RPA for Superfluid Nuclei and Extensions

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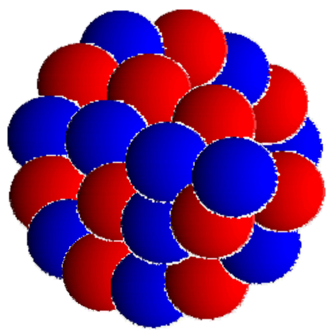


Content

- Static density functionals in nuclei
- Time dependent density functionals in nuclei
- Quasiparticle RPA
- Applications:

  - relativistic RPA
  - continuum RPA
  - deformed RPA
  - pn - RPA

- Extensions

  - energy dependent KS-fields
  - Mixing of deformed configurations
  - Symmetry restoration before variation

- Conclusions and outlook

ab initio: 3 scales

> 1 GeV

- **QCD:** non-linear gauge theory, **quarks, gluons**
- confinement
- running coupling constant
- at low energies **non-perturbative**
- effective degrees of freedom: nucleon, pion

~ 100 MeV

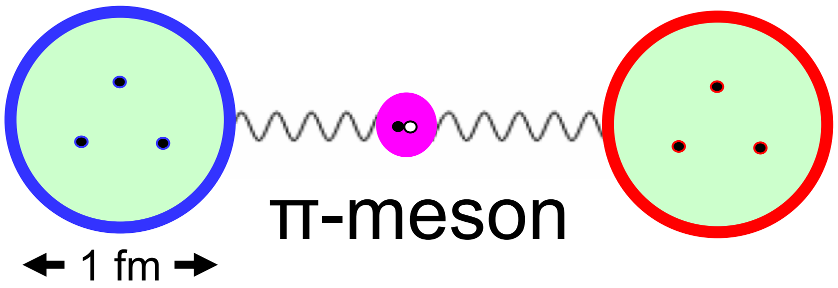
- effective Lagrangian in **nucleons and pions**
- parameters (LEC) so far phenomenological
- non renormalizable
- at low momenta: **chiral perturbation theory: χPT**
- → bare nucleon-nucleon interaction: NNNL **N3LO**

~ 100 keV

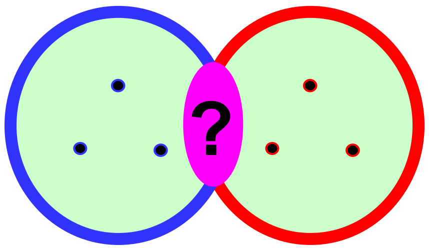
- effective forces within the nucleon
- density dependent
- configuration mixing, **density functional theory**

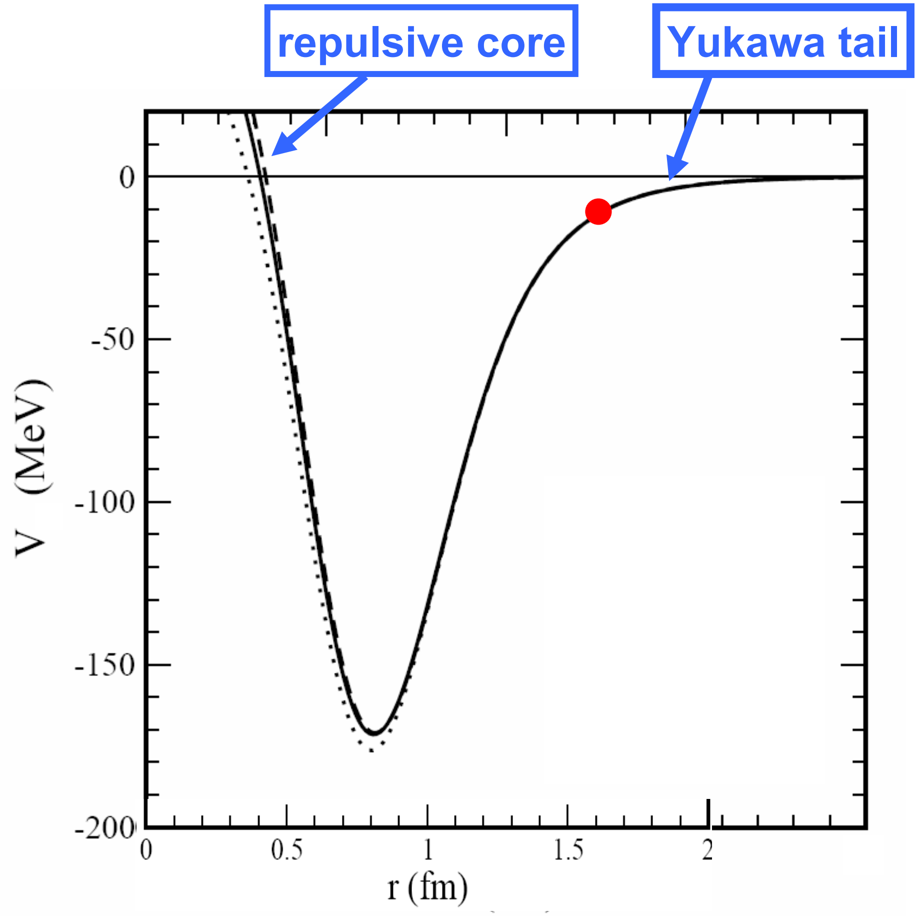
bare nucleon-nucleon interaction:

distance > 1 fm: attractive



distance < 0.8 fm: repulsive





three-body forces ?

Density functional theory in nuclei

D.Brink
D.Vauterin

Skyrme

$$E[\rho] = \langle\Psi|H|\Psi\rangle \approx \langle\Phi|H_{eff}(\rho)|\Phi\rangle$$

$|\Phi\rangle$ Slater determinant $\Longleftrightarrow$ ρ density matrix

$$|\Phi\rangle = \mathcal{A}\{\varphi_1(\mathbf{r}_1)\ldots\varphi_{(}\mathbf{r_A})\} \Longleftrightarrow \rho(\mathbf{r},\mathbf{r}') = \sum_{i=1}^{A} |\varphi_i(\mathbf{r})\rangle\langle\varphi_i(\mathbf{r}')|$$

Mean field:

$$\hat{h} = \frac{\delta E}{\delta \rho}$$

Eigenfunctions:

$$h|\varphi_i\rangle = \varepsilon_i|\varphi_i\rangle$$

Interaction:

$$\hat{V} = \frac{\delta^2 E}{\delta\rho\,\delta\rho}$$

Extensions: Pairing correlations, Covariance
Relativistic Hartree Bogoliubov (RHB)

Density functionals in nuclei:

- the are based on **density dependent** two-body interactions **H(ρ)**
  - on the mean field level they contain also **three-body** forces
- they are **completely phenomenological**
  - few parameters are adjusted to binding energies and radii
- they can be represened by **zero range forces** (and gradient corrections)
  - on the mean field level one needs only momenta $\mathbf{k < k_F}$
- for zero range forces **Fock terms** can be absorbed in the parameters
- there are large **spin-orbit** terms
- strong pp-correlations lead in open shell nuclei to **superfluidity**
  - is treated on the mean field level by **Hartree-Fock-Bogoliubov** methods

3 types of functionals are presently used:

- **non relativistic zero range forces (Skyrme)**
- **finite range forces of Gaussian shape (Gogny)**
- **relativistic density functionals (RMF)**

Density functionals in superfluid systems:

$$E[\rho, \kappa] = E_{\mathrm{KS}}[\rho] + E_{\mathrm{pair}}[\kappa]$$

$$\mathcal{R} = \begin{pmatrix} \rho & \kappa \\ -\kappa^* & -\rho^* \end{pmatrix}$$

Valatin density

where

$$\rho = \langle a^\dagger a \rangle \qquad \kappa = \langle a^\dagger a^\dagger \rangle$$

and the Kohn-Sham equations are of the form

$$\begin{pmatrix} h_{\mathrm{KS}} - \mu & \Delta \\ -\Delta^* & -h_{\mathrm{KS}}{}^* + \mu \end{pmatrix} \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} = E_k \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix}$$

with

$$h_{\mathrm{KS}} = \frac{\delta E}{\delta \rho}, \qquad \Delta = \frac{\delta E}{\delta \kappa}$$

Relativistic Kohn-Sham equations:

$$\begin{pmatrix} m - S + V & \vec{\sigma}\vec{p} \\ \vec{\sigma}\vec{p} & -m + S + V \end{pmatrix} \begin{pmatrix} f_i \\ g_i \end{pmatrix} = \varepsilon_i \begin{pmatrix} f_i \\ g_i \end{pmatrix}$$

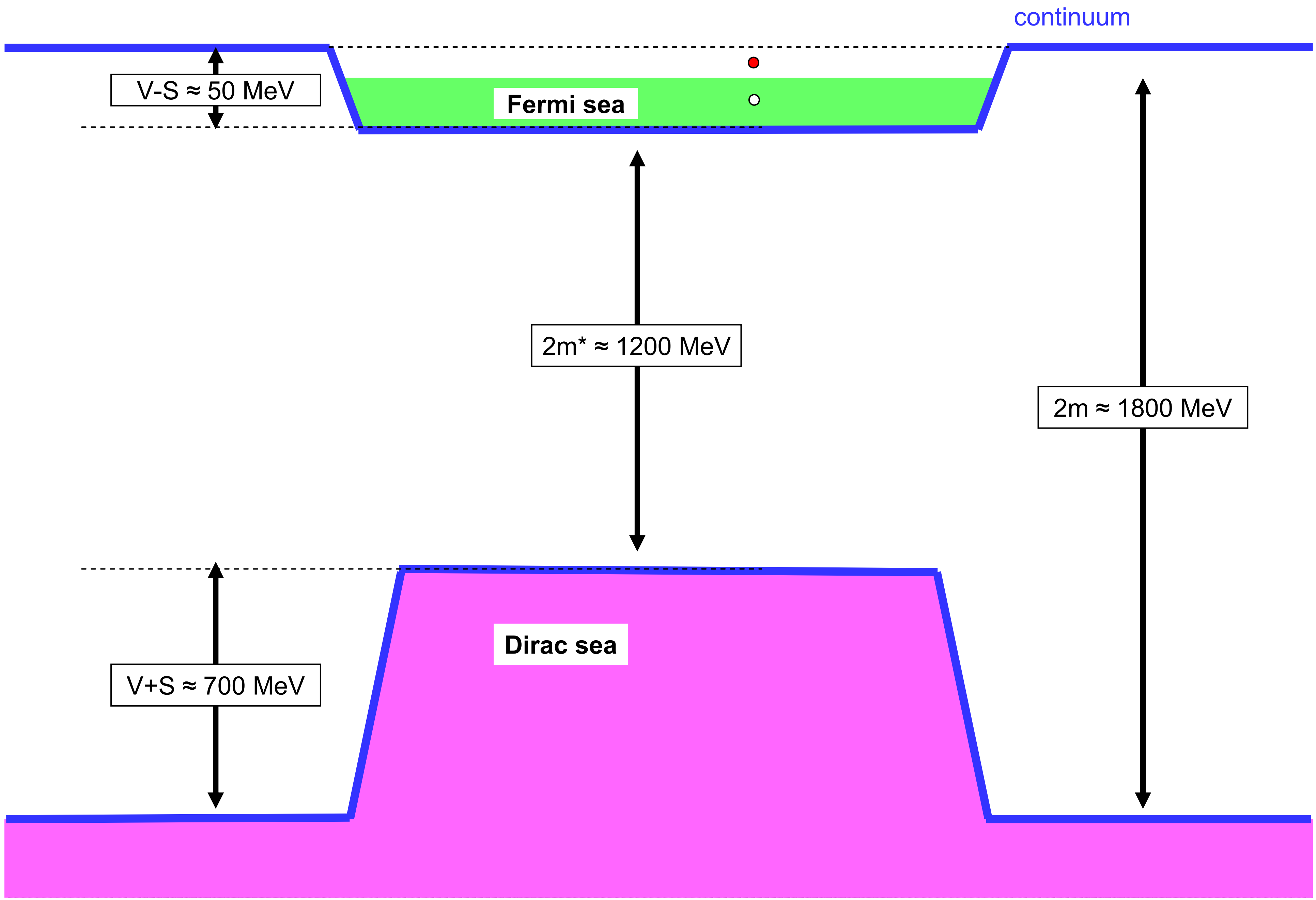
scalar potential: $$S(\mathbf{r}) = G_\sigma \rho_s(\mathbf{r}) = G_\sigma \sum_{i=1}^{A} (|f_i(\mathbf{r})|^2 - |g_i(\mathbf{r})|^2 \approx 400 \text{ MeV}$$

vector potential: $$V(\mathbf{r}) = G_\omega \rho(\mathbf{r}) = G_\omega \sum_{i=1}^{A} (|f_i(\mathbf{r})|^2 + |g_i(\mathbf{r})|^2 \approx 350 \text{ MeV}$$

No-sea approximation

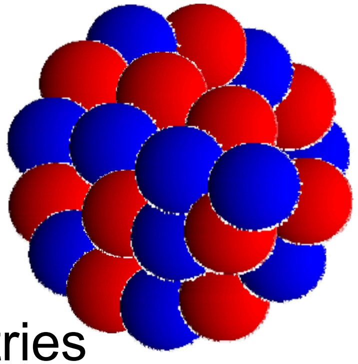
density dependent couplings: G = G(ρ) → rearrangement terms!

