Many-body dynamics in a relativistic framework: spectral properties of exotic nuclei

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NS 2012 Argonne, August 13-17, 2012

Outline

„Many-body dynamics in a relativistic framework: …"

- Quantum theory based on Lorentz symmetry
- For strongly interacting many-body systems (nuclei with $A \geq 16$)
- Modelling of how do the nucleons behave inside nuclei in terms of propagators (Green's functions) for 1,2,3,…, N nucleons in a system of $A \geq N$ nucleons

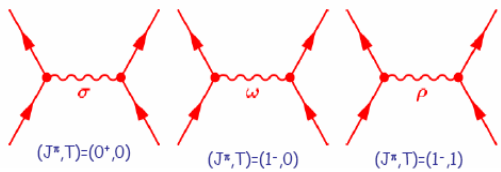
„… spectral properties of exotic nuclei"

- Applications to nuclear properties: single-particle structure, excited states
- Tests on experimentally known nuclei
- Nuclei at extremes: unusual N/Z ratios, exotic modes of excitation, SHN
- Interpretation of experimental data
- Towards a complete and consistent nuclear physics input for astrophysics: neutron capture, electron capture, beta-decay rates, matter & charge distributions… within the same framework

Building blocks

I. Covarant energy density functional (CEDF) theory (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

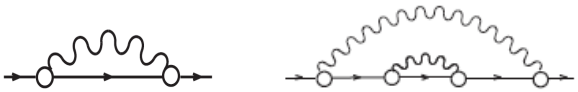
E[R] (7-9 parameters)

Self-consistent Extensions

II. „Correlations": Quasiparticle-vibration Coupling derived SC by field theory technique (Extensions of Landau-Migdal theory)

Single-particle motion:

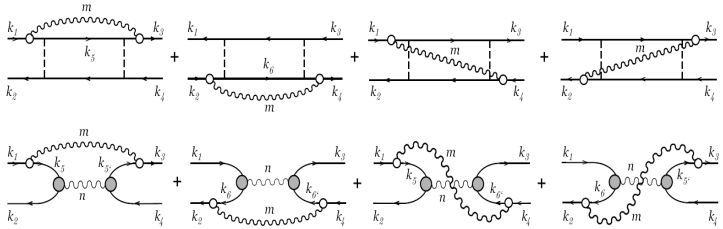
Energies & Spectroscopic factors



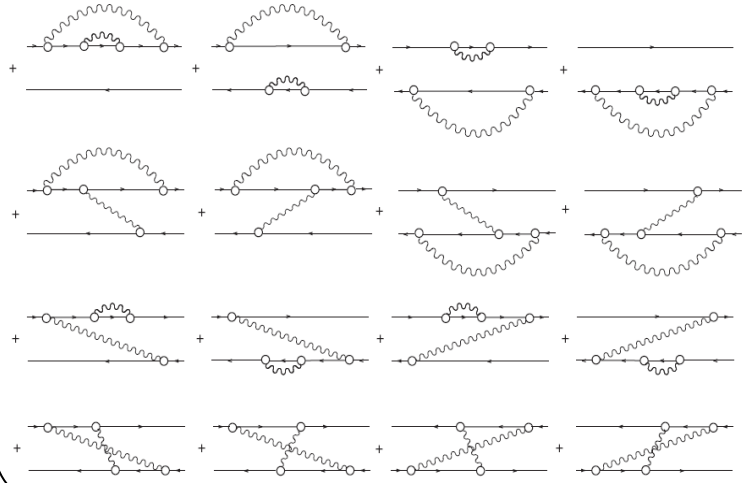
- Generalized to superfluid case
- Covariant formulation

Technique known before

Nuclear Response

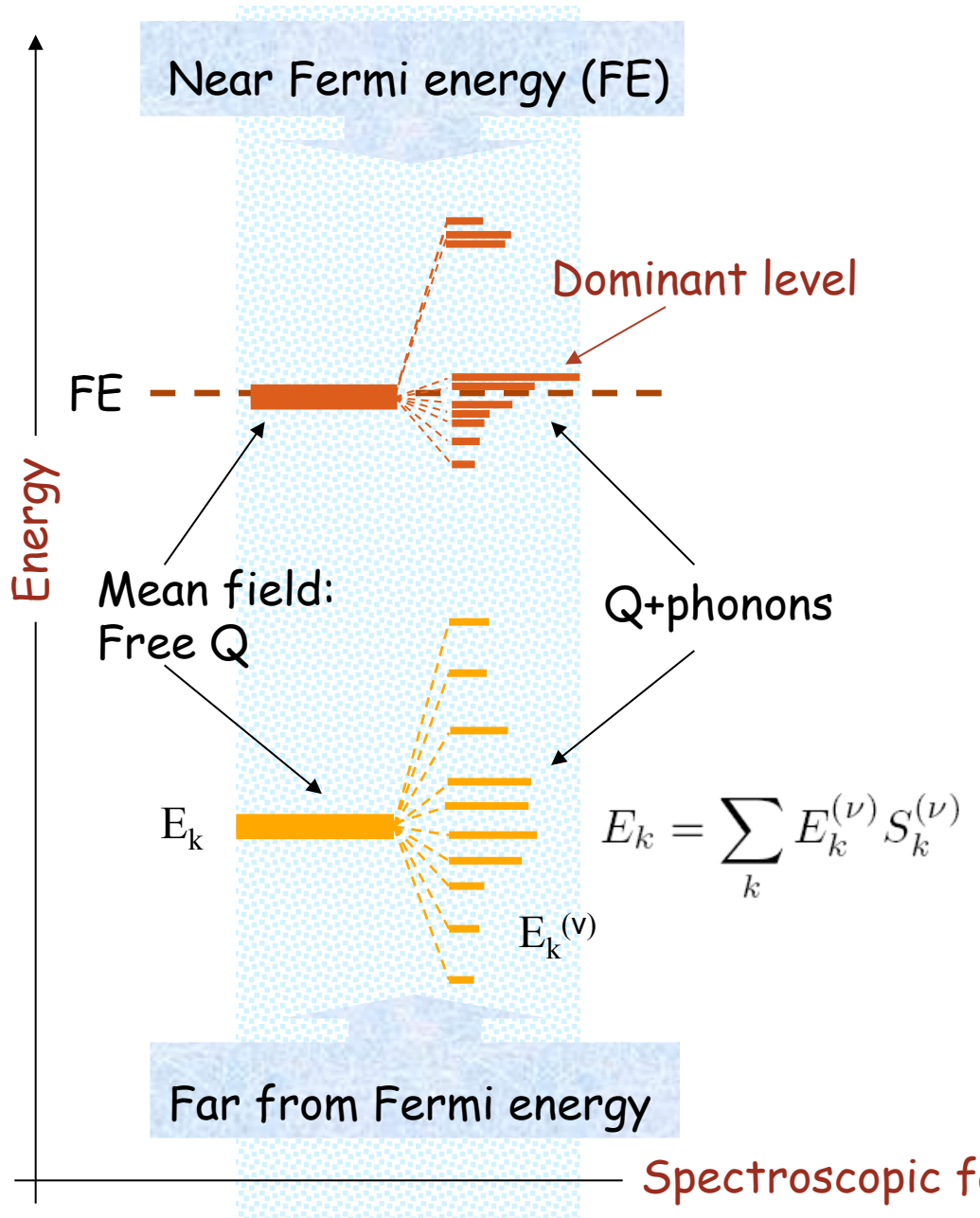


Excitation spectra of collective and non-collective nature

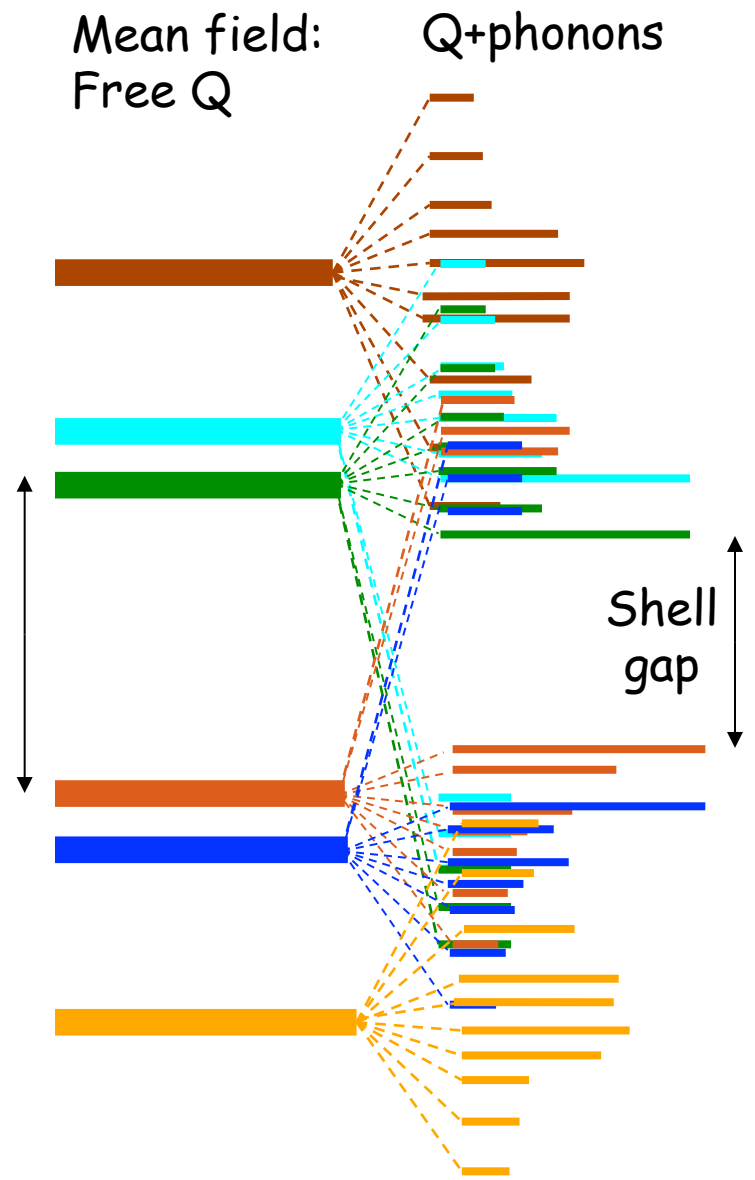


Last 3 years developments

Single-particle states: Fragmentation mechanism (schematic)



