J. Endres, E.L., D. Savran et al., PRL 105. 212503 (2010) & E. Lanza, A. Vitturi, E.L., D. Savran, subm. to PRC (2013)



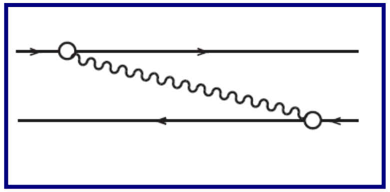


2q+2phonon to be included

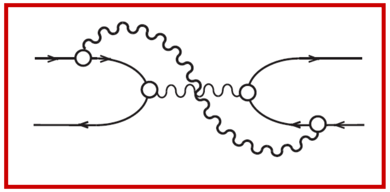


Fine features of dipole spectra: two-phonon effects

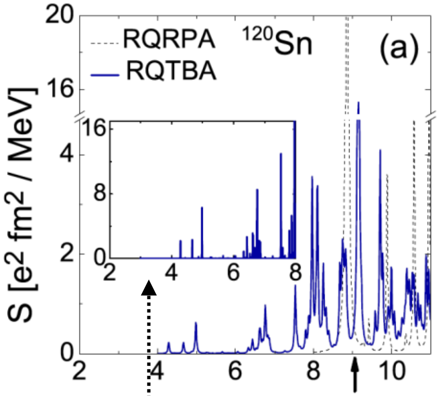
2q+phonon

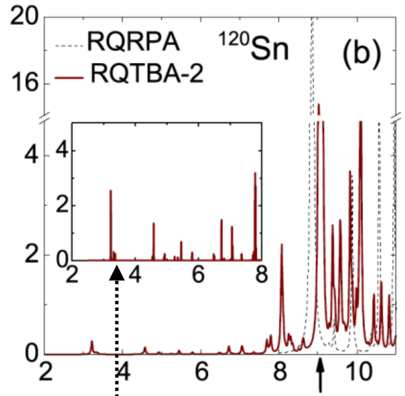


2 phonon



^{120}Sn





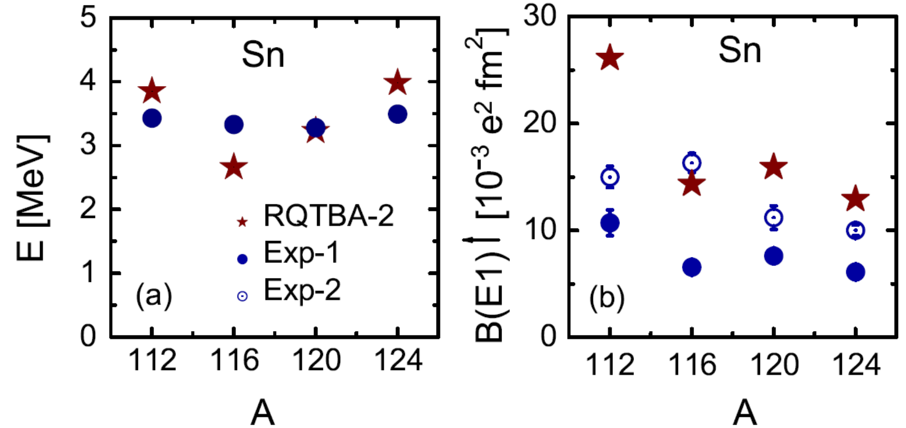
Does not exist

$3^- \otimes 2^+$

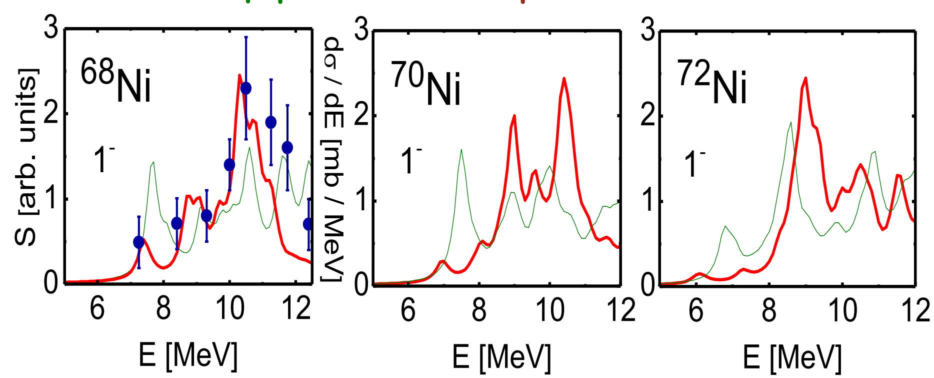
E.L., P.Ring, V.Tselyaev, PRL 105, 02252 (2010)
PRC 88, 044320 (2013)