Relativistic potentials

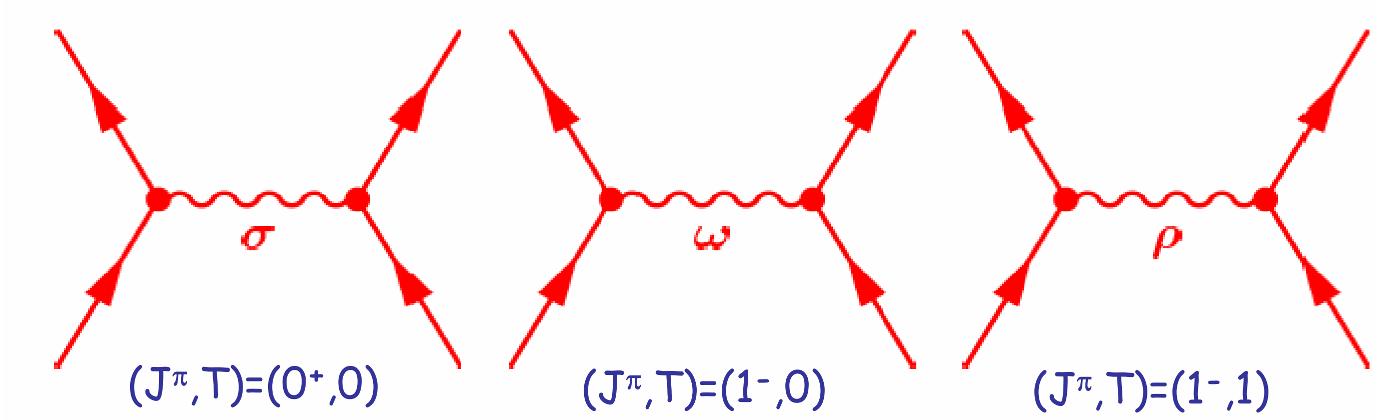


$E[\rho]$

Walecka model



- the basis is an effective Lagrangian with all relativistic symmetries
- it is used in a mean field concept (Hartree-level)
- with the no-sea approximation



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

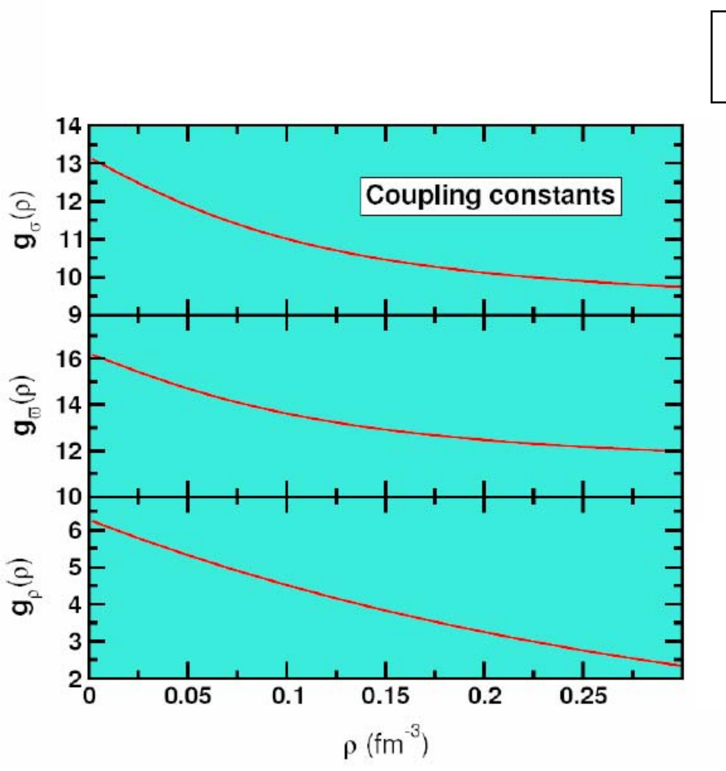
Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive

Rho-meson: isovector field

Effective density dependence:

The basic idea comes from ab initio calculations
density dependent coupling constants include Brueckner correlations
and threebody forces



non-linear meson coupling: **NL3**

Point-coupling models
with derivative terms:

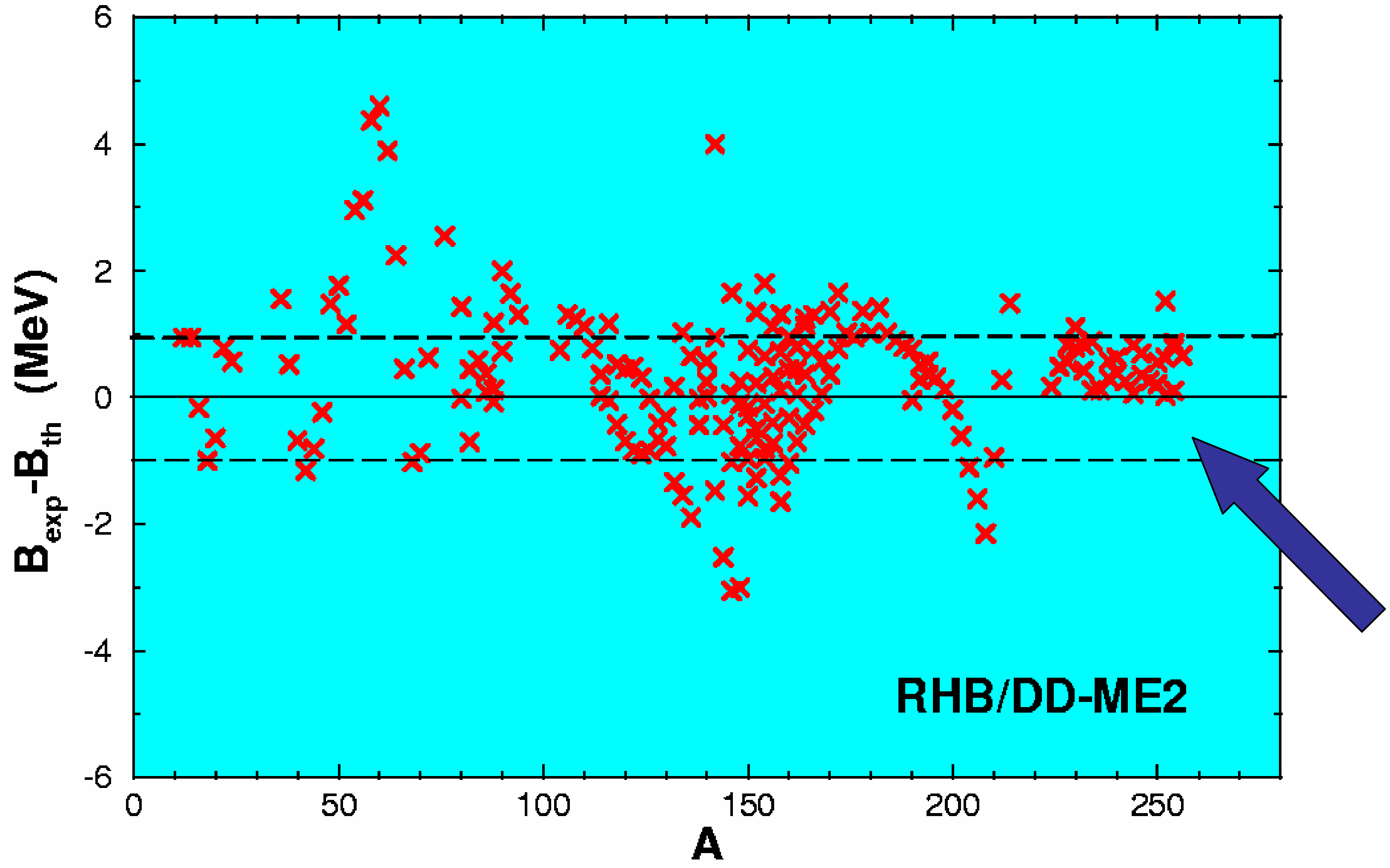
$g_\sigma(\rho)$ $g_\omega(\rho)$ $g_\rho(\rho)$

adjusted to ground state properties of finite nuclei

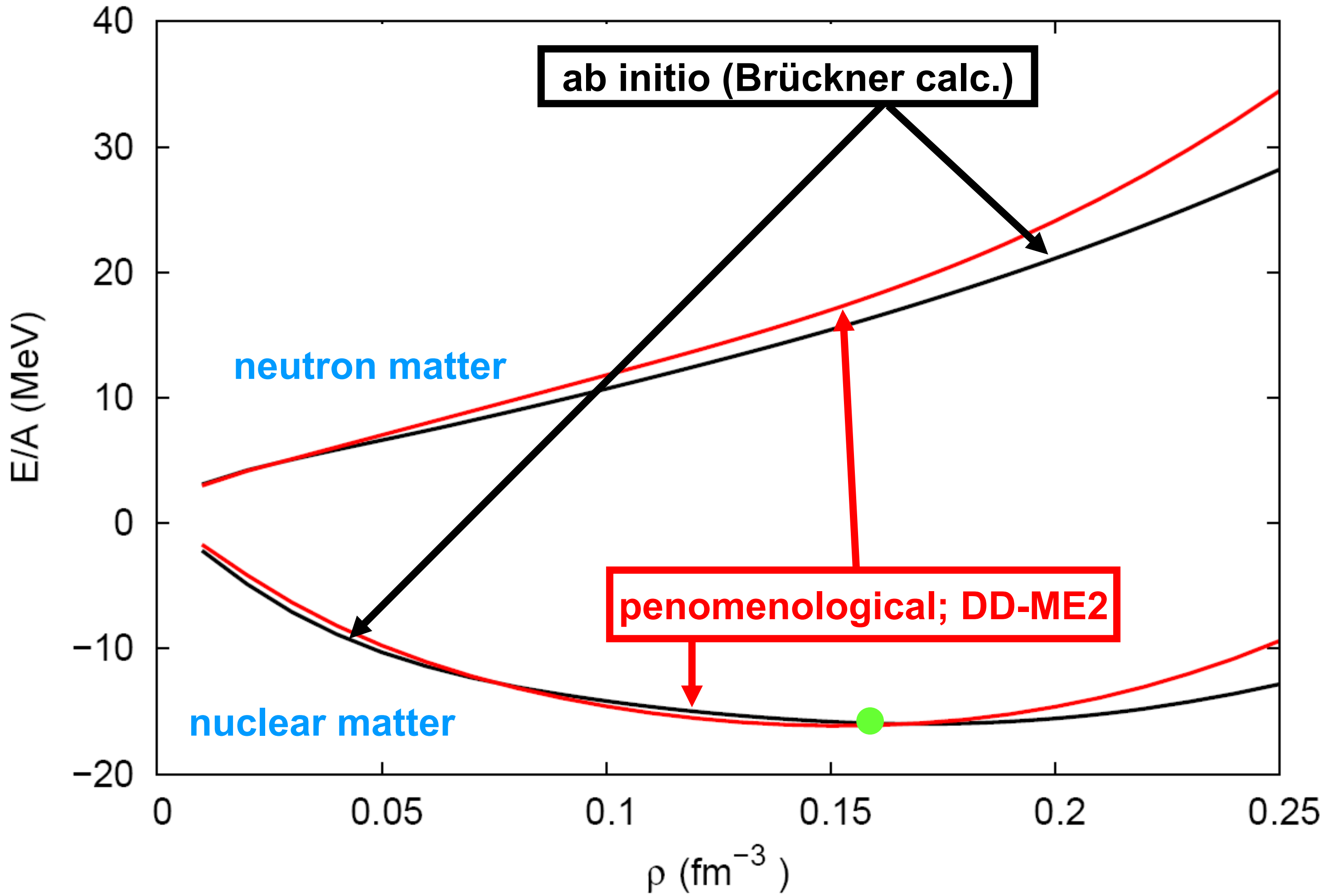
Manakos and Mannel, Z.Phys. **330**, 223 (1988)
Bürvenich, Madland, Maruhn, Reinhard, PRC **65**, 044308 (2002): **PC-F1**
Niksic, Vretenar, P.R., PRC 78, 034318 (2008): **DD-PC1**

rms-deviations: masses: Δm = 900 keV
radii: Δr = 0.015 fm

Lalazissis, Niksic, Vretenar, Ring, PRC 71, 024312 (2005)



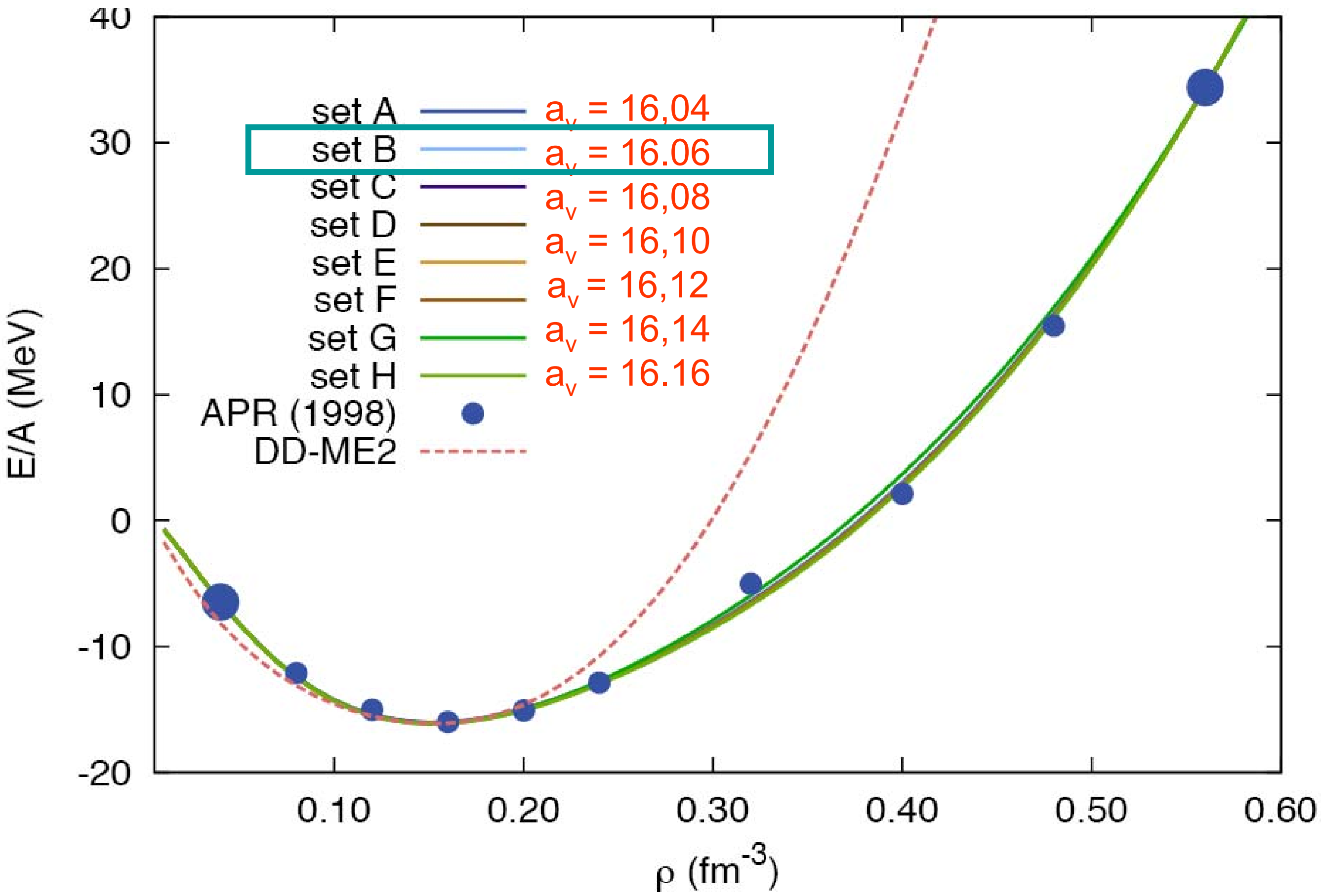
Comparison with ab initio calculations:



we find excellent agreement with ab initio calculations of Baldo et al.