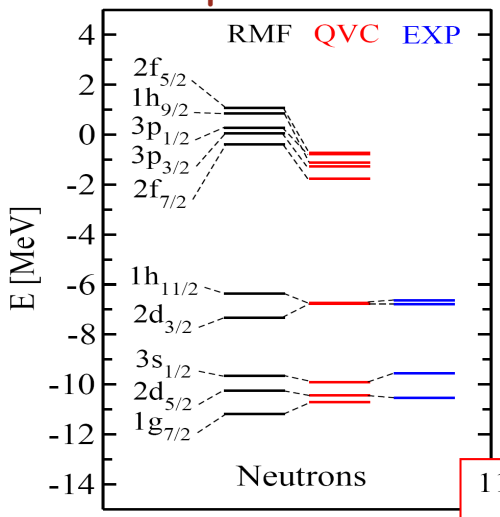
$$E_k = \sum_k E_k^{(\nu)} S_k^{(\nu)}$$



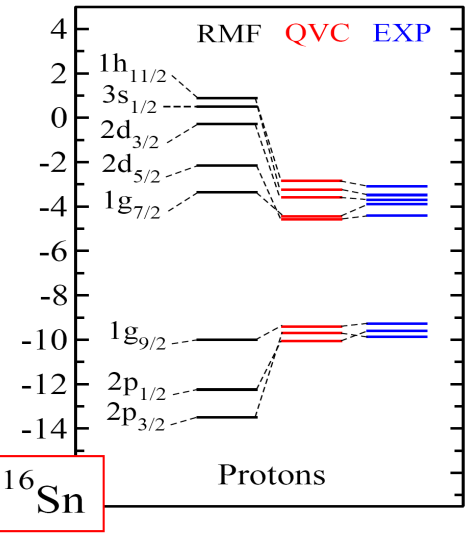
Spectroscopic factors $S_k^{(\nu)}$

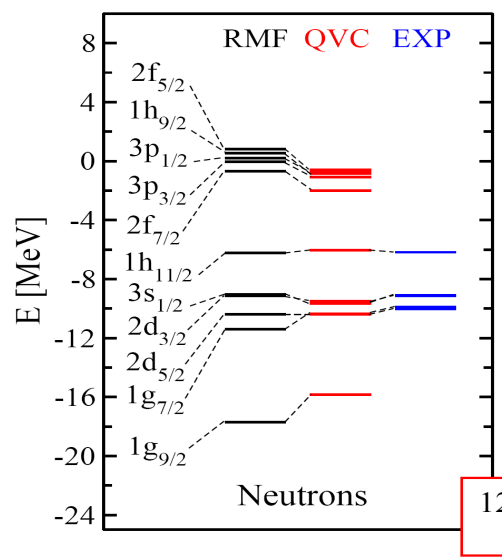
Quasiparticle-vibration coupling:
Pairing correlations of the superfluid type + coupling to phonons

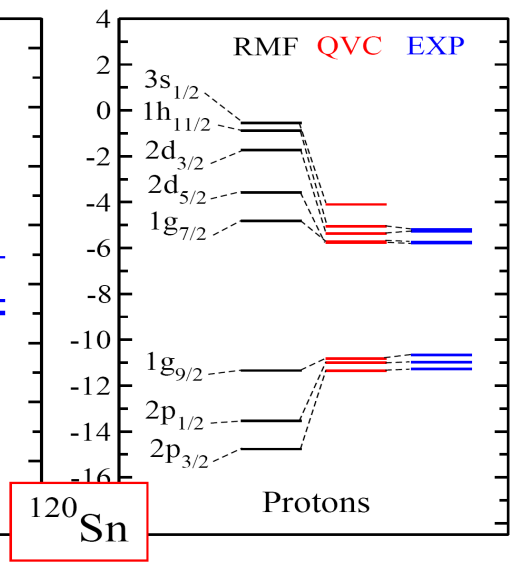
Open shell



Closed shell







Spectroscopic factors in ^{119,121}Sn:

(nlj) ν	S^{th}	S^{exp}
$2d_{5/2}$	0.32	0.43
$1g_{7/2}$	0.40	0.60
$2d_{3/2}$	0.53	0.45
$3s_{1/2}$	0.43	0.32
$1h_{11/2}$	0.58	0.49
$2f_{7/2}$	0.31	0.35
$3p_{3/2}$	0.58	0.54

Spectroscopic factors in ^{133}Sn:

(nlj) ν	S^{th} *	S^{exp} **
$2f_{7/2}$	0.89	0.86±0.16
$3p_{3/2}$	0.91	0.92±0.18
$1h_{9/2}$	0.88	
$3p_{1/2}$	0.91	1.1±0.3
$2f_{5/2}$	0.89	1.1±0.2

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

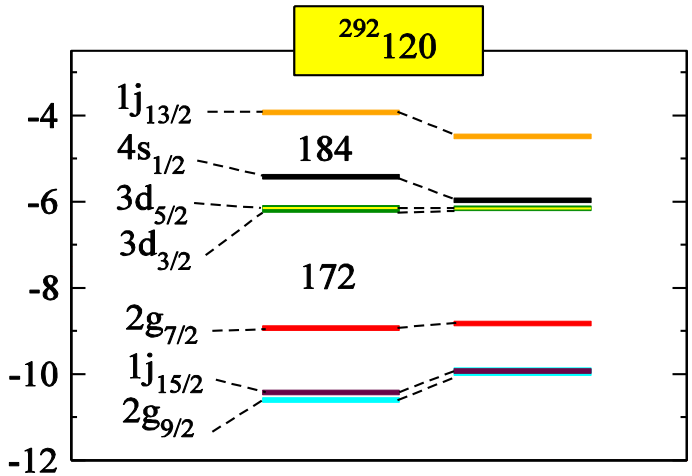
*E. L., A.V. Afanasjev, PRC 84, 014305 (2011)

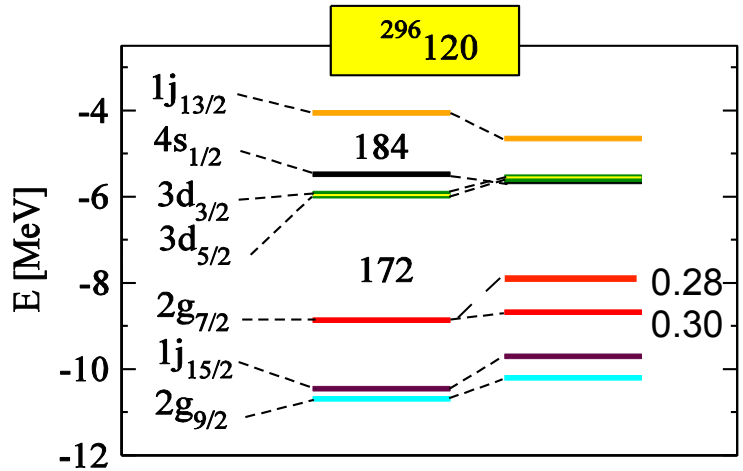
**K.L. Jones et al., Nature 465, 454 (2010)

Dominant neutron states in Z = 120

N=172

„Magic"



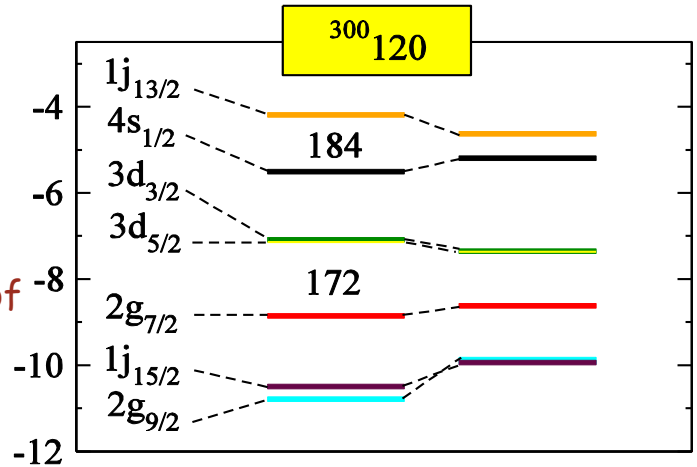


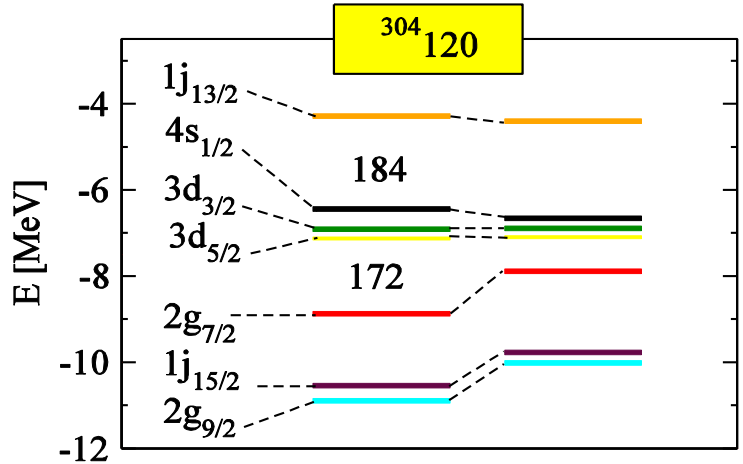
N=176

Comparable Spectroscopic strengths

N=180

PC+QVC: Formation of the „shell gap" !