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

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



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



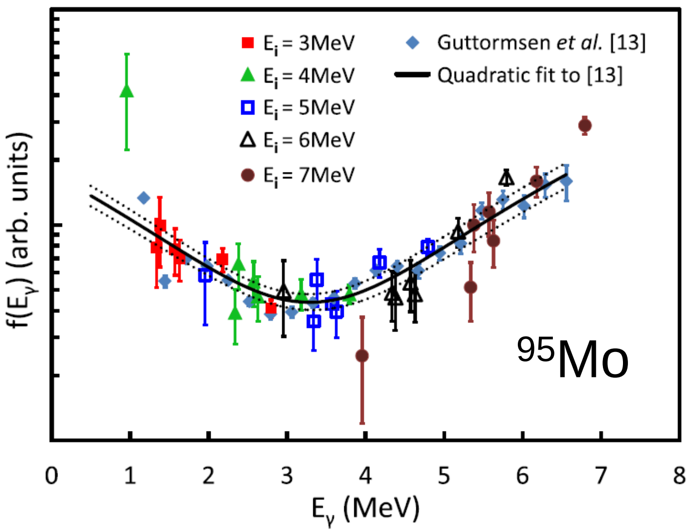
Data: O. Wieland et al., PRL 102, 092502 (2009)

(n,γ) via compound nucleus: γ-transitions between excited states in the quasicontinuum

Low-energy enhancement of γ-strength

A. Voinov et al., PRL 93, 142504 (2004)
M. Guttormsen et al., PRC 71, 044307 (2005)
Oslo method

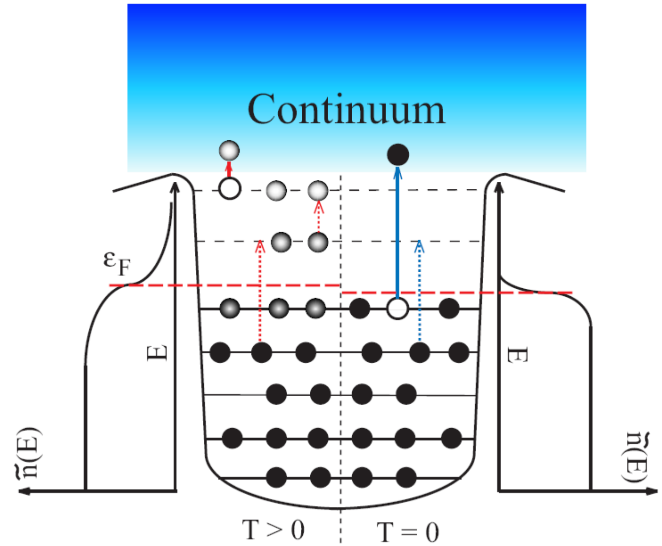
M. Wiedeking et al., PRL 108, 162503 (2012):

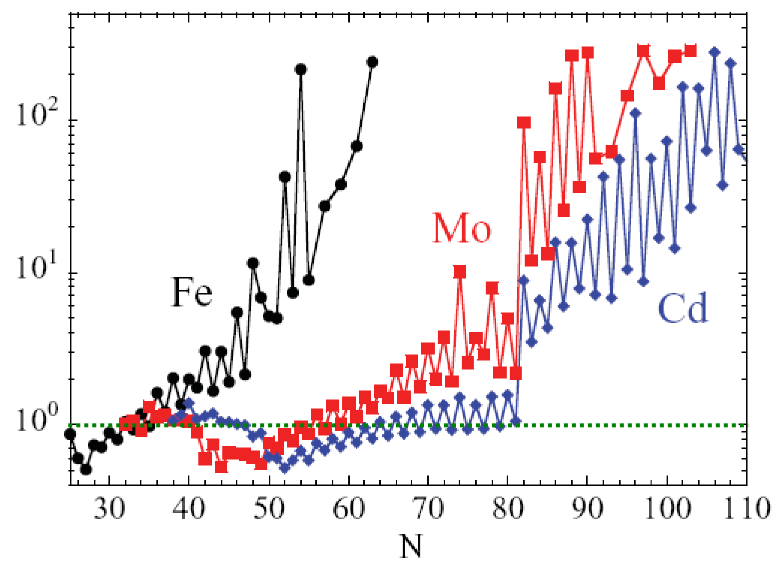


$$\frac{(n,\gamma)\text{ reaction rate (enh.)}}{(n,\gamma)\text{ reaction rate (no enh.)}} = \eta$$