Fit to ab-initio results

point coupling model is fitted to microscopic nuclear matter:



ρ_{sat} = 0.152 fm^{-3}
m* = 0.58m
K_{nm} = 230 MeV

DD-PC1

A. Akmal, V.R. Pandharipande, and D.G. Ravenhall, PRC. 58, 1804 (1998).

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Time dependent mean field theory:

$$\int dt \left\{ \langle \Phi(t) | i\partial_t | \Phi(t) \rangle - E[\hat{\rho}(t)] \right\} = 0$$

$$i\partial_t \hat{\rho} = \left[\hat{h}(\hat{\rho}) + \hat{f}, \hat{\rho} \right]$$

$$i\partial_t \psi(t) = [(\vec{\alpha}(\vec{p} - \vec{V}(t)) + V(t) + \beta(m - S(t))]\psi(t)$$

We neglect retardation and find for the fields at each time-step:

$$S(t) = G_\sigma \rho_s(t)$$

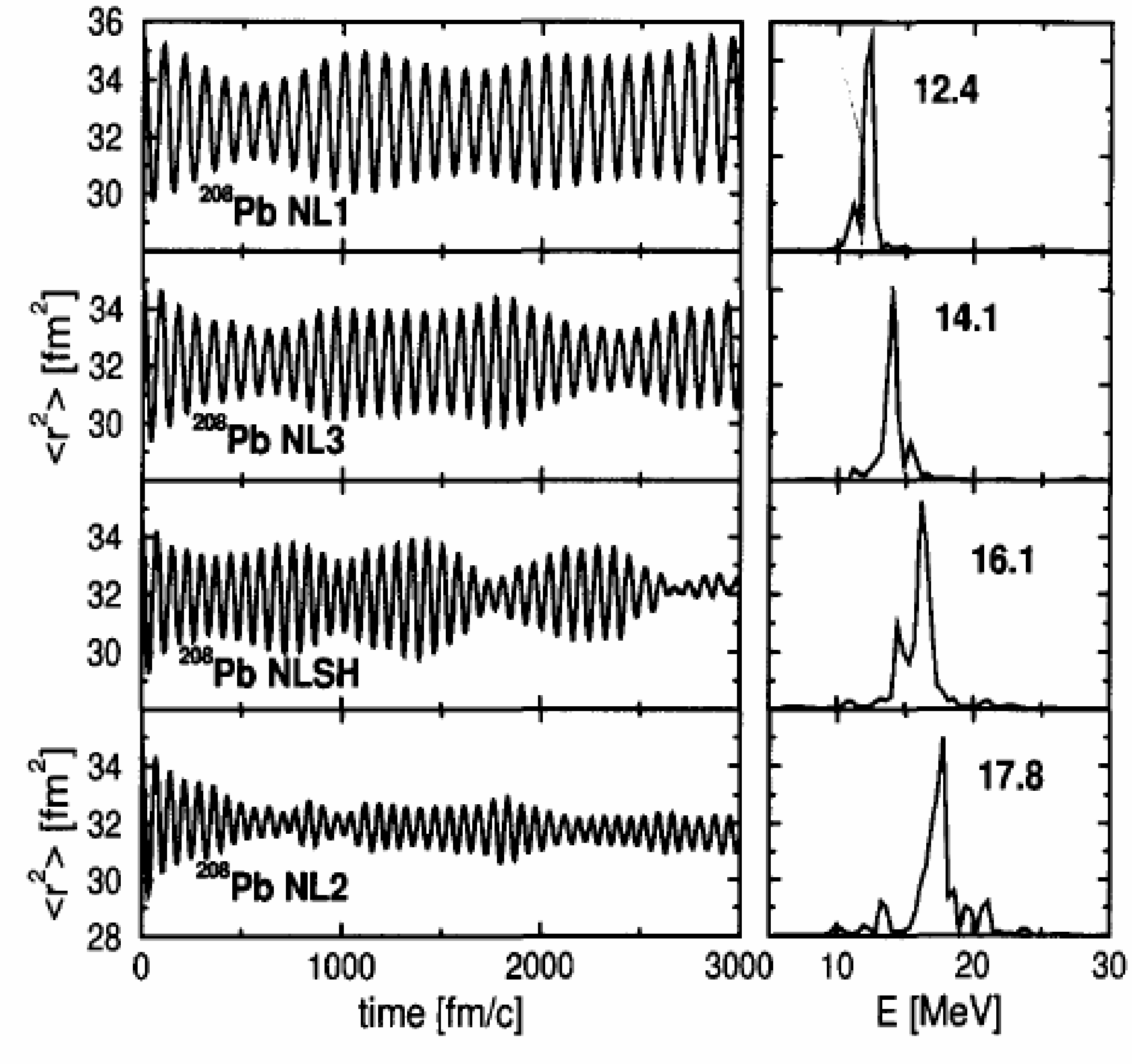
$$V(t) = G_\omega \rho(t)$$

$$\vec{V}(t) = G_\omega \vec{j}(t)$$

and similar equations for the isovector and electromagnetic-fields

$$\left\langle \Phi(t) \middle| r^2 \middle| \Phi(t) \right\rangle$$

Breathing mode: ^{208}Pb



K_∞=211

K_∞=271

K_∞=355

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Small amplitude limit gives RPA:

Small amplitude limit:

$$\hat{\rho}(t) = \hat{\rho}^{(0)} + \delta\hat{\rho}(t)$$

ground-state density

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \hbar\omega \begin{pmatrix} X \\ Y \end{pmatrix}$$

$\delta\rho_{ph}$, $\delta\rho_{\alpha h}$

$\delta\rho_{hp}$, $\delta\rho_{h\alpha}$

RPA matrices:

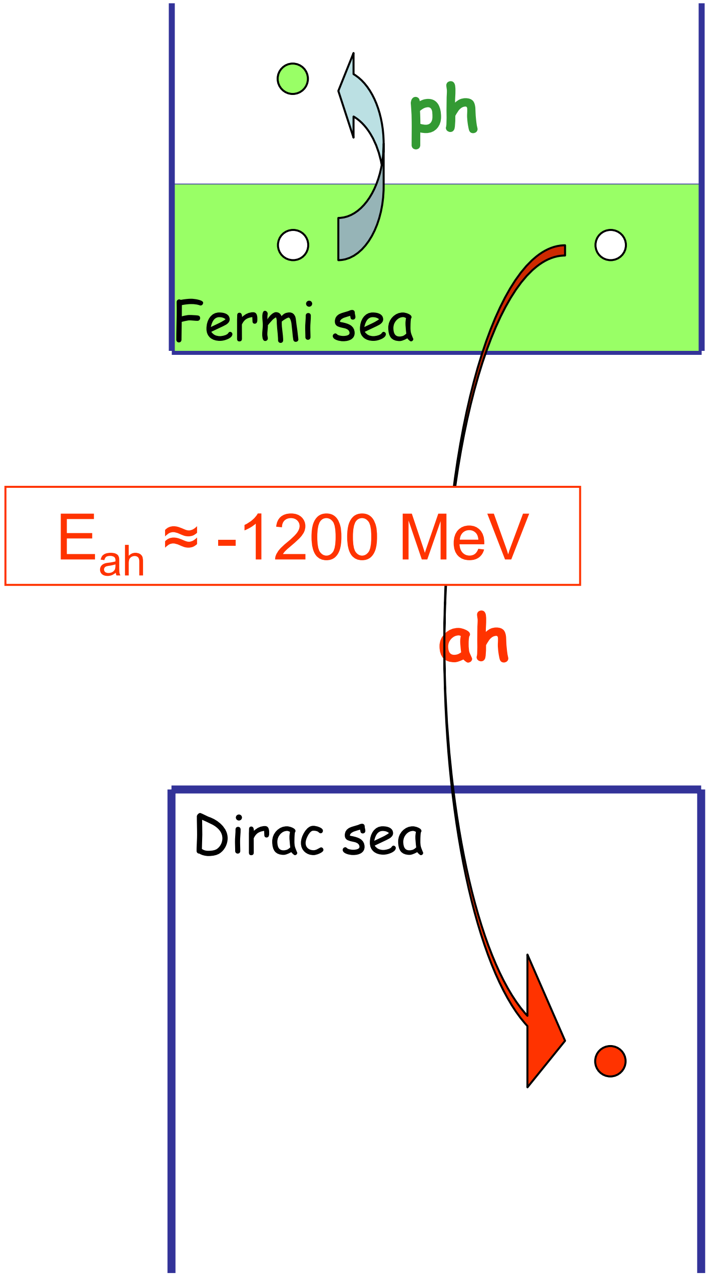
$$A_{minj} = (\epsilon_n - \epsilon_i)\delta_{mn}\delta_{ij} + \frac{\partial h_{mi}}{\partial \rho_{nj}}, \qquad B_{minj} = \frac{\partial h_{mi}}{\partial \rho_{jn}}$$

⇨ the same effective interaction determines the Dirac-Hartree single-particle spectrum and the residual interaction

Interaction:

$$\hat{V} = \frac{\delta^2 E}{\delta\hat{\rho}\,\delta\hat{\rho}}$$

In superfluid systems: quasiparticle RPA



$E_{ph} \approx 10$ MeV

Selfconsistent Symmetries

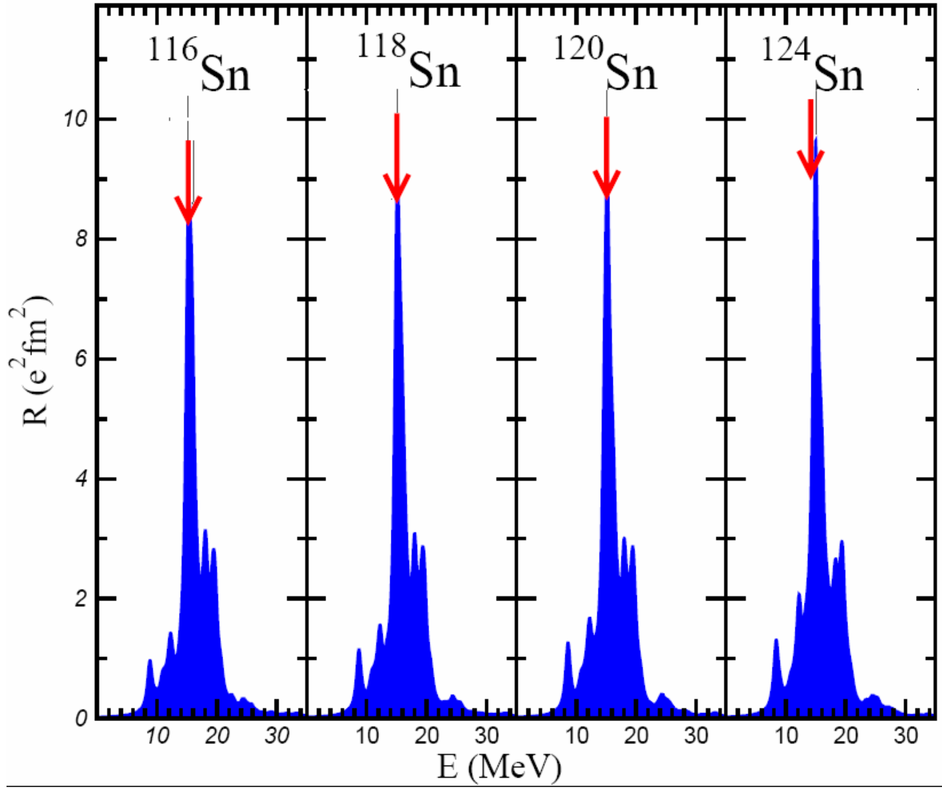
$\langle ph|V_\omega|ah\rangle \approx 0$ for vector mesons

$\langle ph|V_\sigma|ah\rangle \neq 0$ for scalar mesons

1. size of matrix.element
2. the same quantum numbers possible
3. large degeneracy

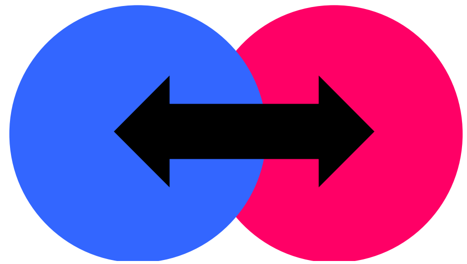
P. R. et al., NPA 694 (2001) 249

Relativistic (Q)RPA calculations of giant resonances

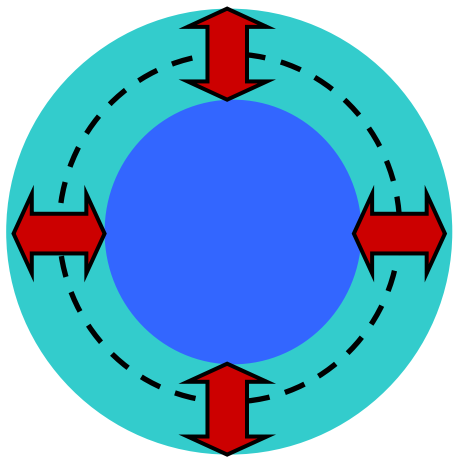


Isovector dipole response

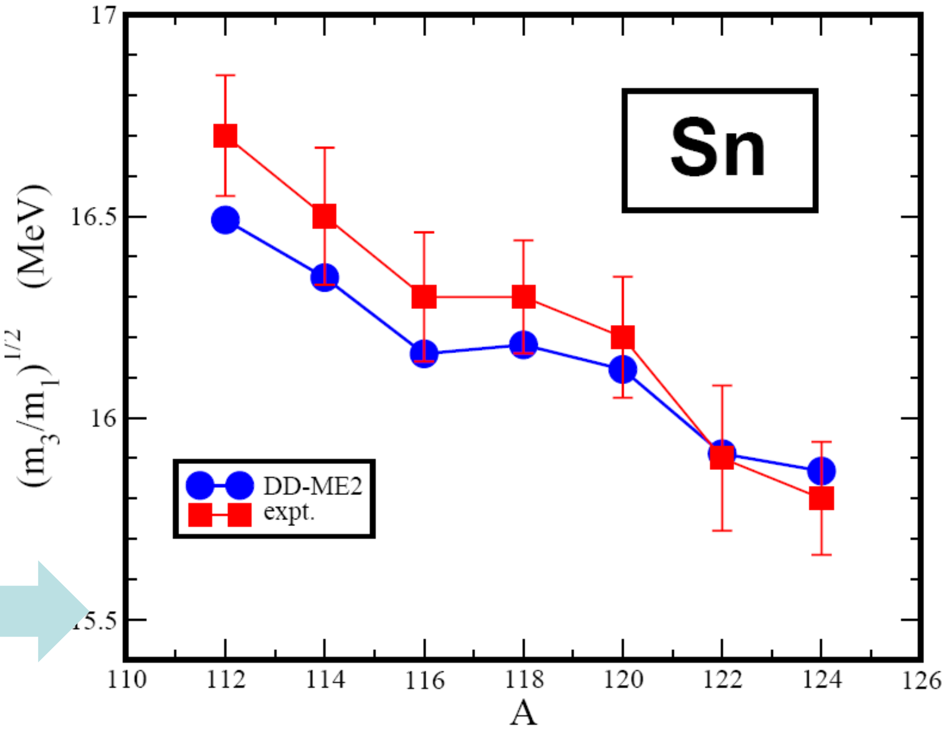
protons



neutrons



Isoscalar monopole response



Linear response theory:

Strength function:
$$S(\omega) = -\frac{1}{\pi}\,\mathrm{Im}\,R_{FF}(\omega),$$

Response function:
$$R_{cc'}(\omega) = \sum_{\mu>0} \frac{\langle 0|Q_c^\dagger|\mu\rangle\langle\mu|Q_{c'}|0\rangle}{\omega-\Omega_\mu+i\eta} - \frac{\langle\mu|Q_c^\dagger|0\rangle\langle 0|Q_{c'}|\mu\rangle}{\omega+\Omega_\mu+i\eta}.$$

without interaction:
$$|\mu\rangle \;\rightarrow\; |ph\rangle, \qquad \Omega_\mu \;\rightarrow\; \epsilon_p-\epsilon_h$$

$$R^0_{cc'}(\omega) = \sum \frac{\langle h|Q_c^\dagger|p\rangle\langle p|Q_{c'}|h\rangle}{\omega-\epsilon_p+\epsilon_h} - \ldots$$

separable interaction:
$$V^{ph}(1,2) \;=\; \sum_c \int_0^\infty dr\; Q_c^{(1)}(r)\; v_c(r)\; Q_c^{\dagger(2)}(r)$$

lin. Bethe Salpeter Eq:
$$R(\omega) = R^0(\omega) + R^0(\omega)V^{ph}R(\omega)$$

solution by inversion:

$$R(\omega) = \frac{1}{1 - R^0 V} R^0 = \frac{1}{R^{0-1} - V}$$

in the ph-basis:

$$= \frac{1}{\omega - \begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix}}$$