N=184

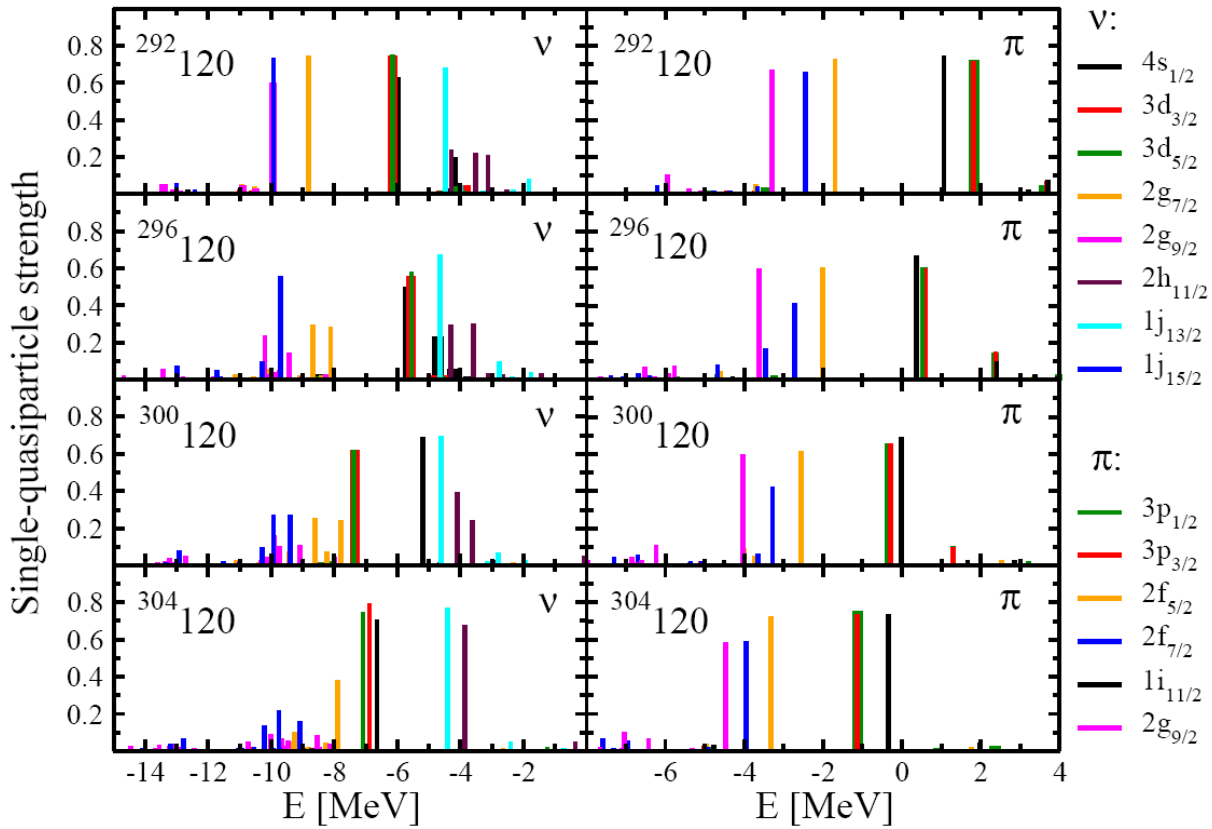
„Magic"

RMF+BCS | …+QVC

RMF+BCS | …+QVC

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

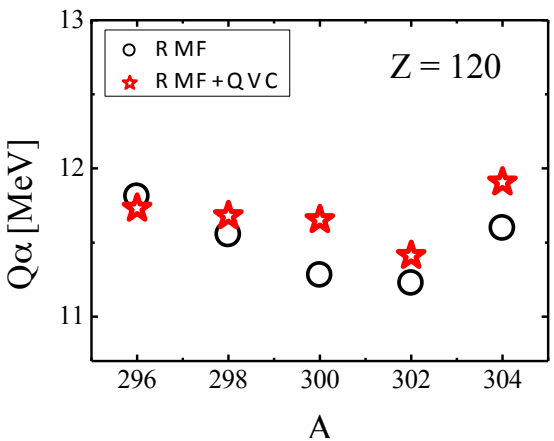
1. Relativistic Mean Field: spherical minima
2. π: collapse of pairing, clear shell gap
3. ν: survival of pairing coexisting with the shell gap
4. Very soft nuclei: large amount of low-lying collective vibrational modes (~100 phonons below 15 MeV)



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:

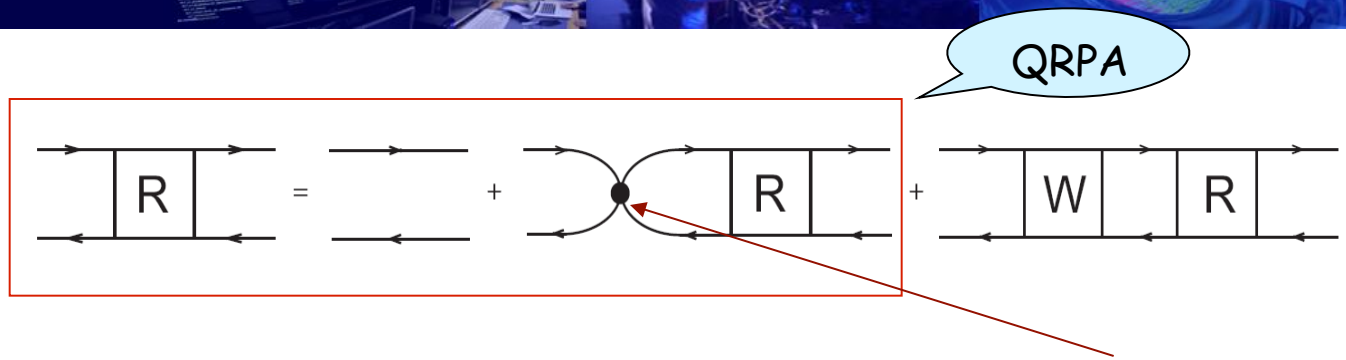
1. Impact on the shell gaps
2. Smearing out the shell effects

Shell stabilization & vibration stabilization/destabilization (?)

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

Excited states: nuclear response function

Nuclear response function R: two-body propagation in the nuclear medium

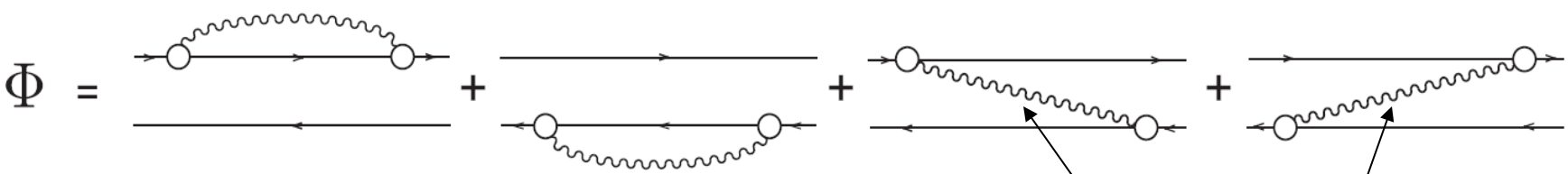


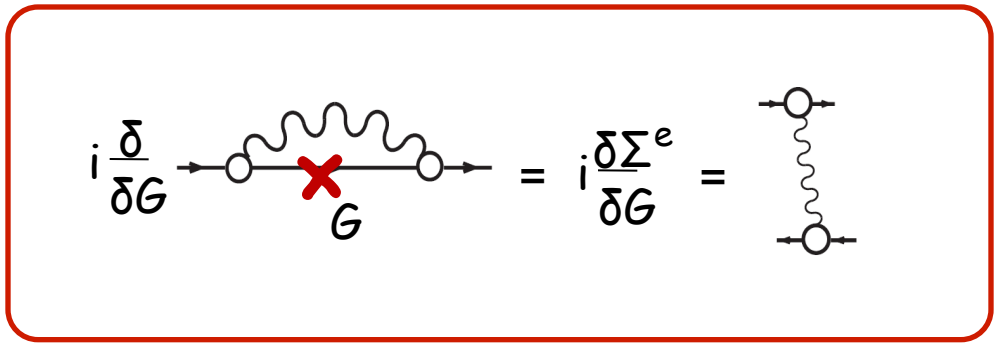
Bethe-Salpeter Equation (BSE)

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

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

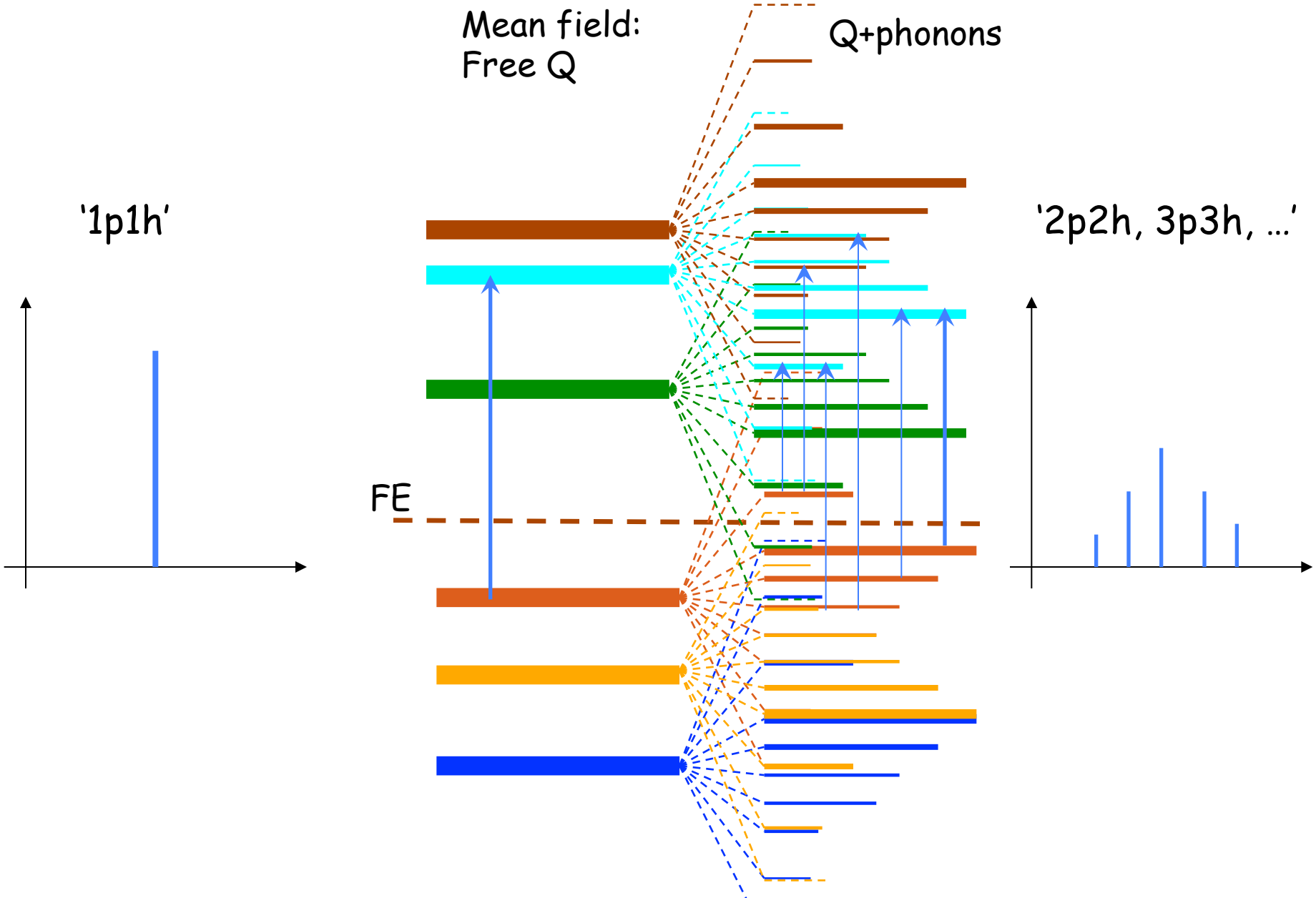
$$W(\omega) = \Phi(\omega) - \Phi(0)$$





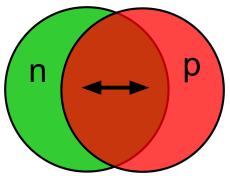
$$U^e = i\,\frac{\delta\Sigma^e}{\delta G}$$