A.C. Larsen, S. Goriely, PRC 014318 (2010)
Oslo data

Correlations due to coupling to single-particle continuum

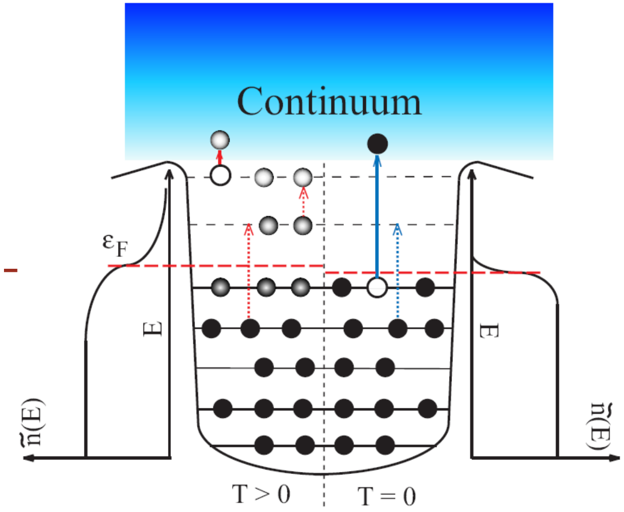




Mechanism of the RSF formation at low Eγ

$$\tilde{n}_i(E_i,T) = (1 - v_i^2(T))n_i(E_i,T)$$

$$\tilde{n}_i(E_i,T) = v_i^2(T)(1 - n_i(E_i,T))$$



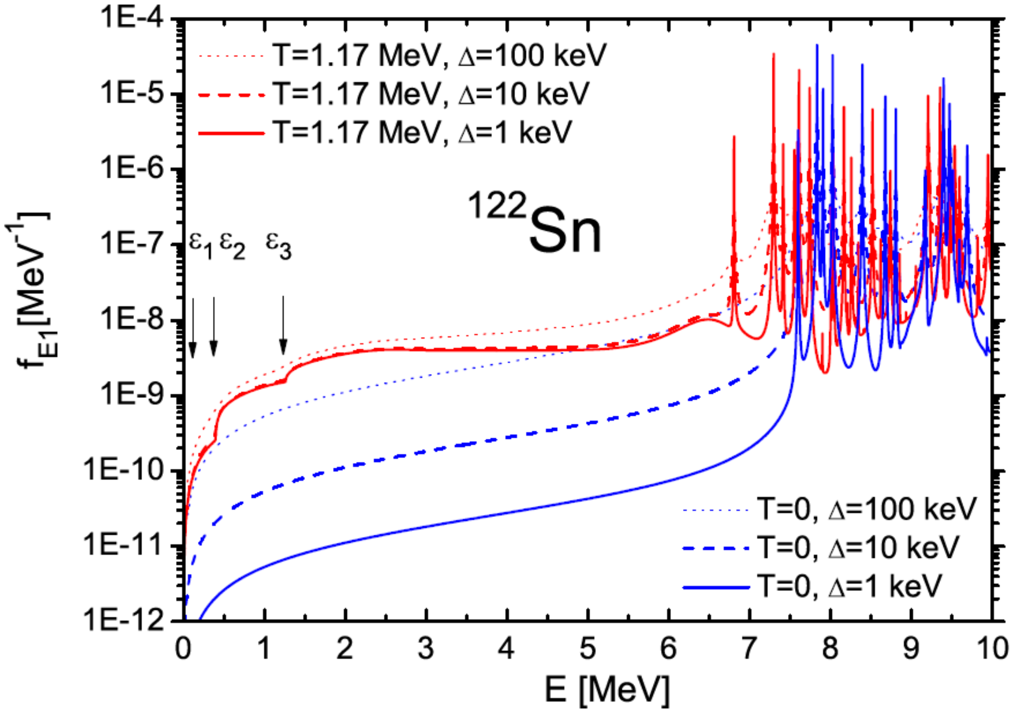
$$v_i^2$$

1. Saturation of RSF with Δ at Δ = 10 keV for T>0

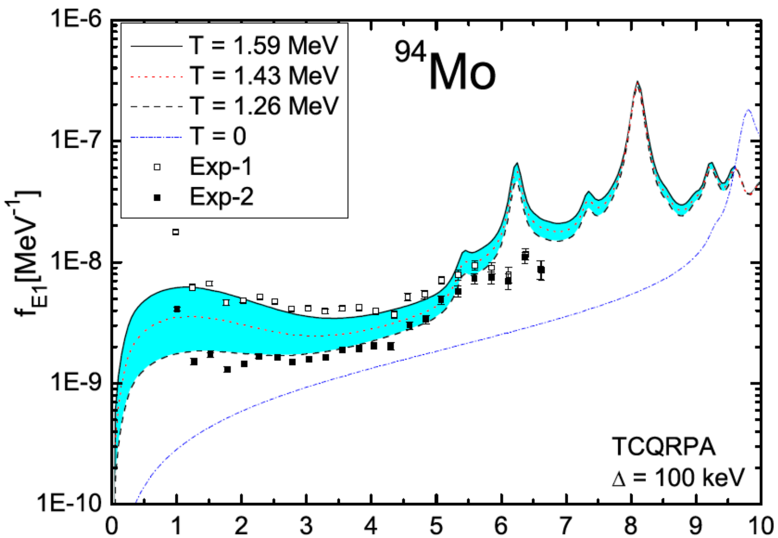
2. The low-energy RSF is not a tail of the GDR and not a part of PDR!