Treatment of the continuum:

Bertsch 1974

$$R^0_{cc'}(\omega) = \sum_{ph} \frac{\langle h|Q_c^\dagger|p\rangle\langle p|Q_{c'}|h\rangle}{\omega - \epsilon_p + \epsilon_h} - \ldots$$

$$= \sum_h \langle h|Q_c^\dagger \frac{1}{\omega + \epsilon_h - \hat{h}_D} Q_{c'}|h\rangle - \ldots$$

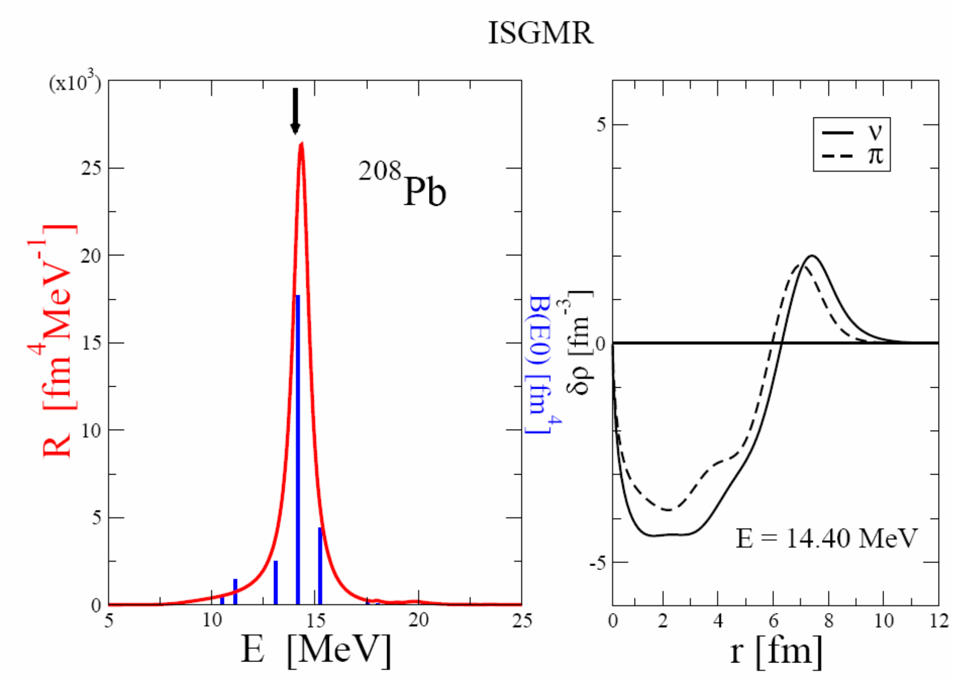
$$= \sum_h \langle h|Q_c^\dagger G(\omega + \epsilon_h) Q_{c'}|h\rangle - \ldots$$

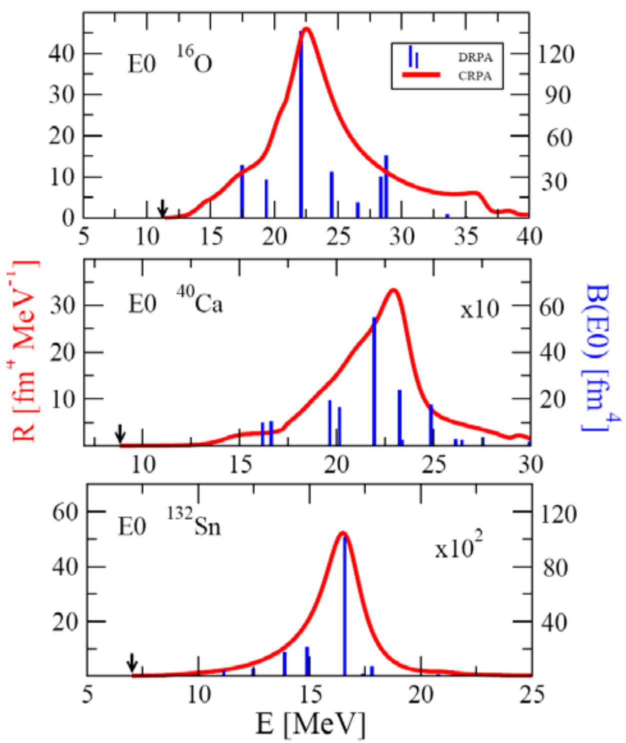
single particle Greens function:

$$G(E) = \frac{1}{E - \hat{h}_D}$$

$$\left(E - \hat{h}_\kappa(r)\right) G_\kappa(r, r'; E) = \delta(r - r'),$$

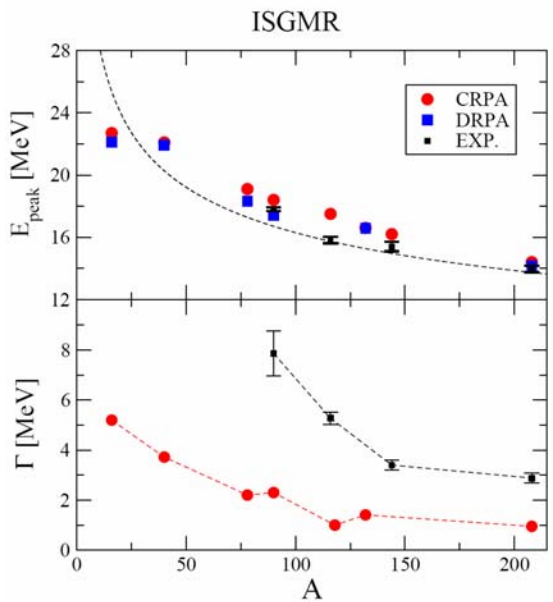
Applications: E0



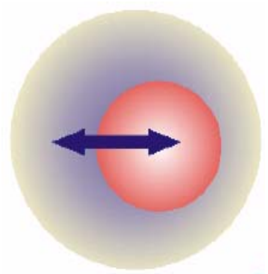


peak energy:

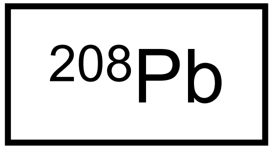
escape width:



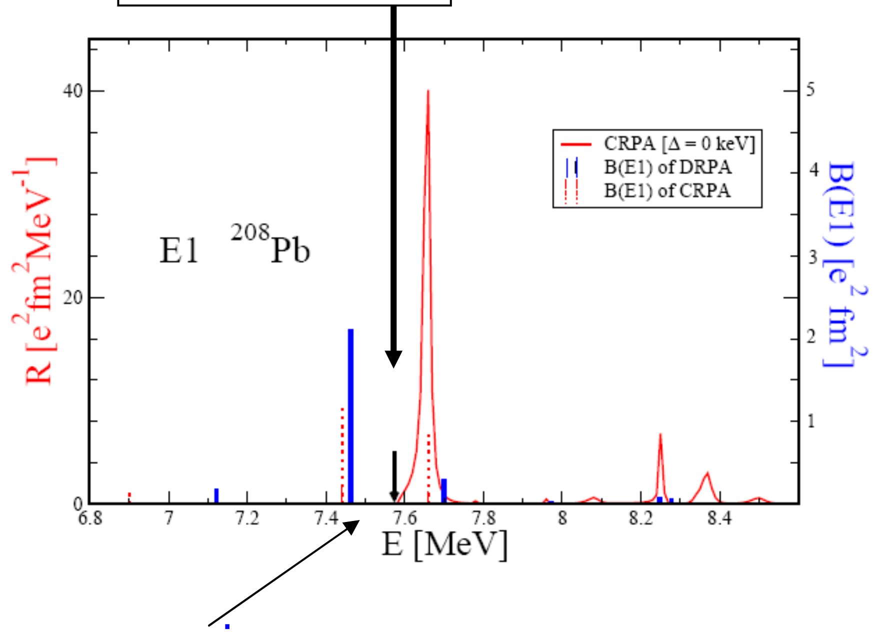
IV-dipole strength



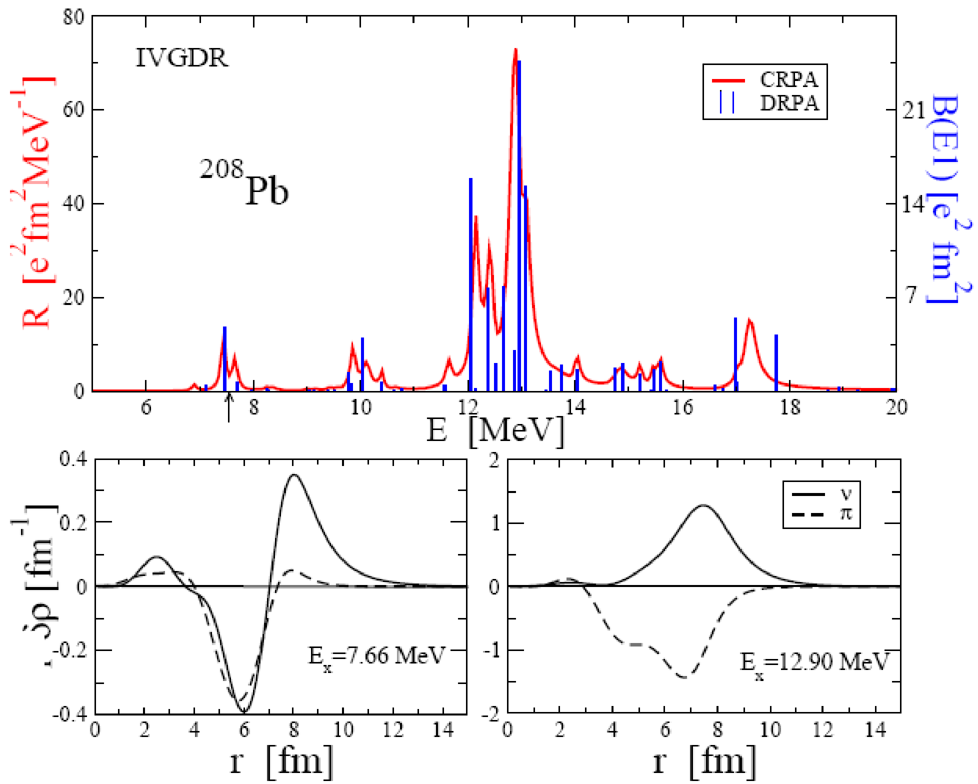
pygmy-mode



neutron threshold:



pygmy-region

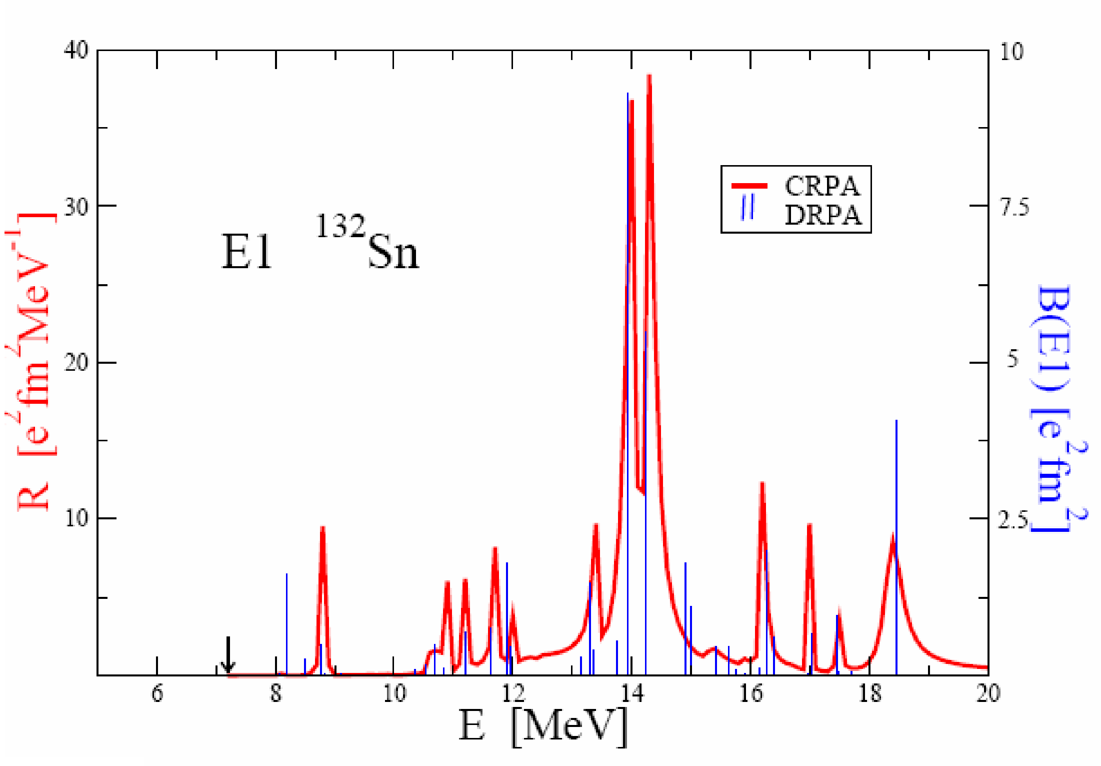


	CRPA		DRPA	
No.	E	B(E1)	E	B(E1)
1	6.90	0.19	7.12	0.23
2	7.44	1.45	7.46	2.82
3	*7.66*	*1.11*	7.69	0.40
Σ		2.75		3.45

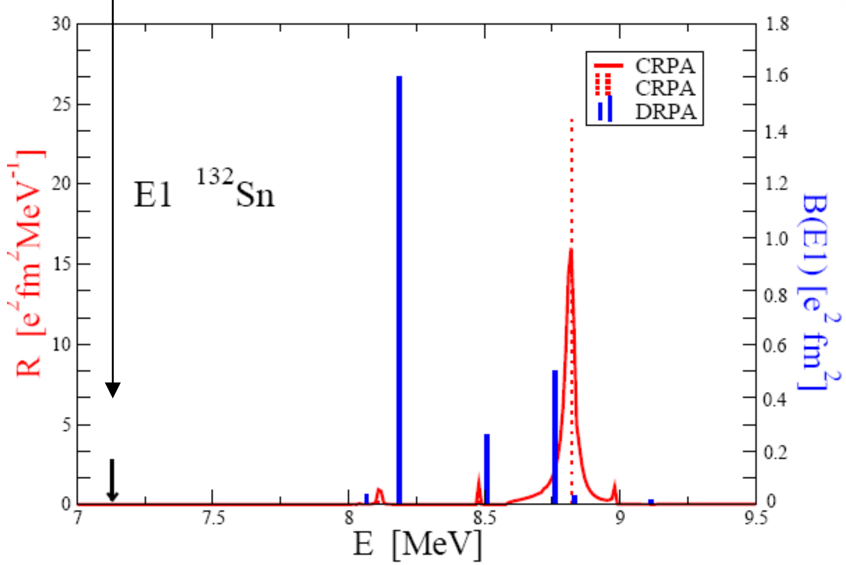
1.9 % 2.8 % of EWSR

IV-dipole strength

^{132}Sn



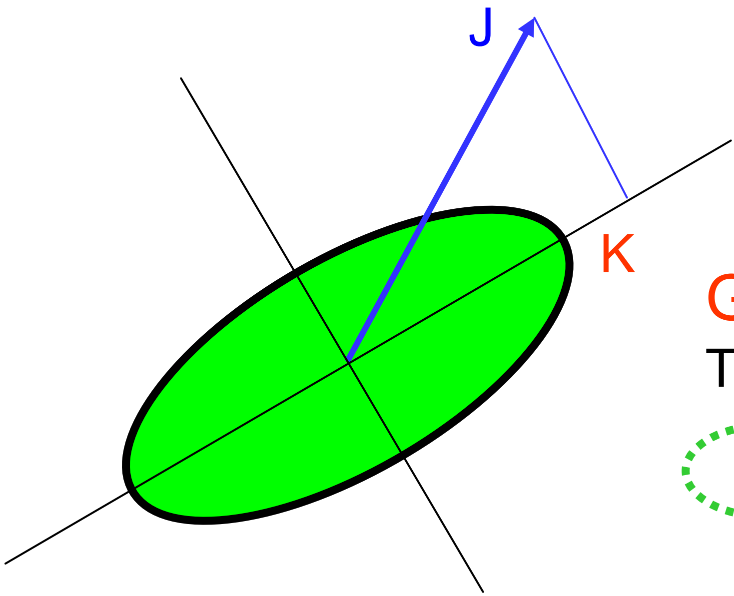
neutron threshold:



	CRPA		DRPA	
No.	E	B(E1)	E	B(E1)
1	8.11	0.03	8.067	0.037
2	8.48	0.02	8.186	1.601
3	8.82	1.44	8.511	0.260
Σ		1.490		1.898

2.4 %   3.4 % of EWSR

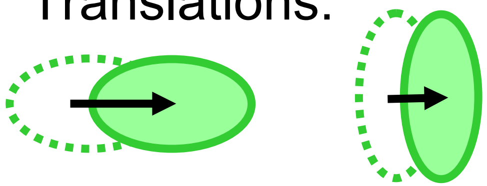
Vibrations in deformed nuclei



T=0	T=1

Goldstone modes

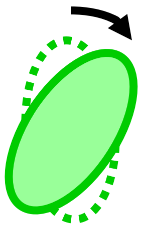
Translations:



$K=0^-$ $K=1^-$

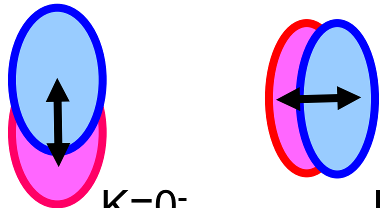
Rotations:

$K=1^+$



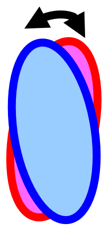
Gauge rotations: $K=0^+$

Giant dipole modes:



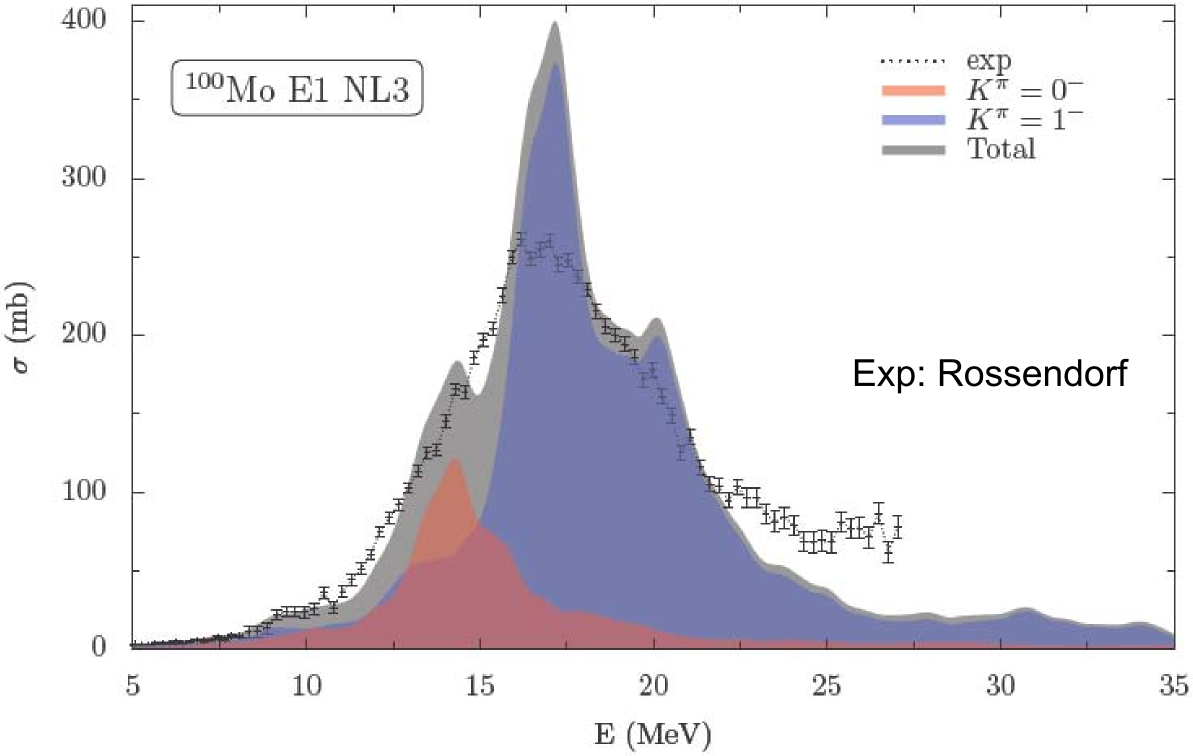
$K=0^-$ $K=1^-$

Scissor modes:



$K=1^+$

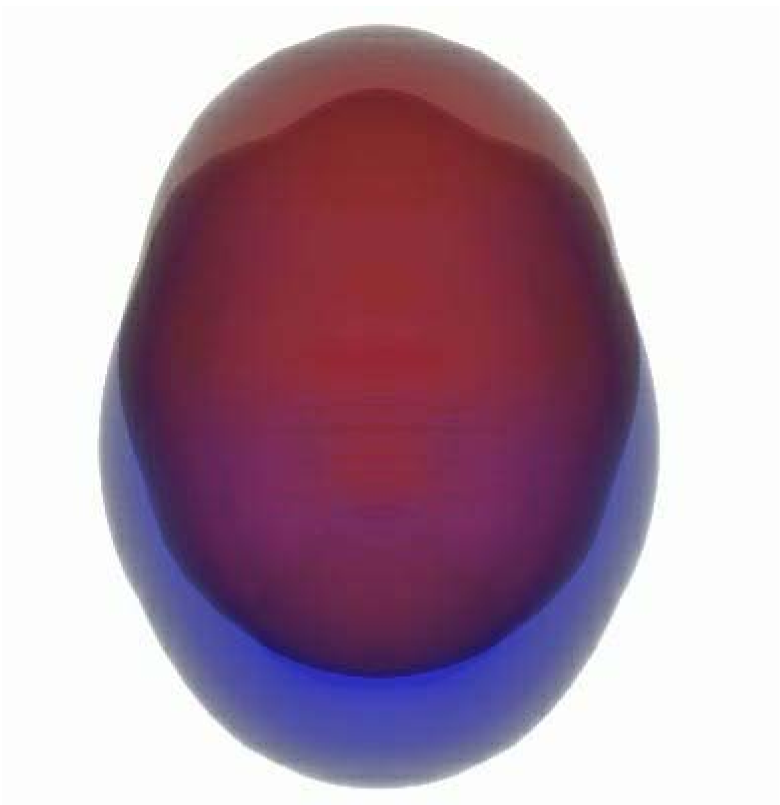
isovector-dipole response in ^{100}Mo



	m_1/m_0	$\sqrt{\frac{m_3}{m_1}} - \frac{m_1}{m_0}$	$\bar{E}_{E1}$	Γ_{E1}
NL3	17.4	1.4	17.2	2.4
DD-ME2	18.3	1.2	18.5	3.3
Exp	18.0	1.4	17.4	3.6