Transitions: fragmentation mechanism (schematic)

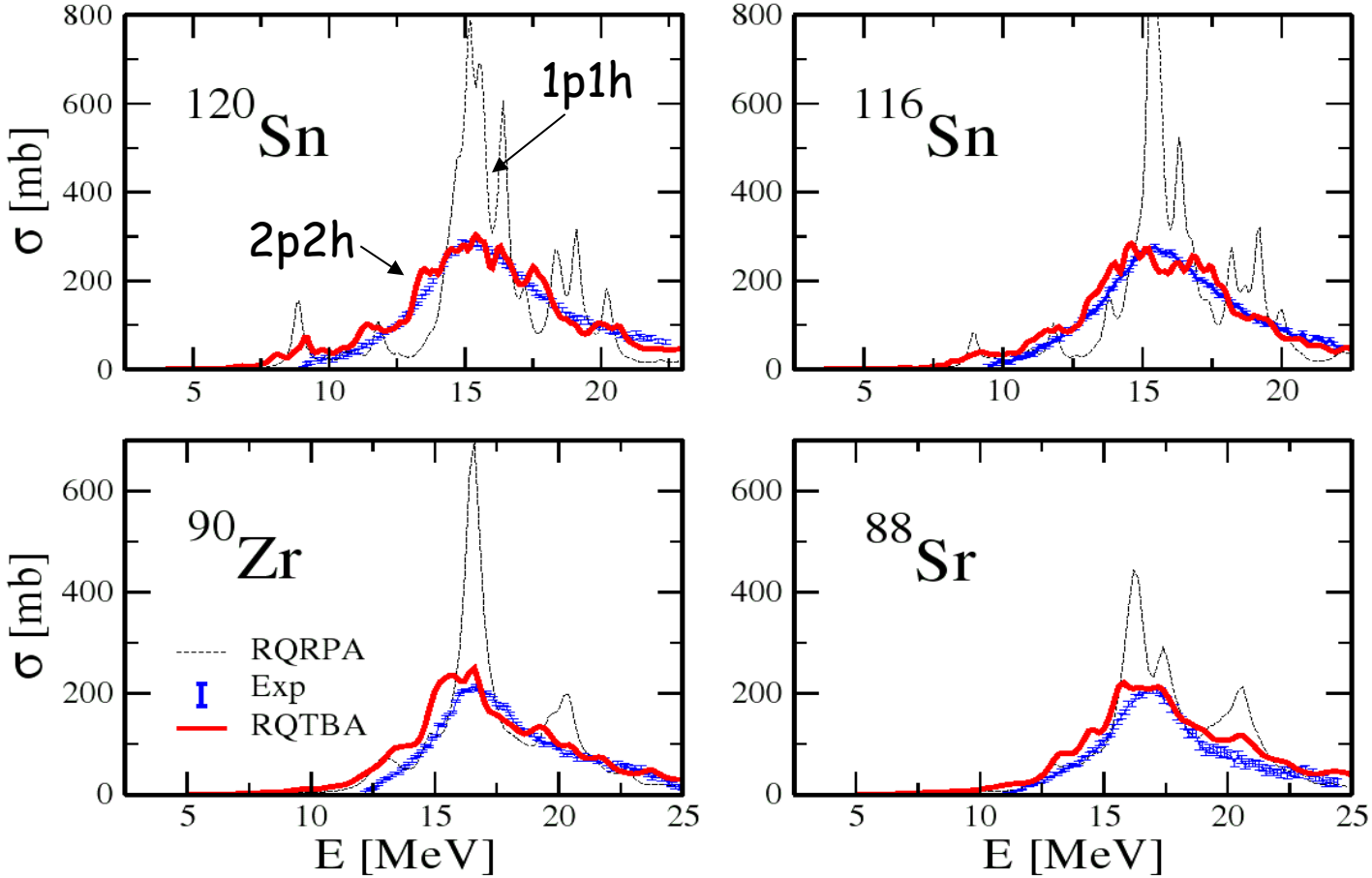


Giant Dipole Resonance
within Relativistic Quasiparticle Time Blocking Approximation (RQTBA)*

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



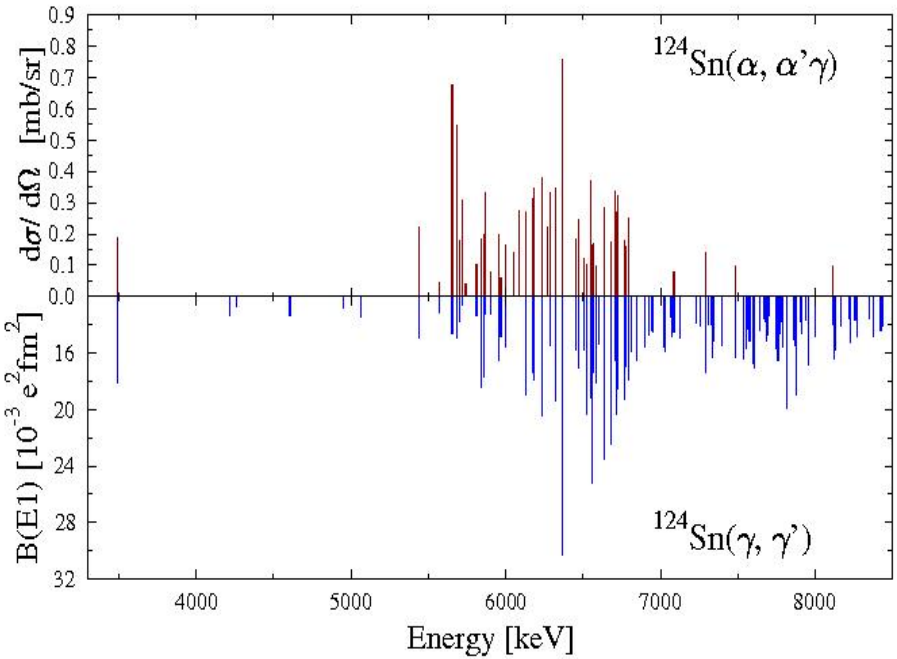
ΔL = 1
ΔT = 1
ΔS = 0



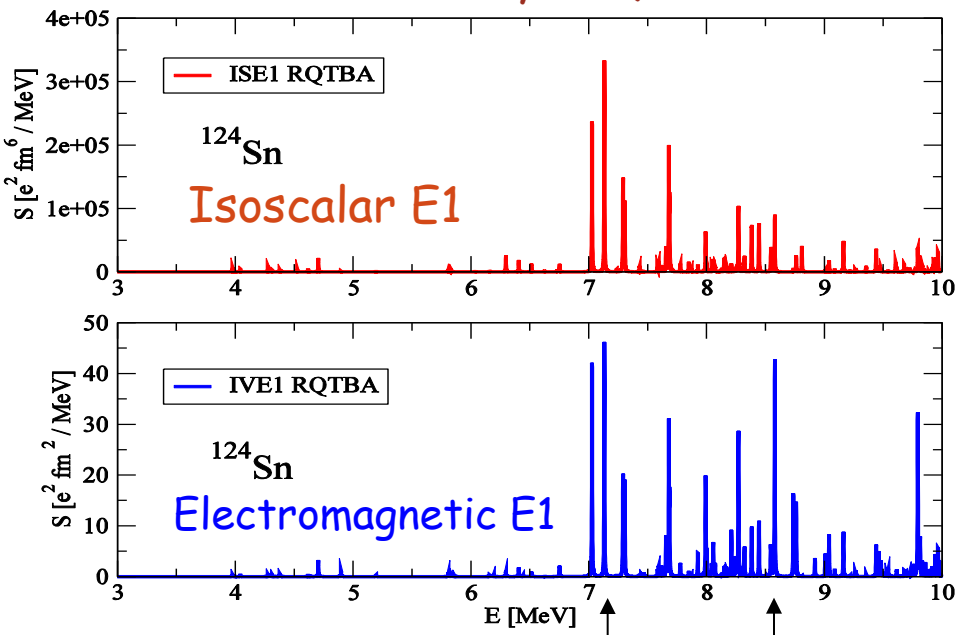
*E. L., P. Ring, and V. Tselyaev, Phys. Rev. C 78, 014312 (2008)

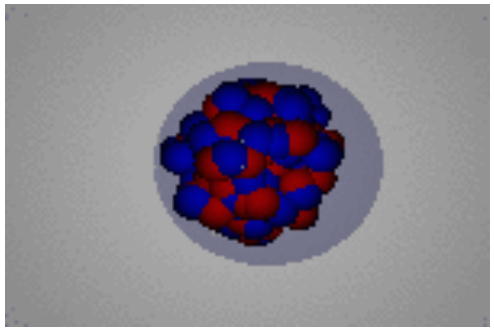
Isospin structure of the pygmy dipole resonance in ^{124}Sn