3. The nature of RSF at E_γ-> 0 is continuum transitions from the thermally unblocked states

4. Spurious translation mode should be eliminated exactly



Low-energy limit of the RSF in even-even Mo isotopes

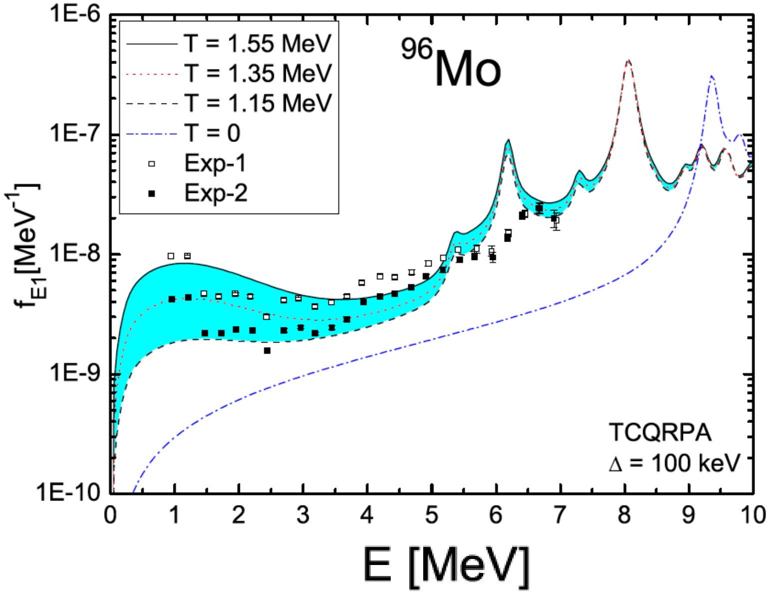


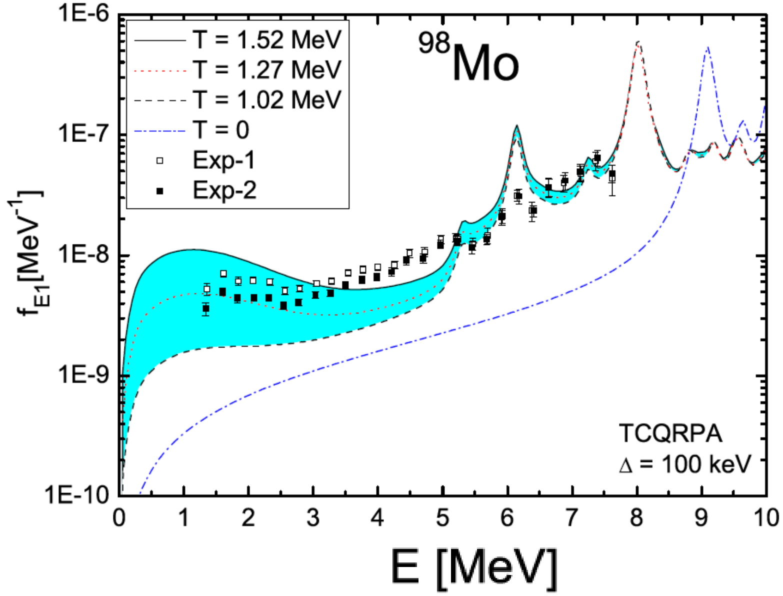
$$T = \sqrt{(E^* - \delta)/a}$$

$a = a_{EGSF} \Rightarrow T_{min}$ (RIPL-3)

$a = \pi^2(g_\nu + g_\pi)/6 \Rightarrow T_{max}$ *(microscopic)*

Exp-1: NLD norm-1,
M. Guttormsen et al., PRC 71, 044307 (2005)
Exp-2: NLD norm-2,
S. Goriely et al., PRC 78, 064307 (2008)

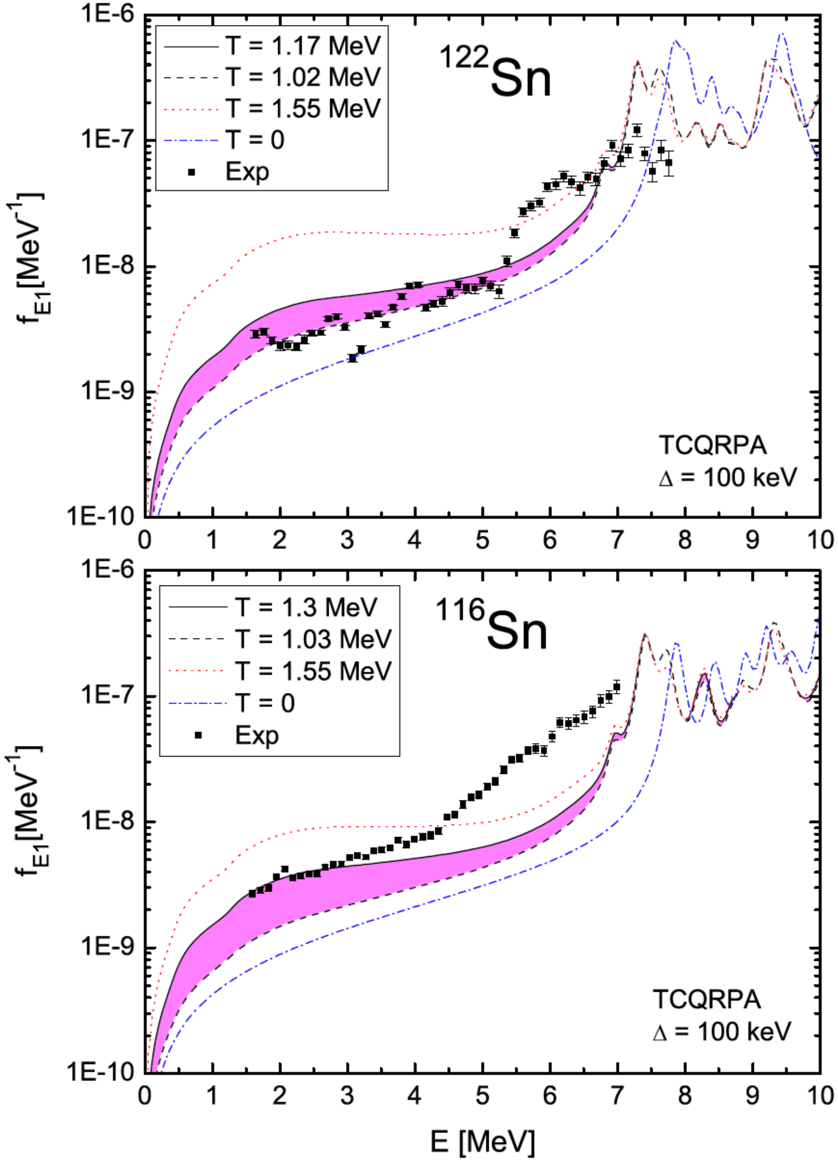




Theory: E. Litvinova, N. Belov, PRC 88, 031302(R)(2013)