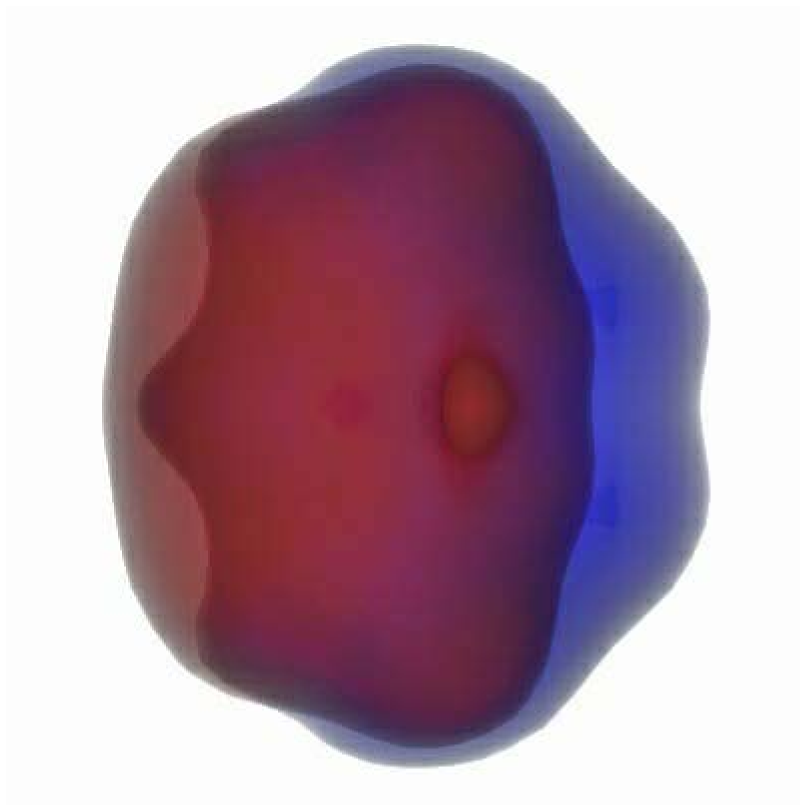
in MeV

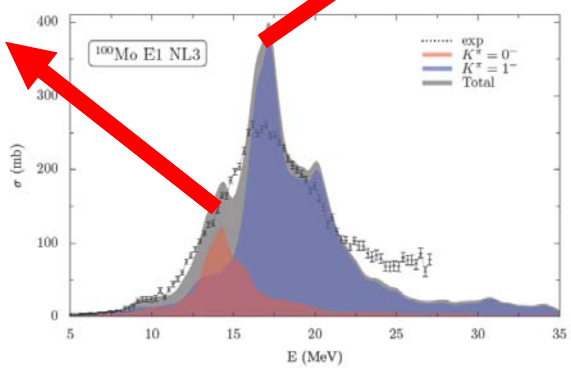
IV-GDR in ^{100}Mo



IV-GDR

$\rho_0 + \delta\rho(t)$

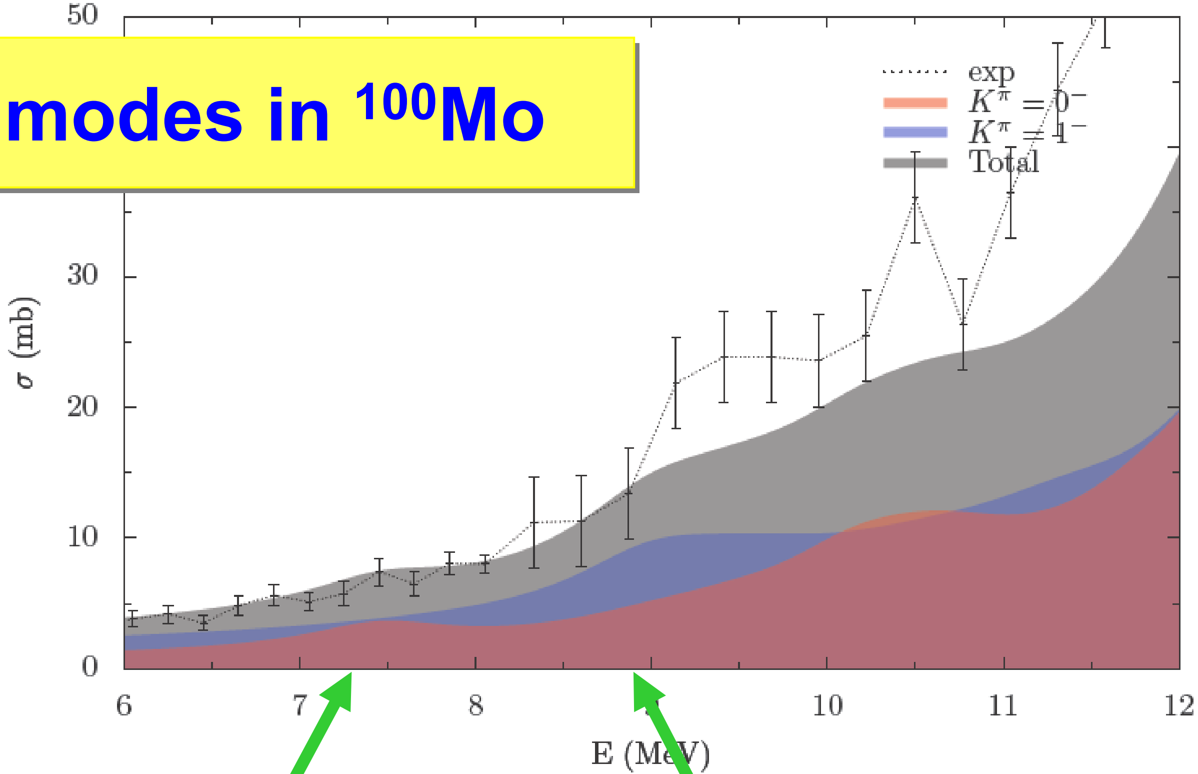


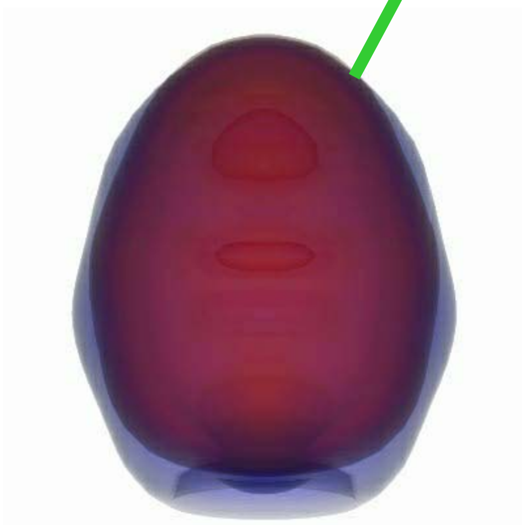


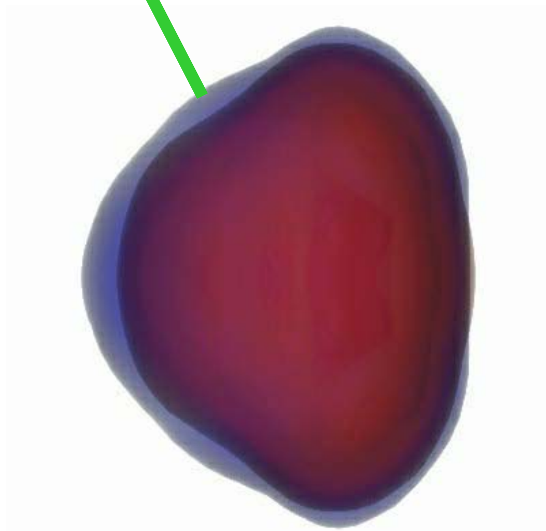
$K=0^-$

$K=1^-$

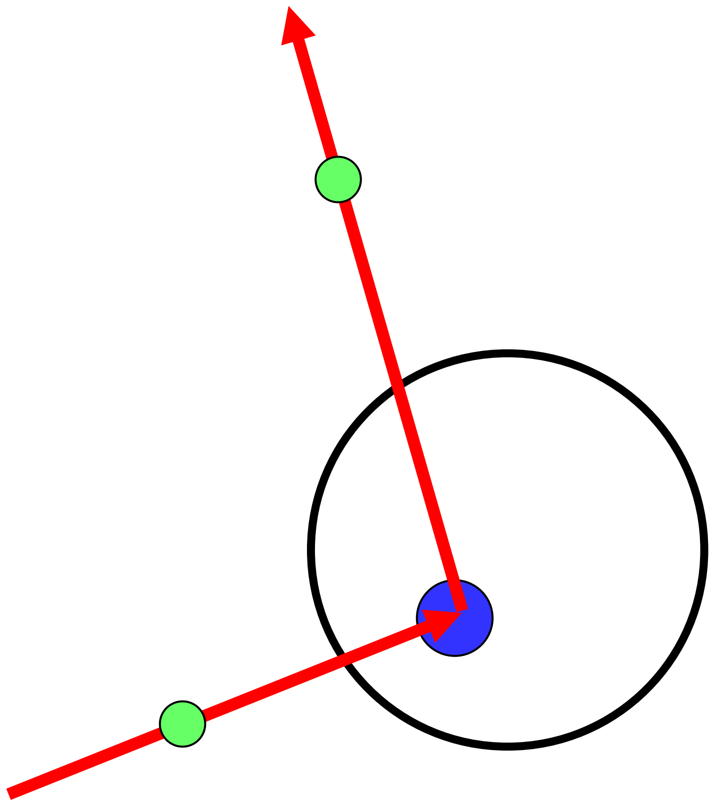
pygmy modes in ^{100}Mo

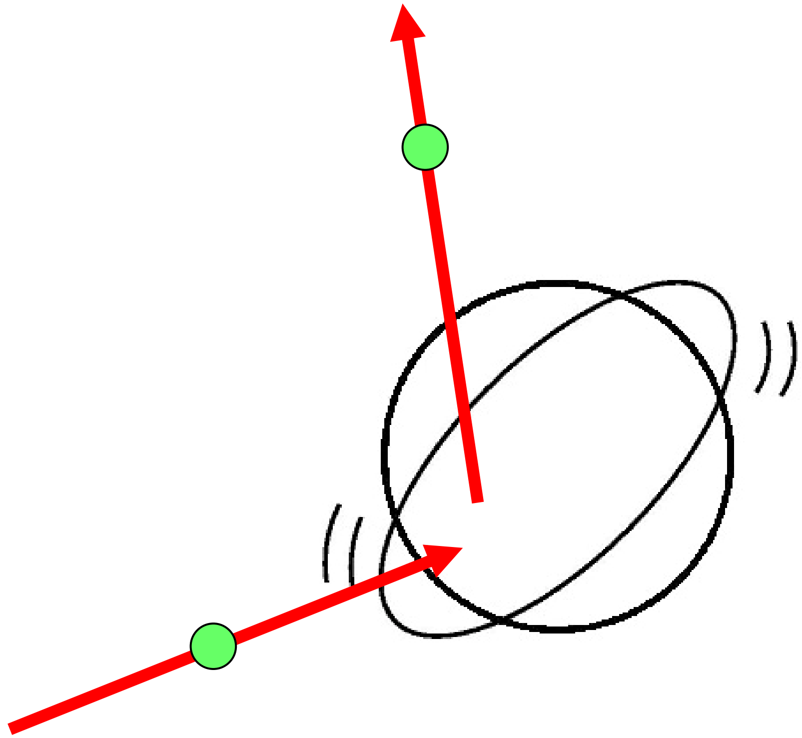






response of the nucleus to an incoming particle

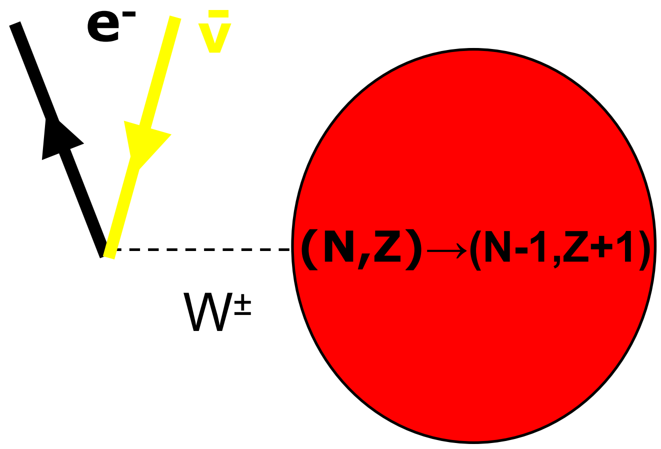


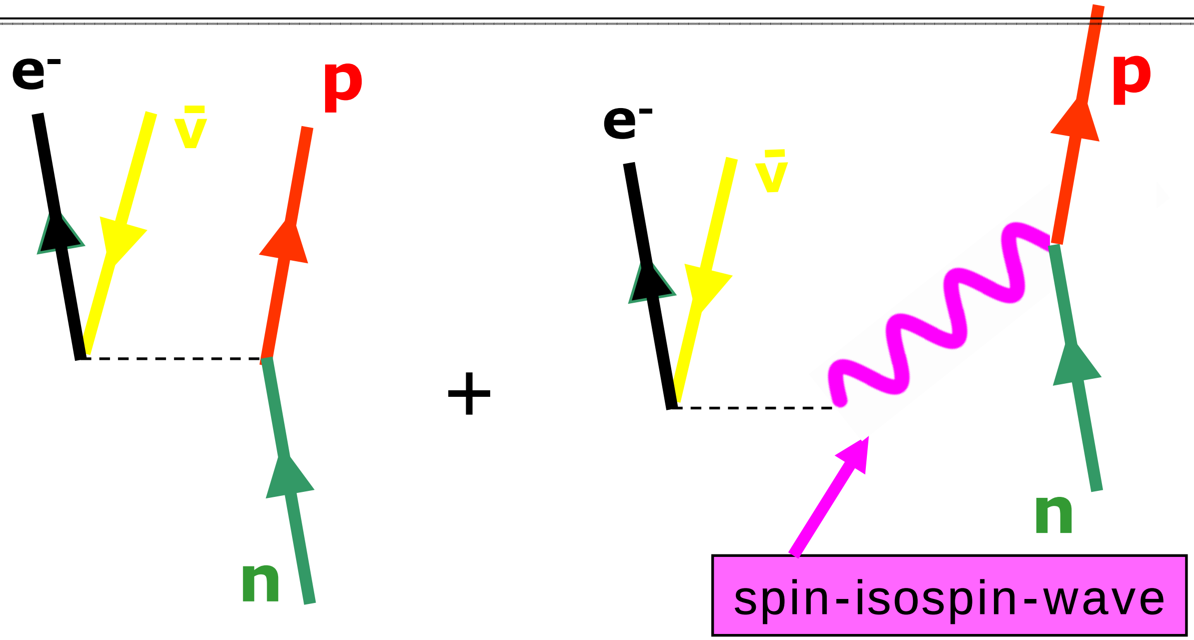


scattering at a single nucleon

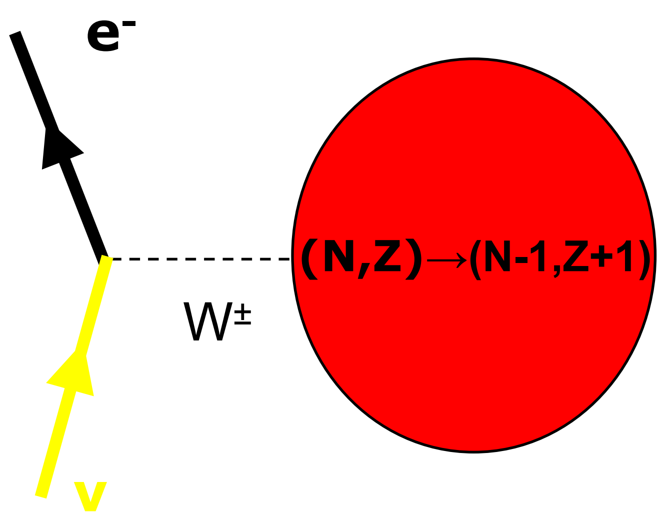
excitation of the entire nucleus
we need the nuclear spectrum

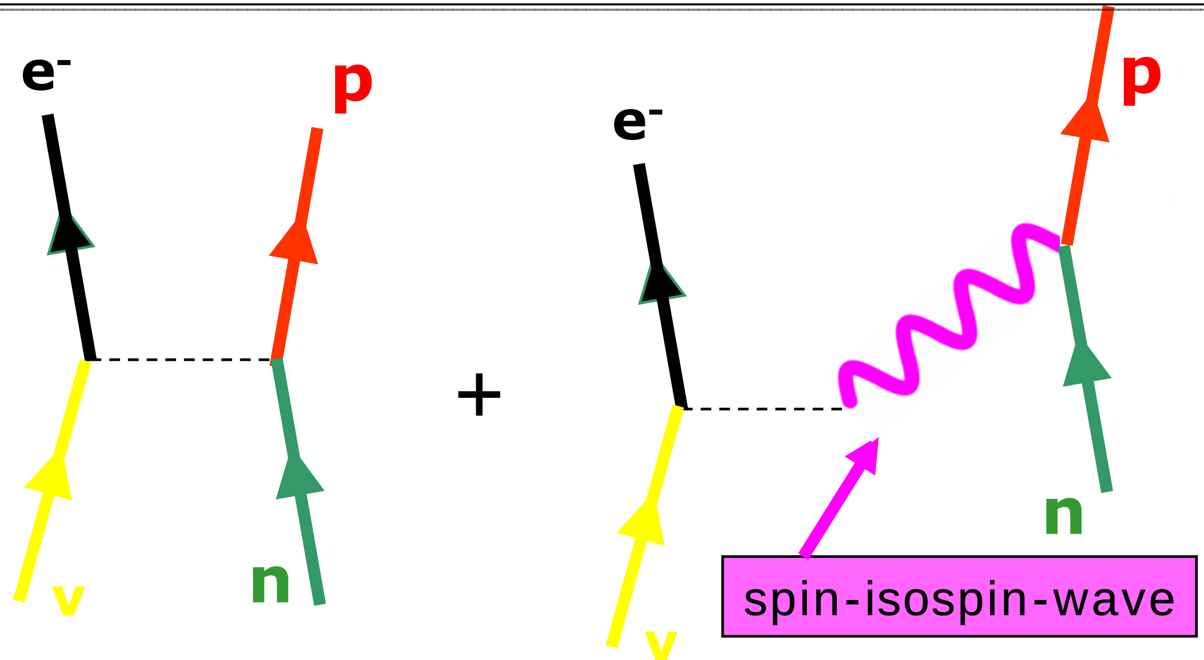
beta-decay





neutrino scattering





Spin-Isospin Resonances: IAR - GTR

Z,N

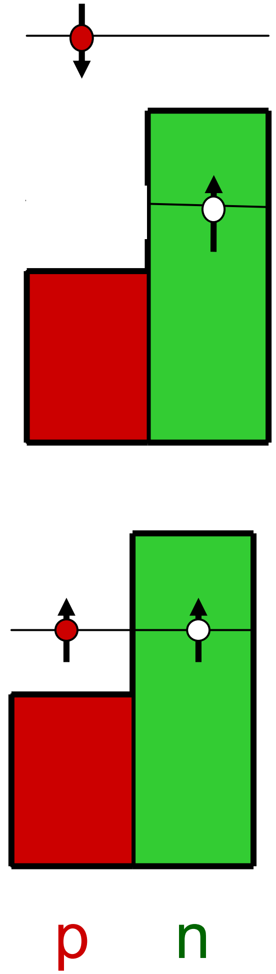
Z+1,N-1

$$|GTR\rangle = S_- T_+ |Z,N\rangle$$

spin flip σ

$$|Z,N\rangle \longrightarrow |IAR\rangle = T_+ |Z,N\rangle$$

isospin flip τ



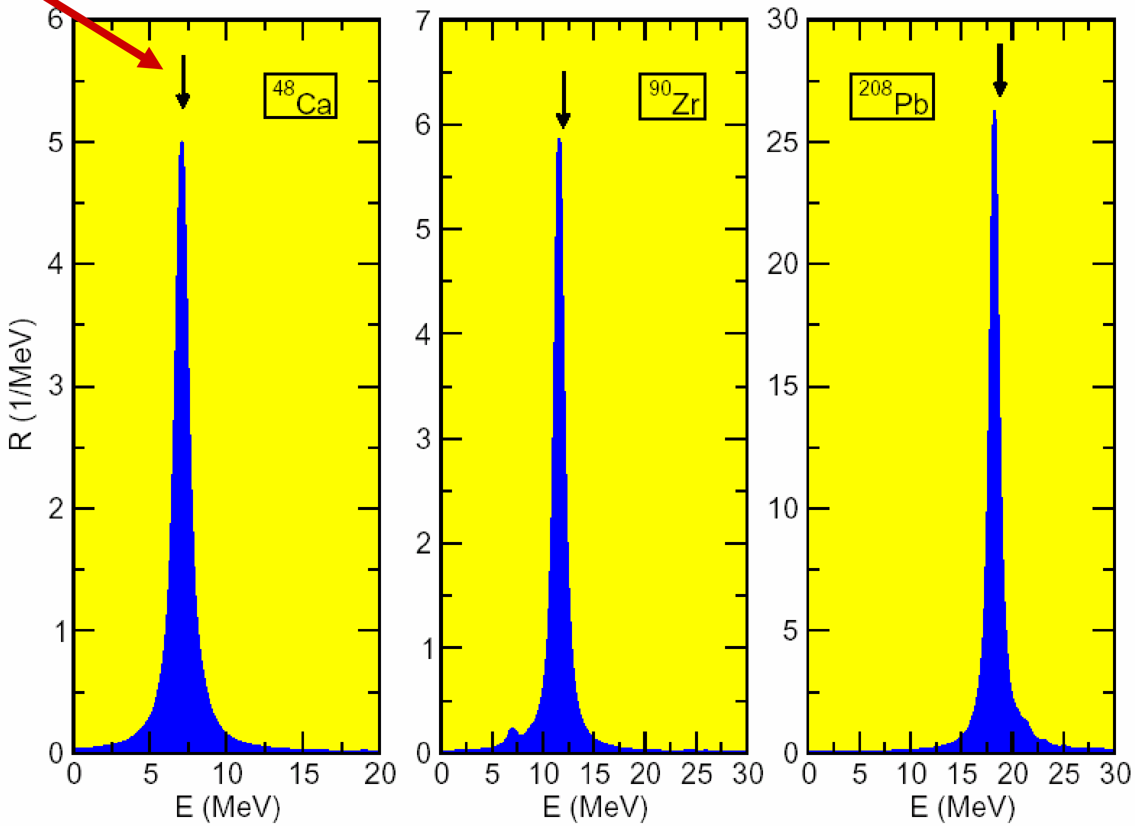
$$E_{GTR} - E_{IAR} \sim \Delta(l \cdot s) \sim \frac{dV}{dr} \sim \text{neutron skin} = r_n - r_p$$