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



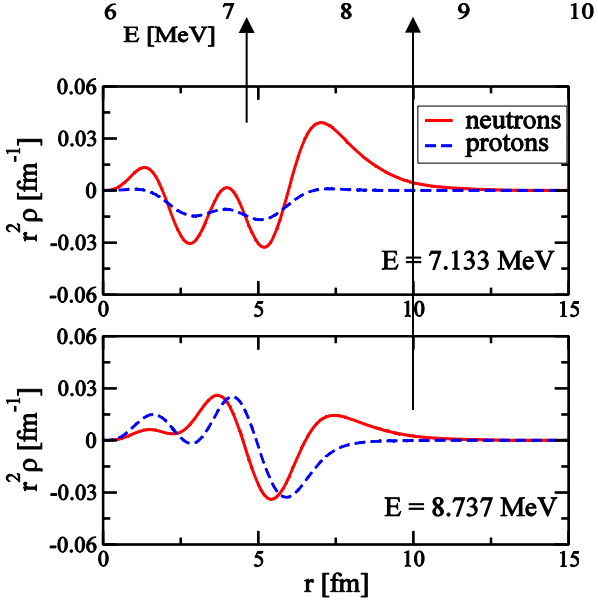
Theory: RQTBA





$B_{IS} \sim \rho^{(n)}+\rho^{(p)}$

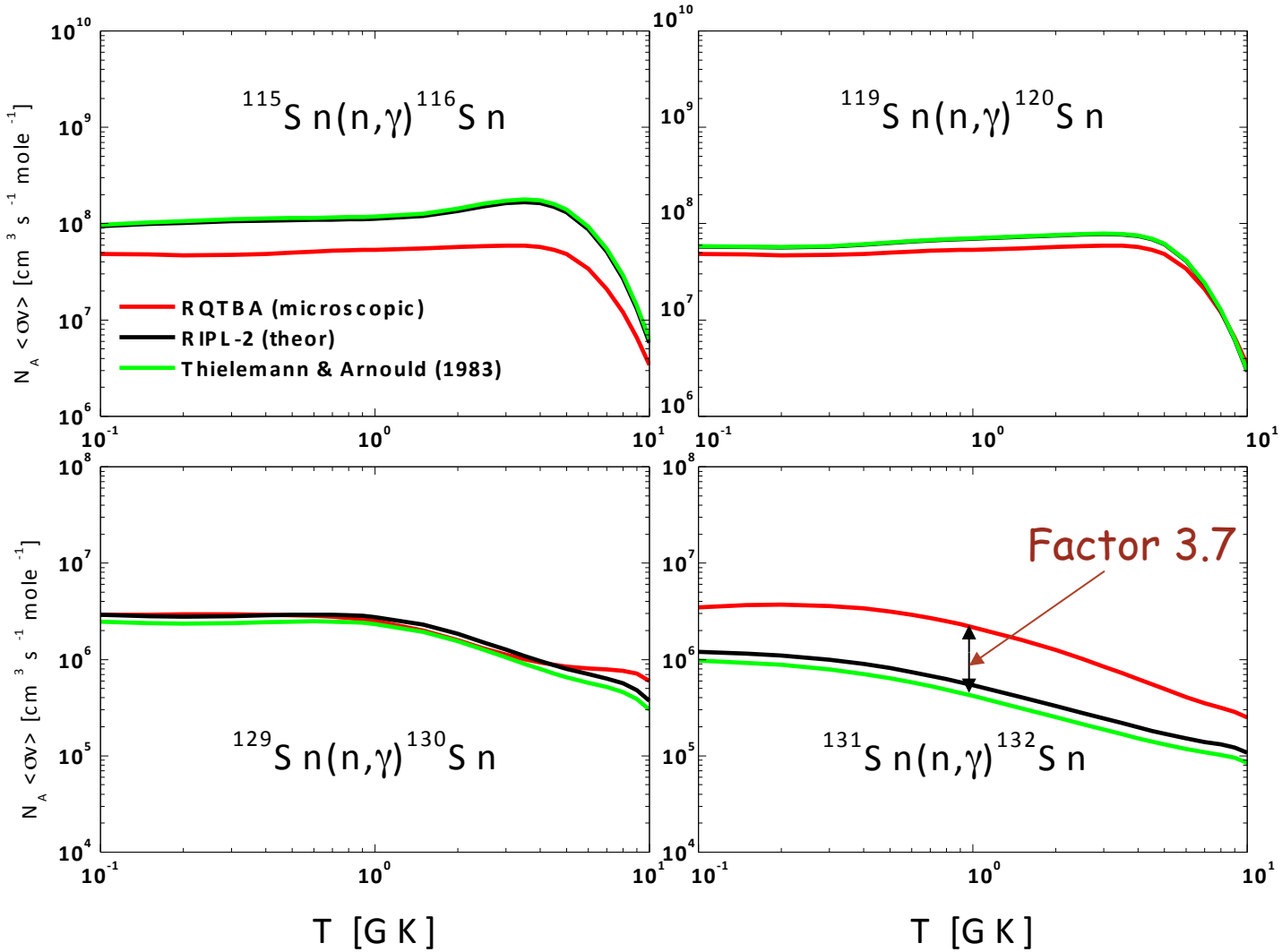
$B_{EM} \sim Z\rho^{(n)}-N\rho^{(p)}$



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

(n,γ) stellar reaction rates

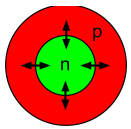
E. L., H.P. Loens, K. Langanke, et al. Nucl. Phys. A 823, 26 (2009).



PDR at neutron threshold

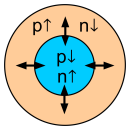
Furthermore for astrophysics: spin & isospin-flip excitations

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



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

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



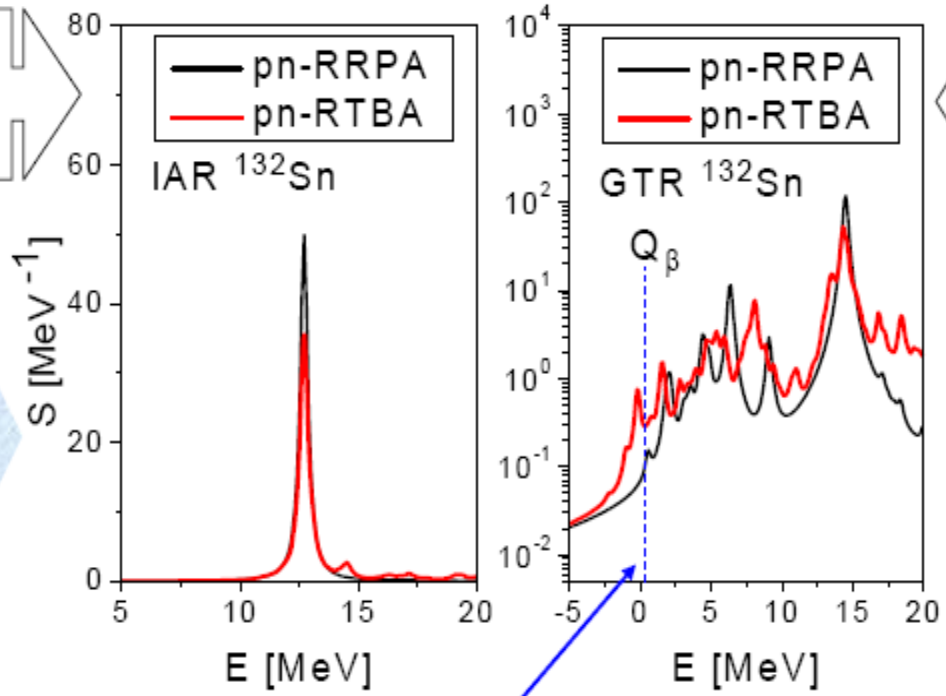
$\Delta L = 0$
$\Delta T = 1$
$\Delta S = 1$

Astrophysical nucleosynthesis studies:
competition between neutron capture and β-decay. (n,γ) and β-decay half-lifes calculations within the same computation scheme are needed!

RRPA (1p1h) vs RTBA (2p2h):