Data: A.C. Larsen, S. Goriely, PRC 014318 (2010)

Low-energy limit of the RSF in $^{116,122}Sn$



No upbend?

Larger microscopic level density parameter a
=> Lower upper limit for the temperature at S_n

Other effects
(ideally, all to be combined in one approach)

At 3-4 MeV:
•2-phonon state (as above)

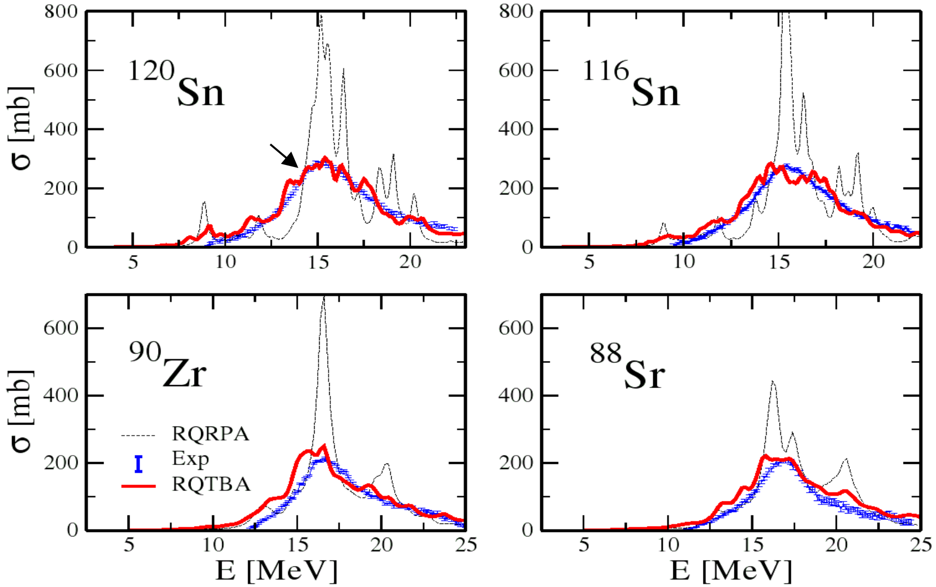
Above 4-5 MeV:
•Coupling to vibrations (as above),
•Thermal fluctuations:
M. Gallardo et al., NPA443, 415 (1985)

•More correct for γ-emission:
„final temperature",
V. Plujko, NPA649, 209c (1999)

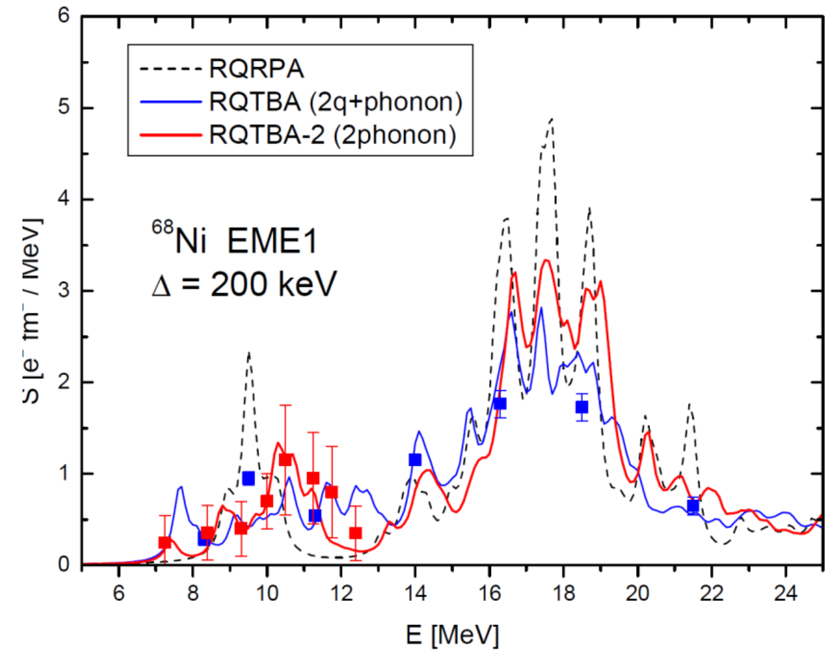
$$T_f = \sqrt{(E^* - \delta - E_\gamma)/a}$$

Theory: E. Litvinova, N. Belov, PRC 88, 031302(R)(2013)

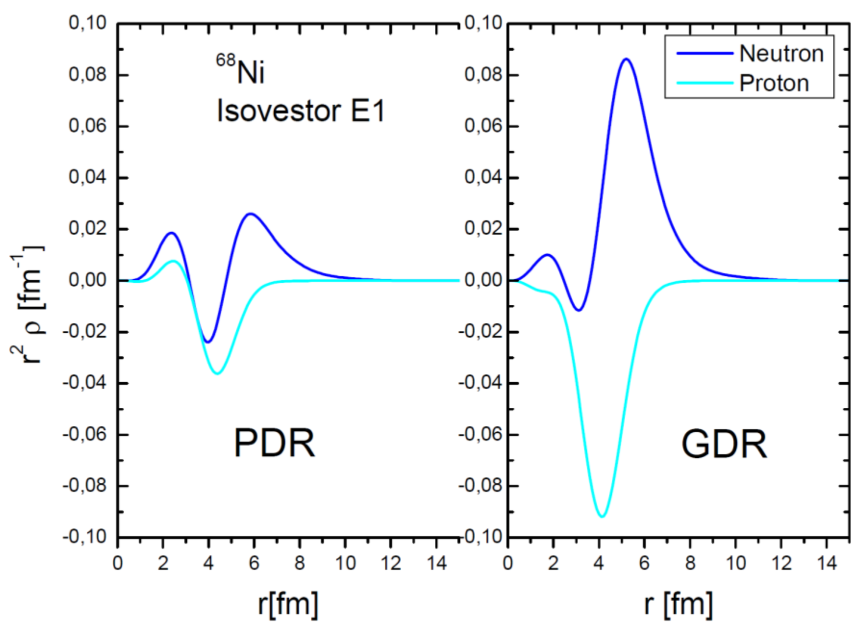
Data: H.K. Toft et al., PRC 81, 064311 (2010), PRC 83, 044320 (2011)



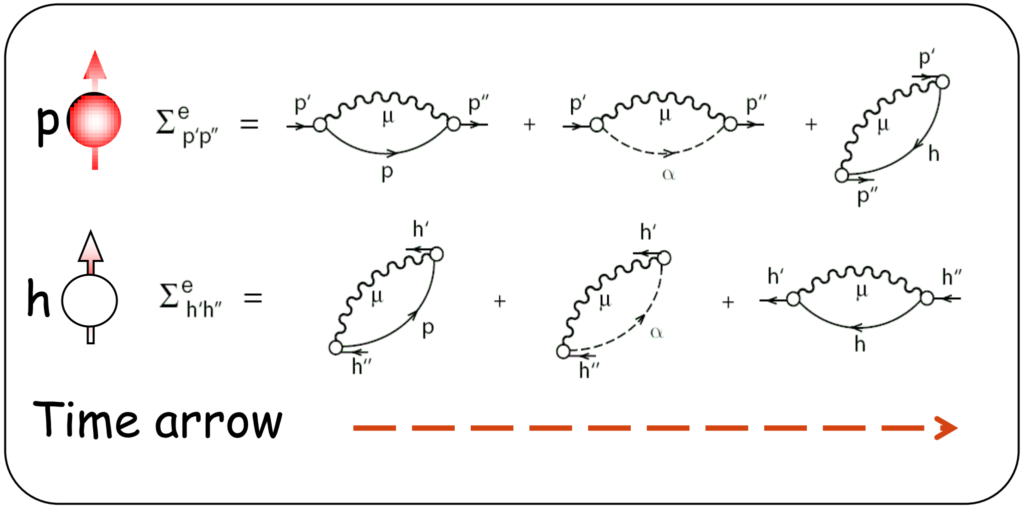
120Sn
116Sn
90Zr
88Sr
σ [mb]
E [MeV]
RQRPA
Exp
RQTBA



RQRPA
RQTBA (2q+phonon)
RQTBA-2 (2phonon)
68Ni EME1
Δ = 200 keV
S [e² fm² / MeV]
E [MeV]



68Ni
Isovestor E1
Neutron
Proton
PDR
GDR
r² ρ [fm⁻¹]
r[fm]
r [fm]



Doubled quasiparticle space:

$$\eta = \pm 1$$

$$\Sigma^{(e)\eta_1\eta_2}_{k_1k_2}(\varepsilon) = \sum_{\eta=\pm1}\sum_{k,\mu}\frac{\gamma^{\eta;\eta_1\eta}_{\mu;k_1k}\;\gamma^{\eta;\eta_2\eta*}_{\mu;k_2k}}{\varepsilon - \eta(E_k + \Omega_\mu - i\delta)}$$

Relativistic mean field

$$\boxed{E_{RMF}[\hat{\rho},\phi] = Tr[(\boldsymbol{\alpha}\mathbf{p}+\beta m)\hat{\rho}] + \sum_m \left\{ Tr[(\beta\Gamma_m\phi_m)\hat{\rho}] \mp \int \left[\frac{1}{2}(\boldsymbol{\nabla}\phi_m)^2 + U(\phi_m)\right] d^3r \right\}}$$

$$\begin{cases} \mathcal{H}_{RHB}|\psi_k^\eta\rangle = \eta E_k|\psi_k^\eta\rangle, \qquad \eta = \pm 1 \\ -\Delta\phi_m(\boldsymbol{r}) + U'(\phi_m(\boldsymbol{r})) = \mp \sum_k V_k^{\mathsf{T}}(\boldsymbol{r})\beta\Gamma_m V_k^*(\boldsymbol{r}) \end{cases}$$