Isobar-analog resonance

IAR remains almost unchanged



Gamow-Teller resonance

RRPA:
$T_{1/2} = \infty$

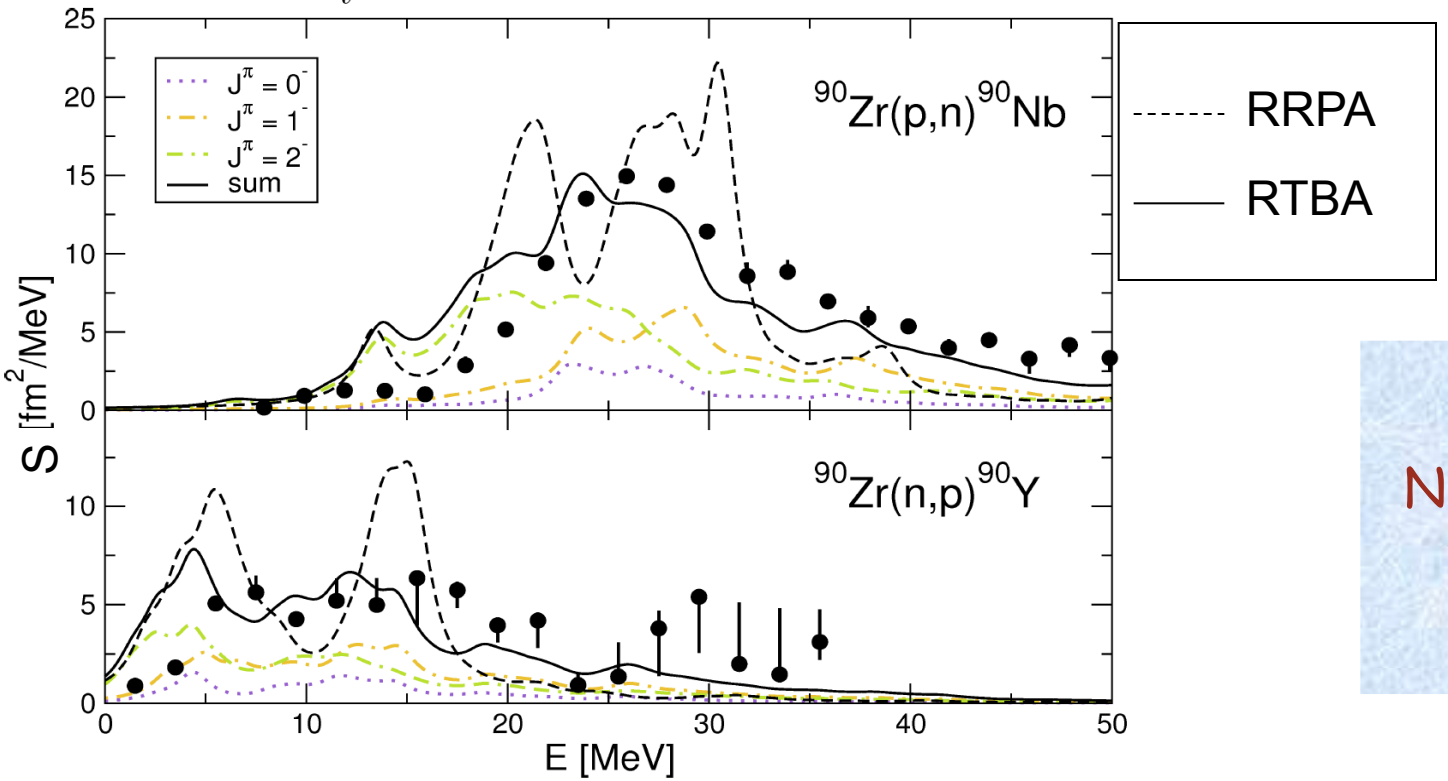
RTBA:
$T_{1/2} \approx 20$ s

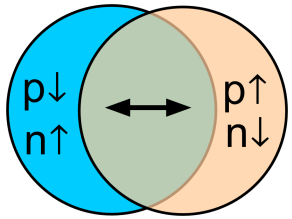
Exp:
$T_{1/2} \approx 40$ s

$$\frac{1}{T_{1/2}} = \frac{2\pi}{\ln 2}\frac{g_A^2}{\hbar}\int dE_e \sum_m |\langle 1_m^+|\sum_n \vec{\sigma}_n \tau_n^+|0^+\rangle|^2 \frac{dn_m}{dE_e}$$

Spin-dipole resonance: beta-decay, electron capture

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





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

Neutron skin thickness

Sum rule:

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

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

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

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

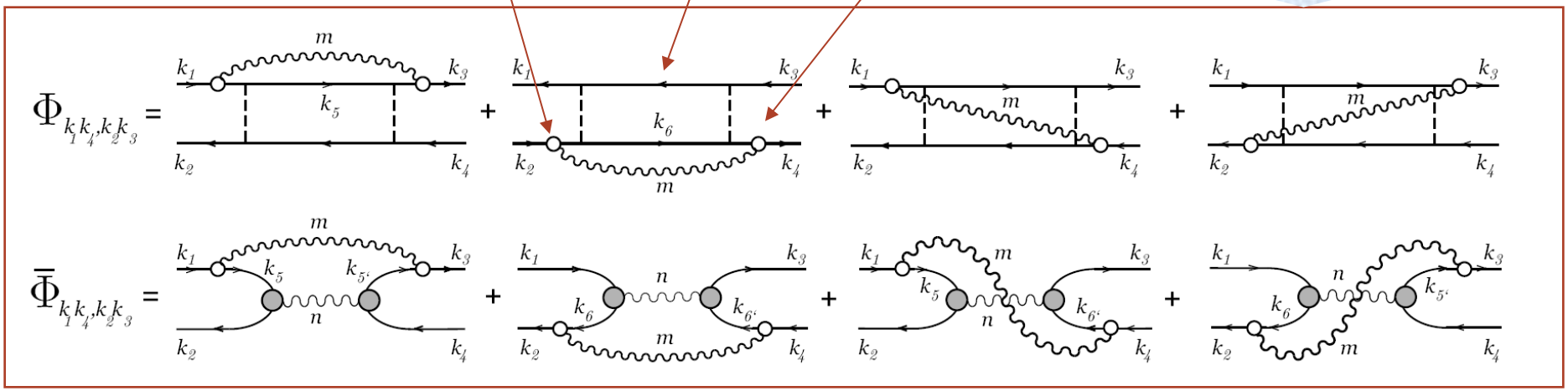
P. Schuck, Z. Phys. A 279, 31 (1976)
V.I. Tselyaev, PRC 75, 024306 (2007)

&

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

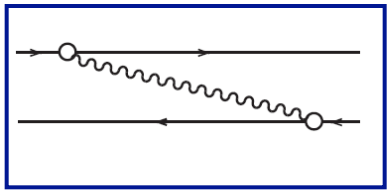
Poles may appear at lower energies:

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

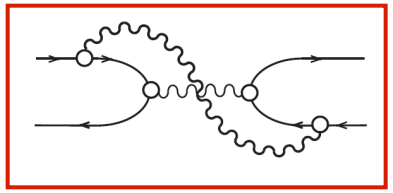
'2 phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu\nu}\, a_{iji'j'}/(\omega - \Omega_\nu - \Omega_\mu)$

Fine features of dipole spectra: two-phonon effects

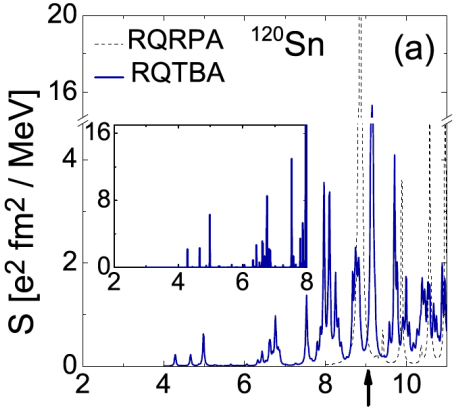
2q+phonon

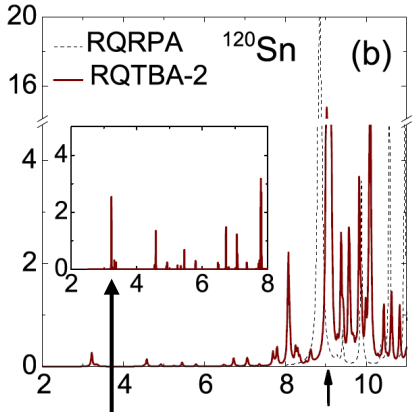


2 phonon



^{120}Sn

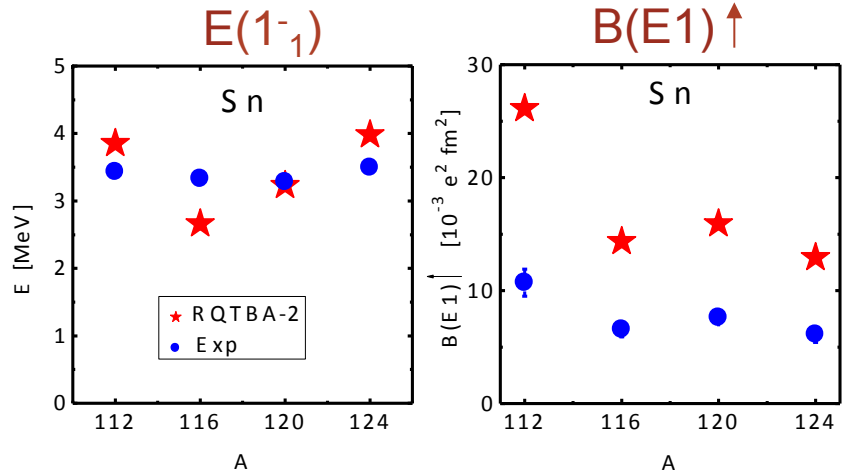




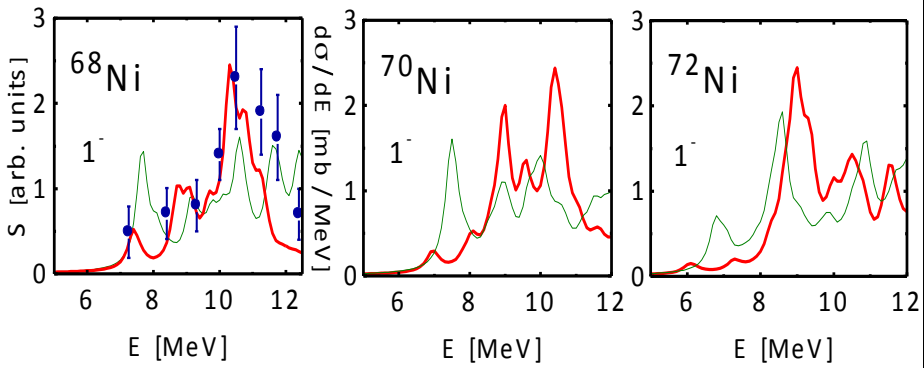
$3^- \otimes 2^+$

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

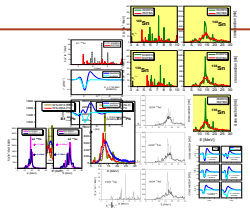
First two-phonon state 1^-_1 : $3^- \otimes 2^+$