Nucleons

Mesons

no sea

RHB Hamiltonian

$$\hat{\mathcal{H}}_{RHB} = \frac{\delta E_{RHB}}{\delta\mathcal{R}} = \begin{pmatrix} h^{\mathcal{D}} - m - \lambda & \Delta \\ -\Delta^* & -h^{\mathcal{D}*} + m + \lambda \end{pmatrix}$$

Dirac Hamiltonian

$$h^{\mathcal{D}} = \boldsymbol{\alpha}\mathbf{p} + \beta(m + \underline{\sum_m \Gamma_m\phi_m(\mathbf{r})})$$

$$\tilde{\Sigma}(\mathbf{r})$$

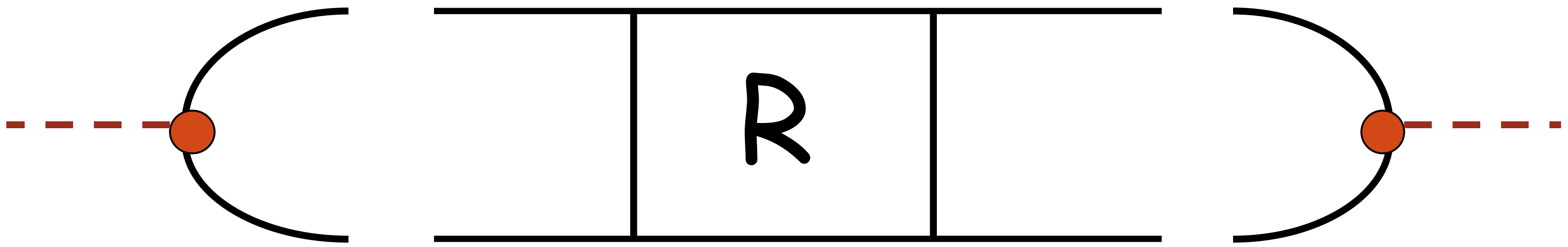
RMF self-energy

$$|\psi_k^+(\boldsymbol{r})\rangle = \begin{pmatrix} U_k(\boldsymbol{r}) \\ V_k(\boldsymbol{r}) \end{pmatrix}$$

Eigenstates

$$|\psi_k^-(\boldsymbol{r})\rangle = \begin{pmatrix} V_k^*(\boldsymbol{r}) \\ U_k^*(\boldsymbol{r}) \end{pmatrix}$$

Nuclear Polarizability

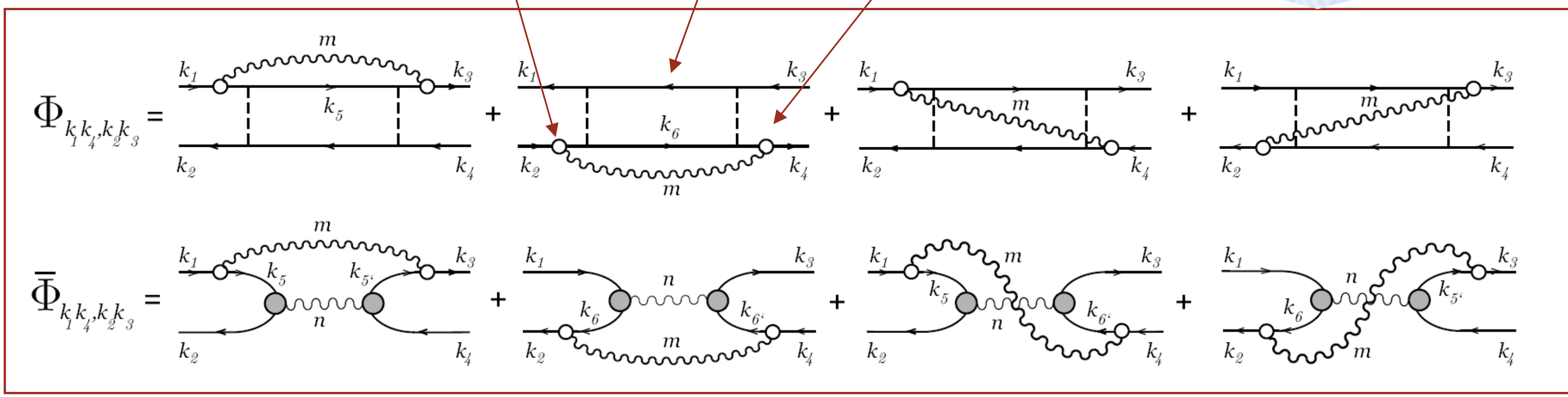


Fine structure of spectra: next-order correlations from “2q+phonon” to “2 phonons”

P. Schuck, Z. Phys. A 279, 31 (1976) & Mode Coupling Theory
V.I. Tselyaev, PRC 75, 024306 (2007) & Time Blocking

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

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



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

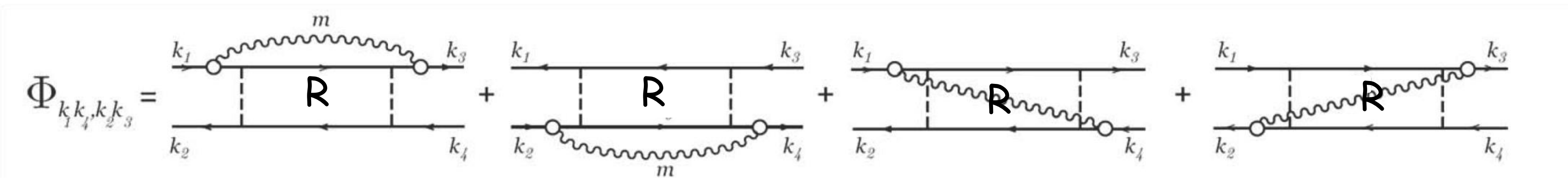
Poles may appear at lower energies:

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

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

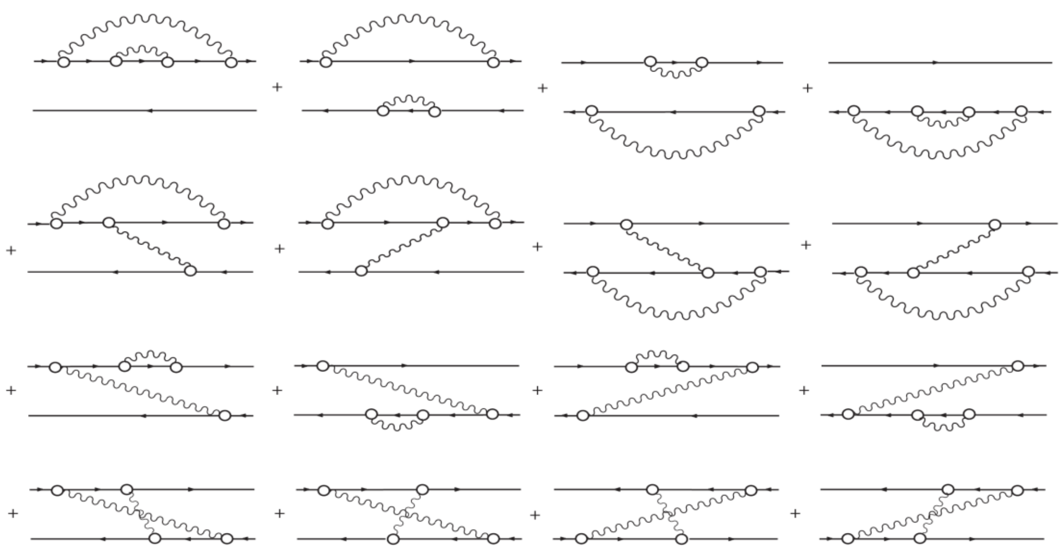
Next-order RQTBA for 3p-3h configurations & iterative procedure for multiphonon response

$$R^{(n+1)} = GG + GG\,[V + \Phi(R^{(n)})]\,R^{(n+1)}$$



Nested configurations

γ^4 terms in Φ-amplitude:



3p3h:
two-fish approximation, …

Response function in the neutral channel

response
$$R(\omega) = \tilde{R}^0(\omega) + \tilde{R}^0(\omega) W(\omega) R(\omega)$$

interaction
$$W(\omega) = V_\sigma + V_\omega + V_\rho + V_e + \Phi(\omega) - \Phi(0)$$

Subtraction to avoid double counting

Static: RQRPA

$$\begin{cases} v_\sigma(1,2) = -g_\sigma^2 \gamma_1^0 D_\sigma(1,2) \gamma_2^0 \\ v_\omega(1,2) = +g_\omega^2 (\gamma^0\gamma_\mu)_1 D_\omega^{\mu\nu}(1,2)(\gamma^0\gamma_\nu)_2 \\ v_\rho^V(1,2) = +g_\rho^2 (\gamma^0\gamma_\mu\vec{\tau})_1 \vec{\tau}_1 \cdot \vec{\tau}_2 D_\rho^{\mu\nu}(1,2)(\gamma^0\gamma_\nu\vec{\tau})_2 \end{cases}$$

Dynamic:

particle-vibration coupling

in time blocking approximation

$$\Phi^{\eta}_{k_1k_4,k_2k_3}(\omega) =$$
$$= \sum_{\mu\xi} \delta_{\eta\xi} \Big[\delta_{k_1k_3} \sum_{k_6} \frac{\gamma^{\eta;-\xi}_{\mu;k_6k_2} \gamma^{\eta;-\xi*}_{\mu;k_6k_4}}{\eta\omega - E_{k_1} - E_{k_6} - \Omega_\mu} + \delta_{k_2k_4} \sum_{k_5} \frac{\gamma^{\eta;\xi}_{\mu;k_1k_5} \gamma^{\eta;\xi*}_{\mu;k_3k_5}}{\eta\omega - E_{k_5} - E_{k_2} - \Omega_\mu}$$
$$- \Big(\frac{\gamma^{\eta;\xi}_{\mu;k_1k_3} \gamma^{\eta;-\xi*}_{\mu;k_2k_4}}{\eta\omega - E_{k_3} - E_{k_2} - \Omega_\mu} + \frac{\gamma^{\eta;\xi*}_{\mu;k_3k_1} \gamma^{\eta;-\xi}_{\mu;k_4k_2}}{\eta\omega - E_{k_1} - E_{k_4} - \Omega_\mu} \Big) \Big]$$