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



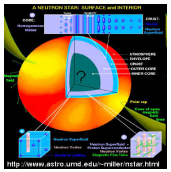
Outlook



Nuclear structure & Astrophysics

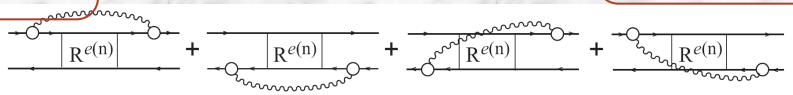
Applications

Nuclear matter, Neutron stars, …

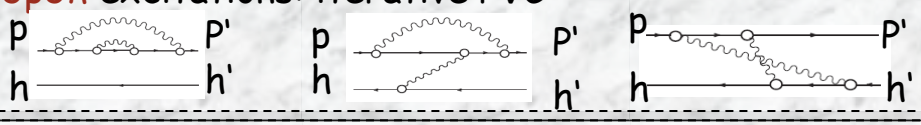


Data => Constraints

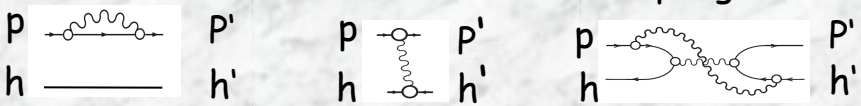
np-nh

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

3p3h excitations: iterative PVC



2p2h excitations: Particle-Vibration Coupling



1p1h excitations: RQRPA

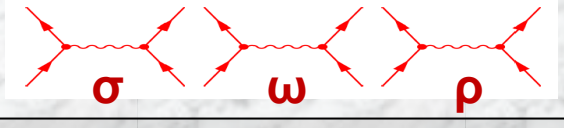
Self-consistency

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

Data => Constraints

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
Chiral DFT, …

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Hans Peter Loens (GSI)
Karlheinz Langanke (GSI)
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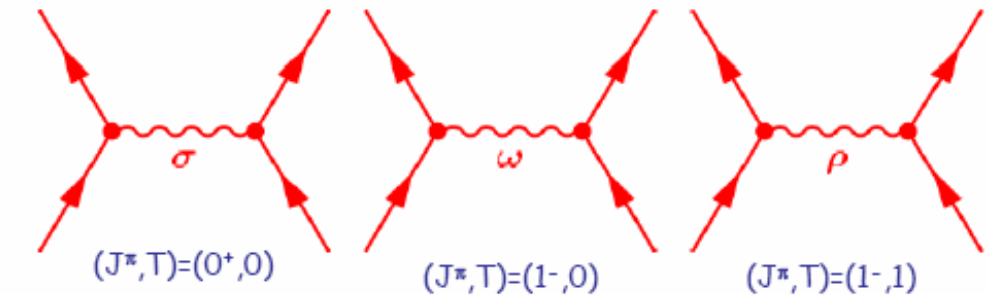
Covariant density functional theory

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

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

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

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

nucleons interaction mesons

Relativistic mean field

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

$$\begin{cases} \mathcal{H}_{RHB}|\psi_k^\eta\rangle = \eta E_k|\psi_k^\eta\rangle, \qquad \eta = \pm 1 \\ -\Delta\phi_m(\boldsymbol{r}) + U'(\phi_m(\boldsymbol{r})) = \mp \sum_k V_k^\intercal(\boldsymbol{r})\beta\Gamma_m V_k^*(\boldsymbol{r}) \end{cases}$$

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

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

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

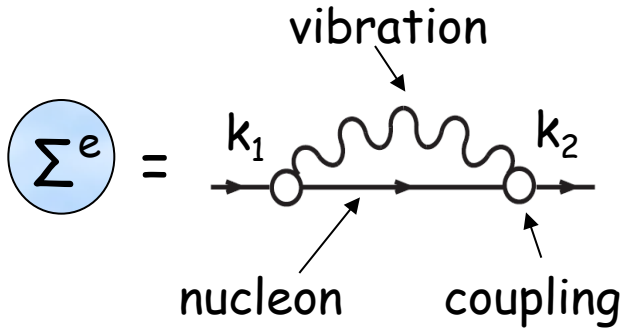
RMF self-energy

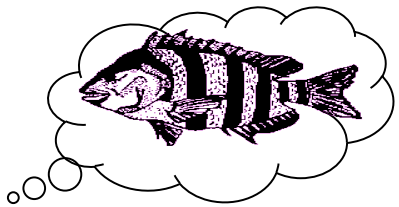
Eigenstates

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

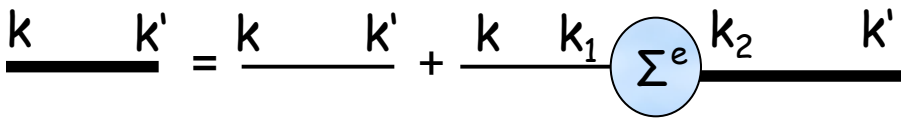
First step beyond relativistic mean field: quasiparticles coupled to vibrations

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





"Fish" diagram



One-body propagator
(Dyson equation)

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

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

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

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

Energy dependence

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

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

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

Algebraic equation for the response function

$$R^{\eta\eta'}_{k_1k_4,k_2k_3}(\omega) = \tilde{R}^{(0)\eta}_{k_1k_2}(\omega)\delta_{k_1k_3}\delta_{k_2k_4}\delta_{\eta\eta'}$$

$$+ \tilde{R}^{(0)\eta}_{k_1k_2}(\omega) \sum_{k_5k_6k_7k_8} \sum_{\eta''} \bar{W}^{\eta\eta''}_{k_5k_8,k_6k_7}(\omega) R^{\eta''\eta'}_{k_7k_4,k_8k_3}(\omega)$$

Mean field propagator

Subtraction to avoid double counting

$$\bar{W}^{\eta\eta'}_{k_1k_4,k_2k_3}(\omega) = \tilde{V}^{\eta\eta'}_{k_1k_4,k_2k_3} + \left(\Phi^{\eta}_{k_1k_4,k_2k_3}(\omega) - \Phi^{\eta}_{k_1k_4,k_2k_3}(0)\right)\delta_{\eta\eta'}$$

2q-phonon coupling amplitude

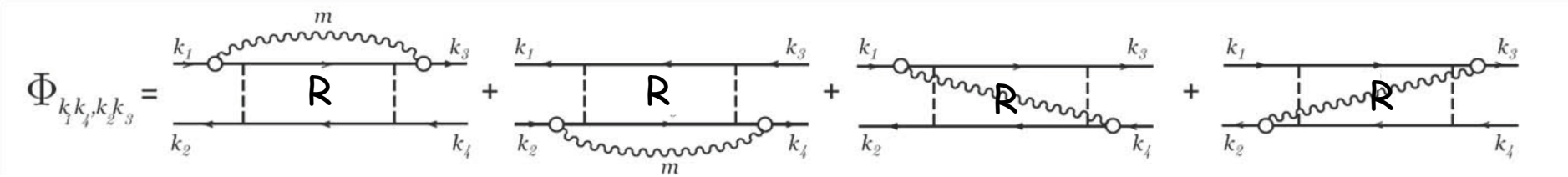
$$\Phi^{\eta}_{k_1k_4,k_2k_3}(\omega) =$$

$$= \sum_{\mu,\xi} \delta_{\xi\eta}\Big[\delta_{k_1k_3} \sum_{k_6} \frac{\gamma^{-\xi*}_{\mu;k_2k_6}\gamma^{-\xi}_{\mu;k_4k_6}}{\eta\omega - E_{k_1} - E_{k_6} - \Omega^{\mu}} + \delta_{k_2k_4} \sum_{k_5} \frac{\gamma^{\xi}_{\mu;k_1k_5}\gamma^{\xi*}_{\mu;k_3k_5}}{\eta\omega - E_{k_5} - E_{k_2} - \Omega^{\mu}}$$

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

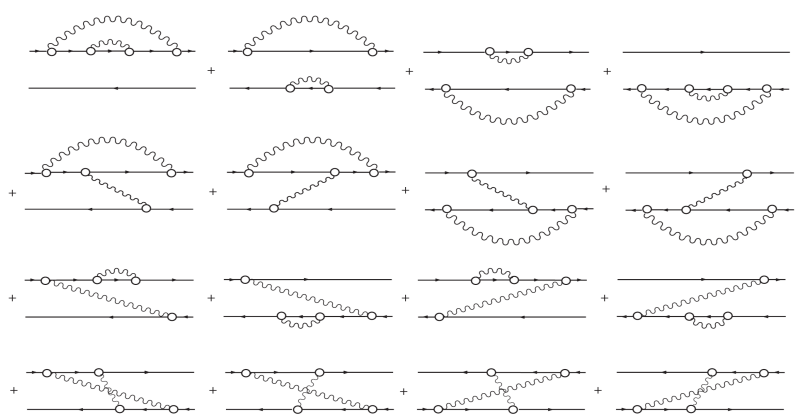
Next-order RQTBA for 3p-3h configurations & iterative procedure for multiphonon response

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



Nested configurations

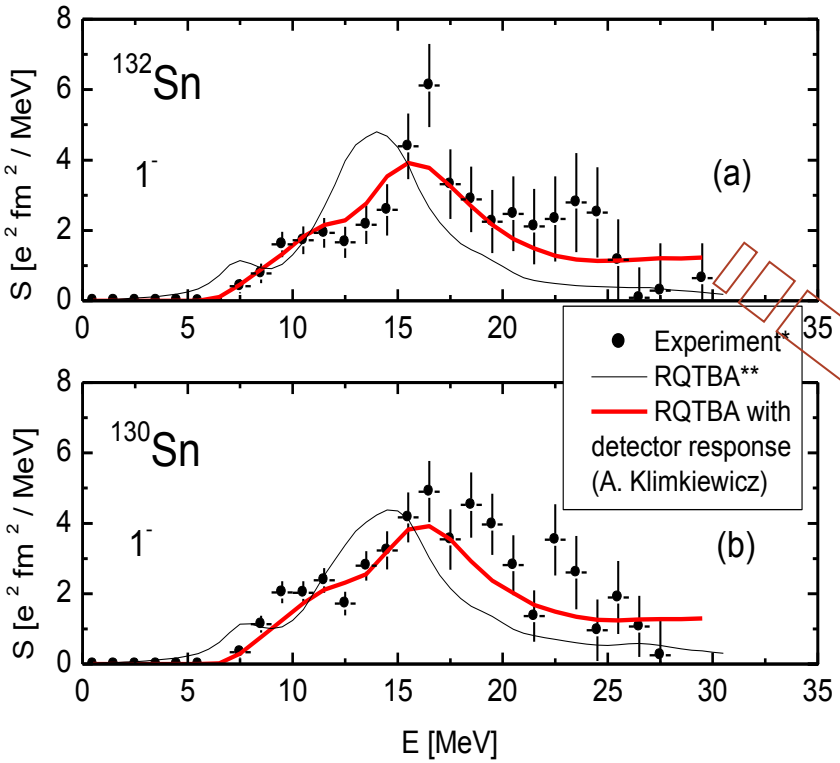
γ^4 terms in Φ-amplitude:

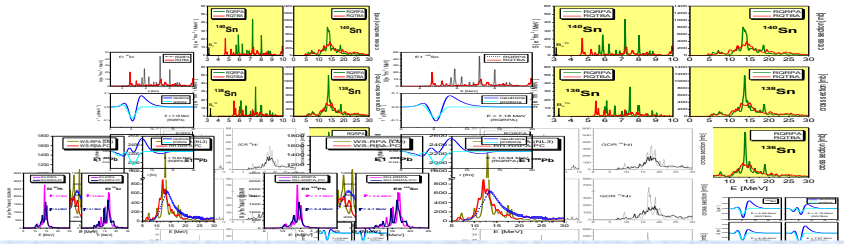


3p3h: two-fish approximation, …

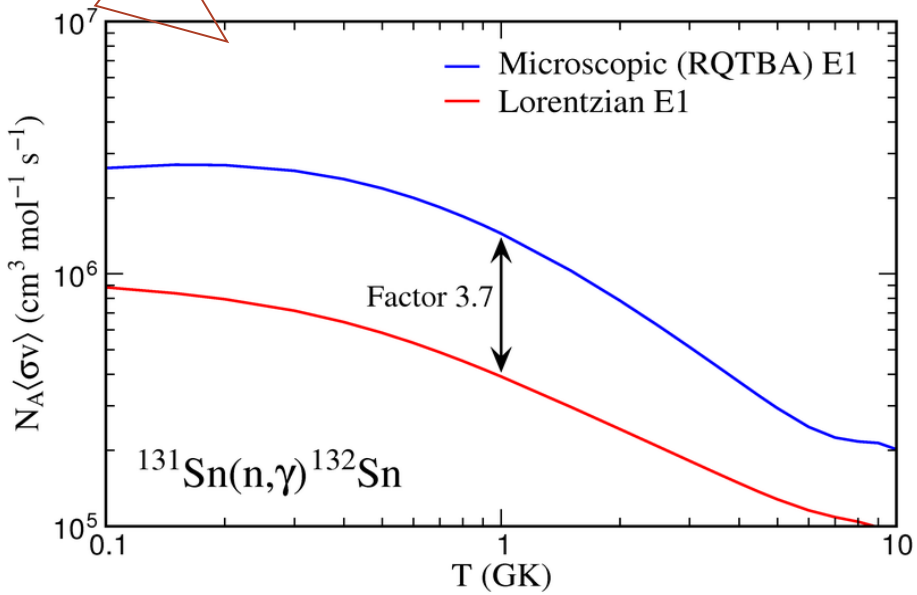
Dipole strength in neutron-rich nuclei: importance for astrophysics

Neutron-rich Sn





Input for astrophysics:
cross sections, reaction rates etc. under astrophysical conditions

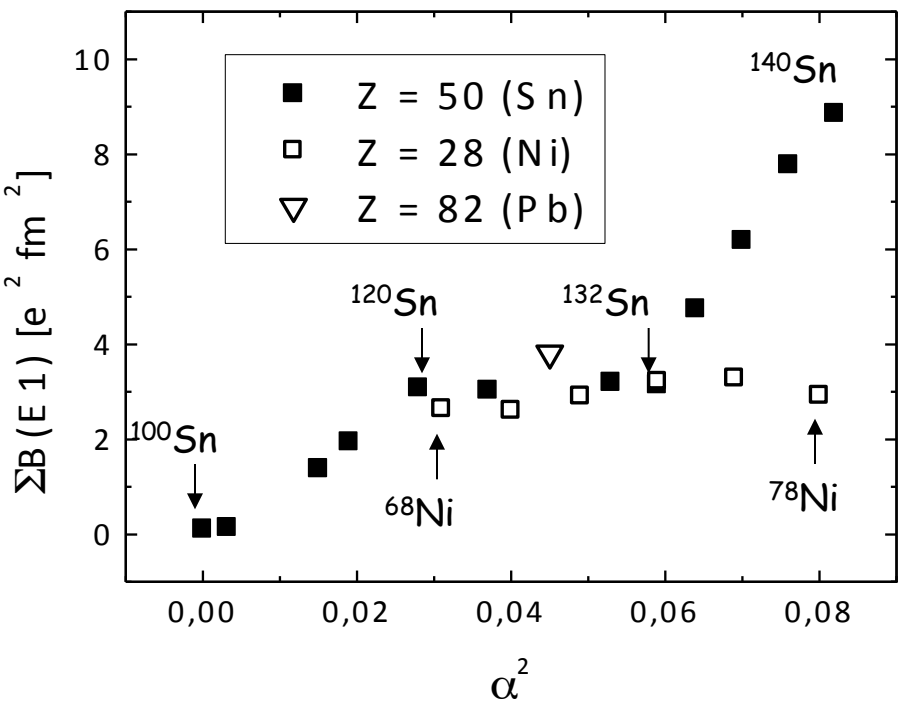


*P. Adrich, et al., PRL 95, 132501 (2005)

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

RQTBA systematics for PDR:

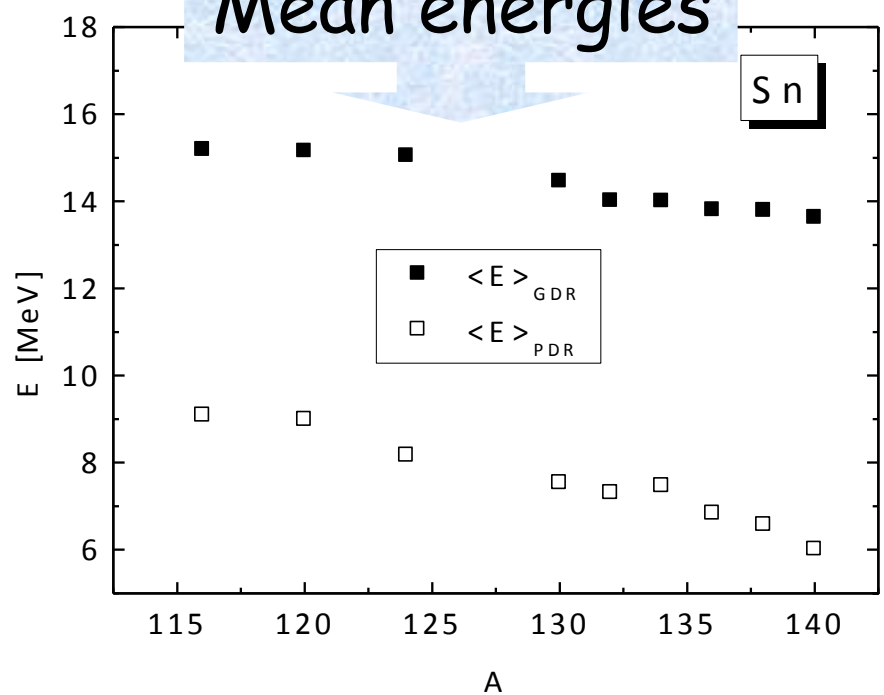
A proper definition of Pygmy Dipole Resonance is important!
PDR = all states with the "isoscalar" underlying structure!



Strength vs α^2

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

Mean energies



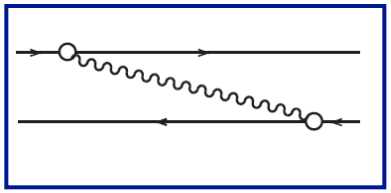
^{120}Sn → ^{132}Sn: 1h11/2 (n)
^{68}Ni → ^{78}Ni: 1g9/2 (n)

Intruder orbits !

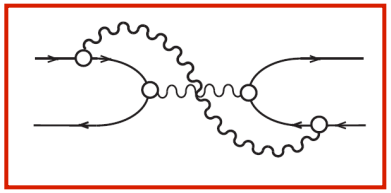
E.L. et al. PRC 79, 054312 (2009)

Fine features of dipole spectra: two-phonon effects

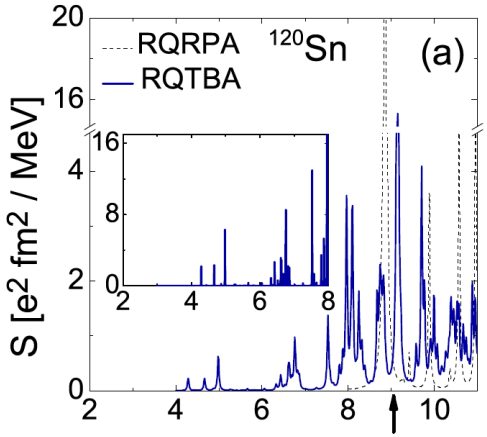
2q+phonon

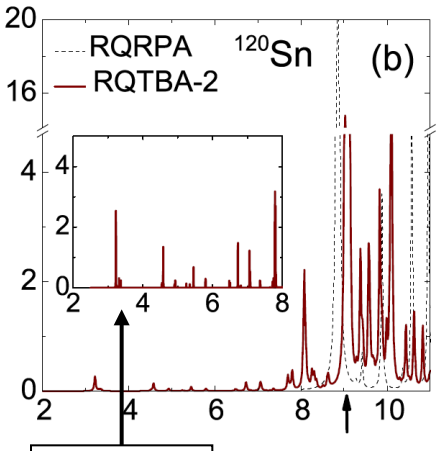


2 phonon



^{120}Sn





$3^- \otimes 2^+$

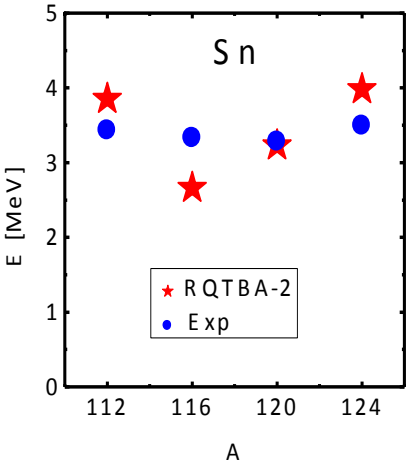
E.L., P.Ring, V.Tselyaev, PRL 105, 02252 (2010)

First two-phonon state 1^-_1

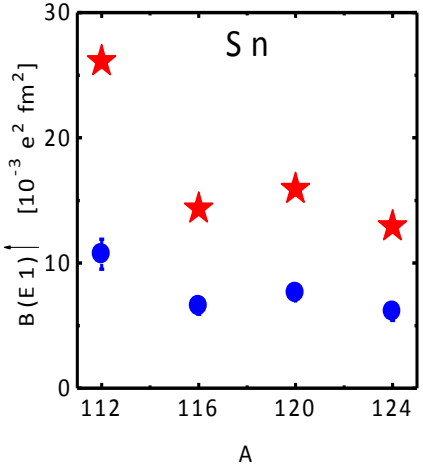
$3^- \otimes 2^+$

$E(1^-_1) \approx E(2^+_1) + E(3^-_1)$

$E(1^-_1)$



$B(E1)\uparrow$



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