Isobaric Analog Resonance: IAR

PR C69, 054303 (2004)

experiment

Isospin-flip excitations



S=0 T=1

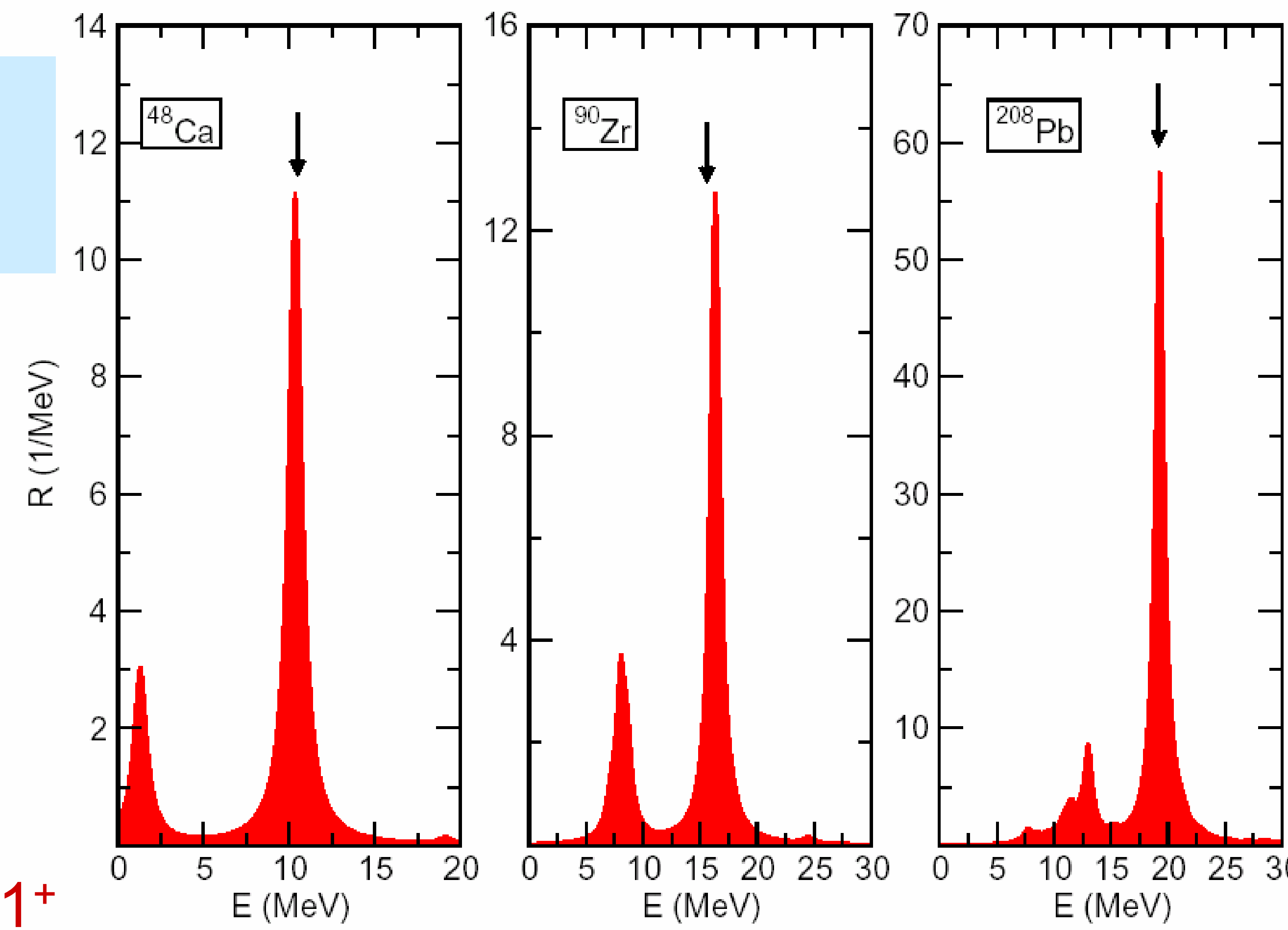
$J^{\pi} = 0^{+}$

GT-Resonances

PR C69, 054303 (2004)

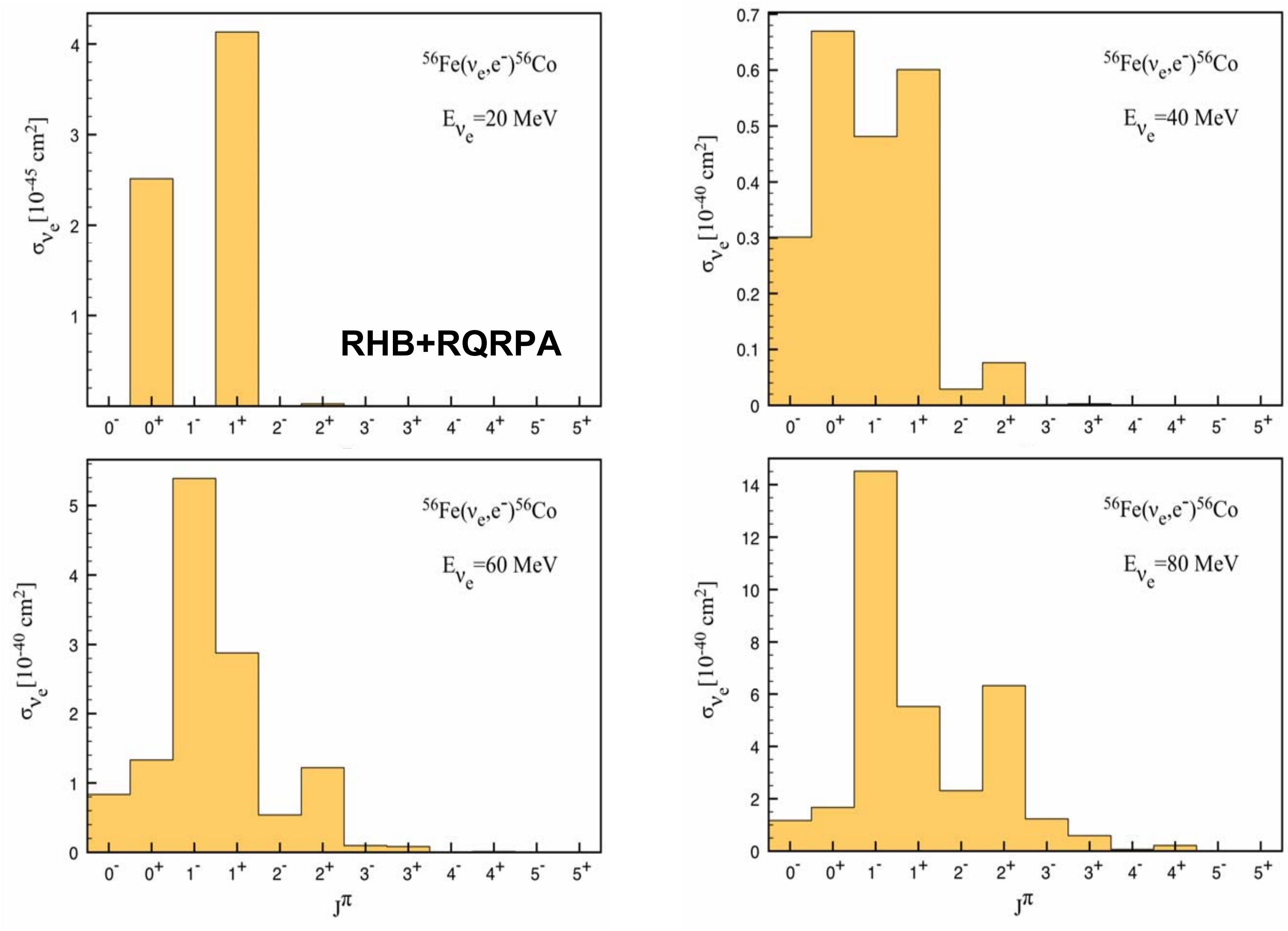
Spin-flip

isospin-flip
excitations



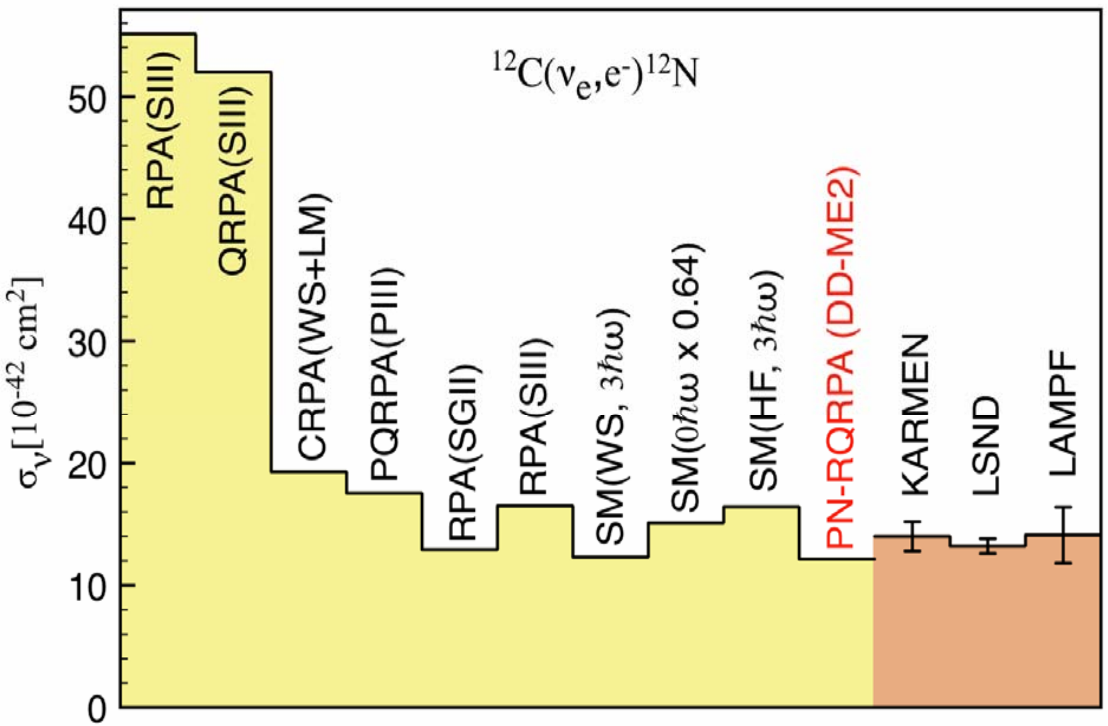
S=1 T=1 $J^\pi = 1^+$

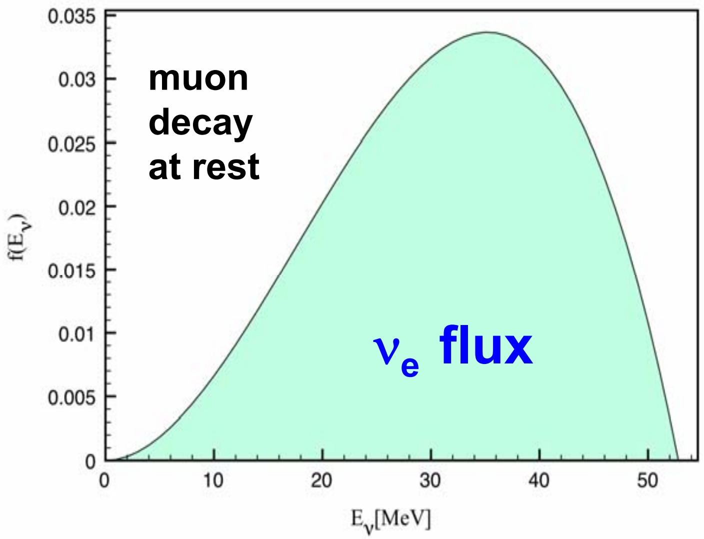
Distribution of cross section over multipolarities



Cross section (ν_e,e^-) averaged over supernova neutrino flux

$$\langle \sigma_\nu \rangle = \frac{\int dE_\nu \sigma_\nu(E_\nu) f(E_\nu)}{\int dE'_\nu f(E'_\nu)}$$





Content

- Static density functionals in nuclei
- Time dependent density functionals in nuclei
- Quasiparticle RPA
- Applications:

  - relativistic RPA
  - continuum RPA
  - deformed RPA
  - pn - RPA

- Extensions

  - energy dependent KS-fields
  - Mixing of deformed configurations
  - Symmetry restauration before variation

- Conclusions and outlook

Problems with mean field:

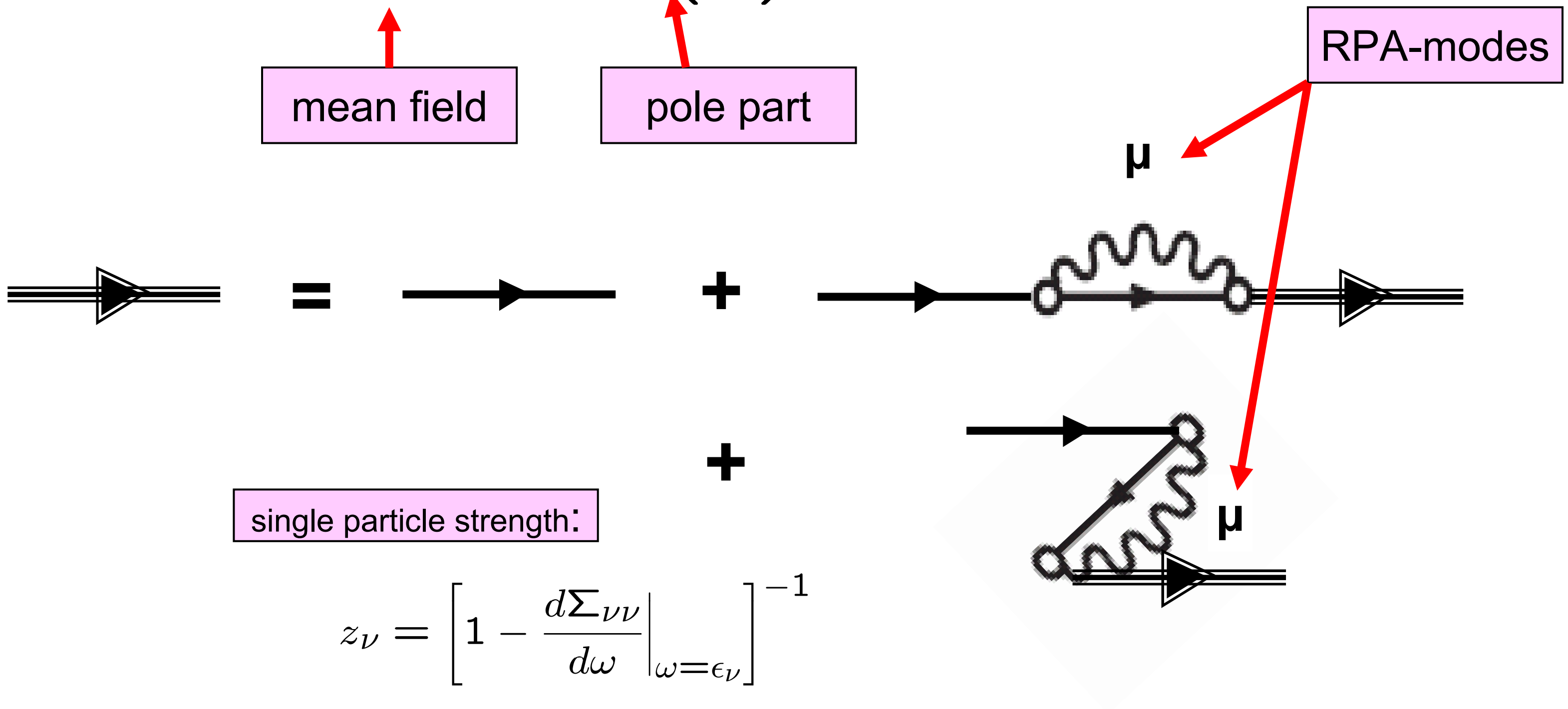
- **no fluctuation** in transitional nuclei
- **no energy dependence** of the self energy
- **symmetry violations** have to be restored
- **no spectroscopy**
- **……**

Particle-vibrational coupling: energy dependent self-energy

$$\Sigma = S + V + \Sigma(\omega)$$

mean field

pole part

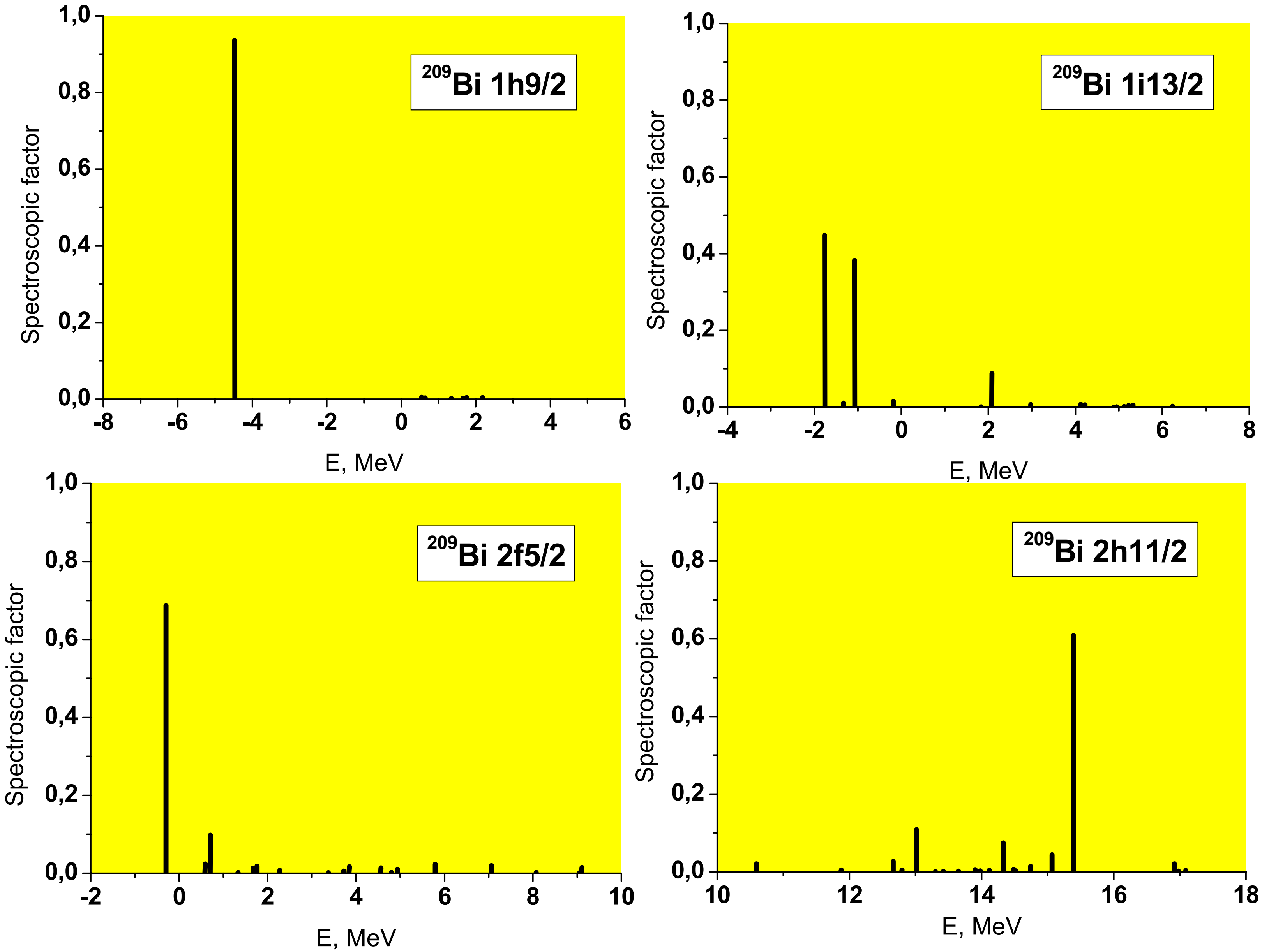


single particle strength:

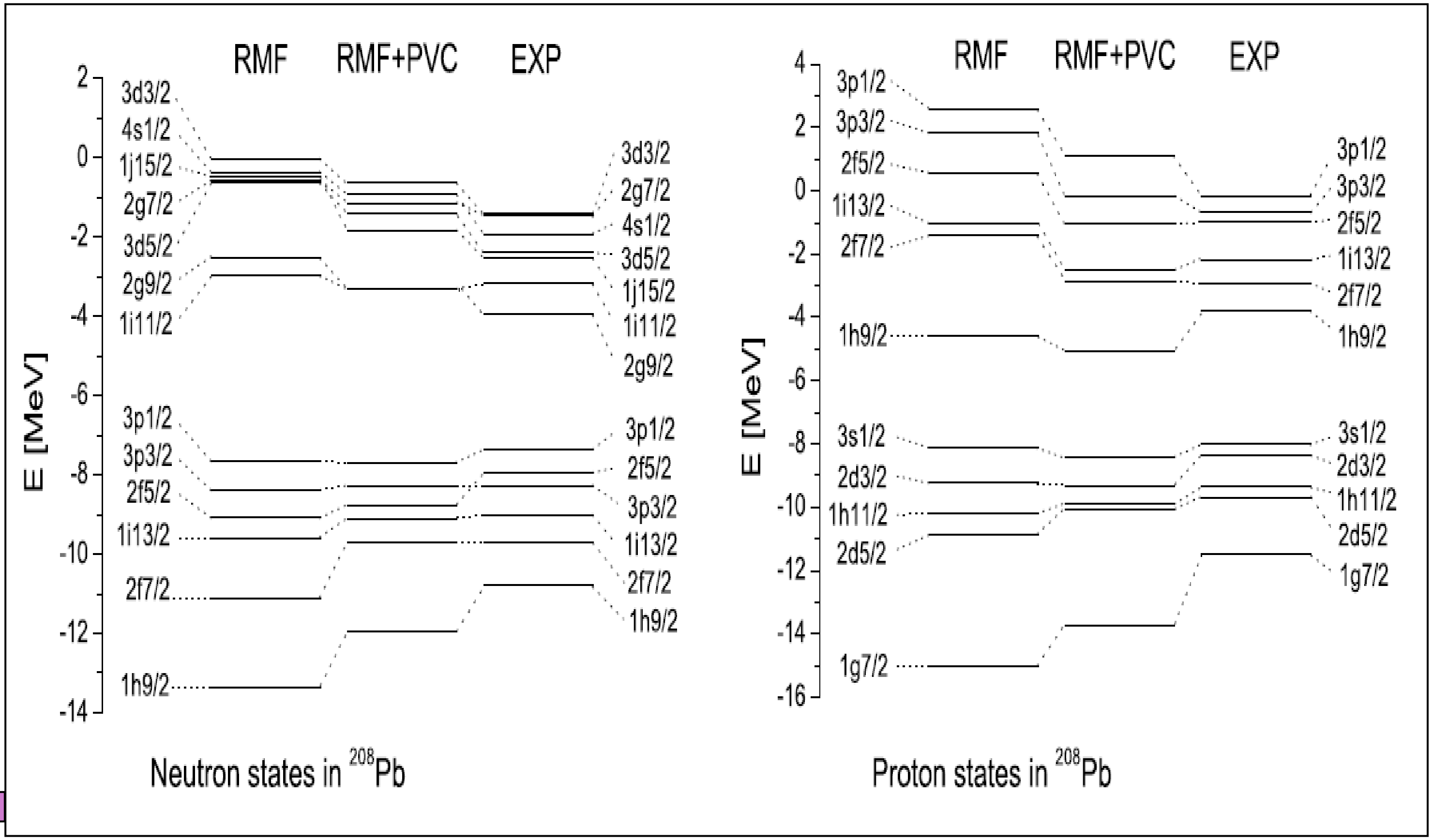
$$z_\nu = \left[1 - \frac{d\Sigma_{\nu\nu}}{d\omega}\bigg|_{\omega=\epsilon_\nu} \right]^{-1}$$

Density functional theory - Landau-Migdal theory

Distribution of single-particle strength in ^{209}Bi



Single particle spectrum in the Pb region



m_{eff} 0.76 0.92 1.0 0.71 0.85 1.0

E. Litvinova, P.R., PRC 73, 44328 (2006)

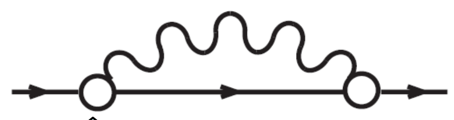
E. Litvinova:

Two-body problem: from self-energy to effective interaction

$$U(14,23) = i\frac{\delta\Sigma(3,4)}{\delta G(1,2)}$$

$$\Sigma^{e}_{12}(\varepsilon) = \sum_{3,\eta,m}\frac{\delta_{\eta,\eta_3}\, g^{m(\eta)*}_{13}\, g^{m(\eta)}_{23}}{\varepsilon - E_3 - \eta\left(\omega_m - i\cdot 0\right)}$$

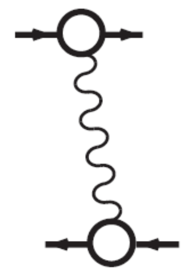
$$\Sigma = \tilde{\Sigma} + \Sigma^{e}$$



Mass operator

g **– phonon amplitudes (QRPA)**

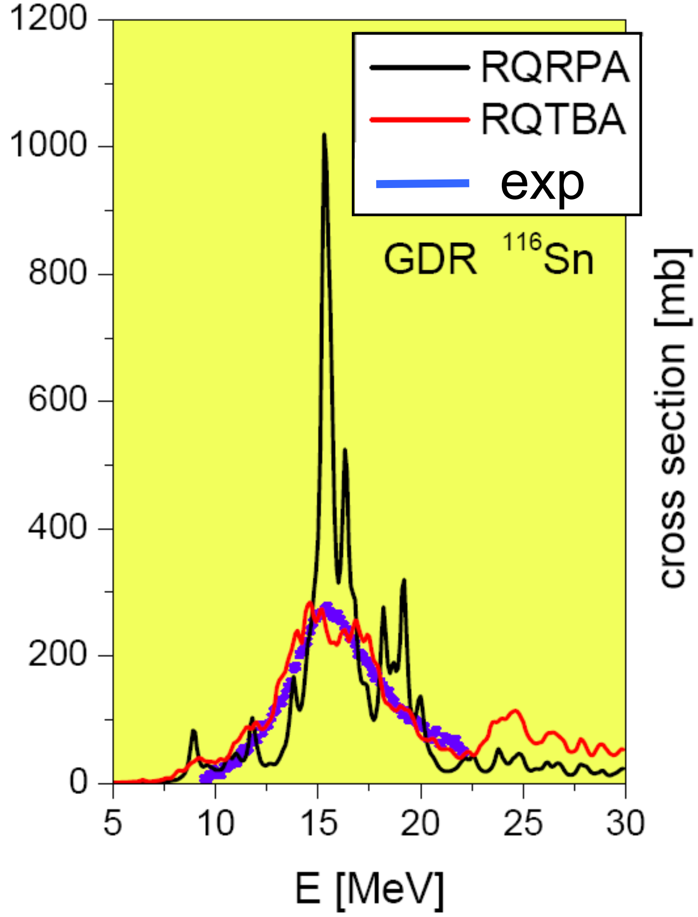
Total | **Mean Field** | **Pole part**

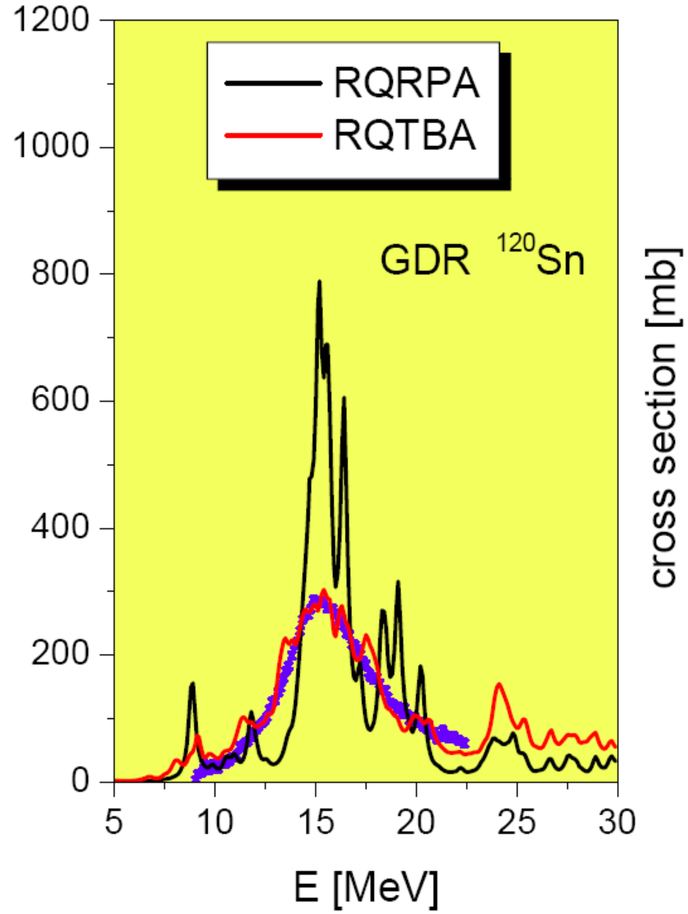


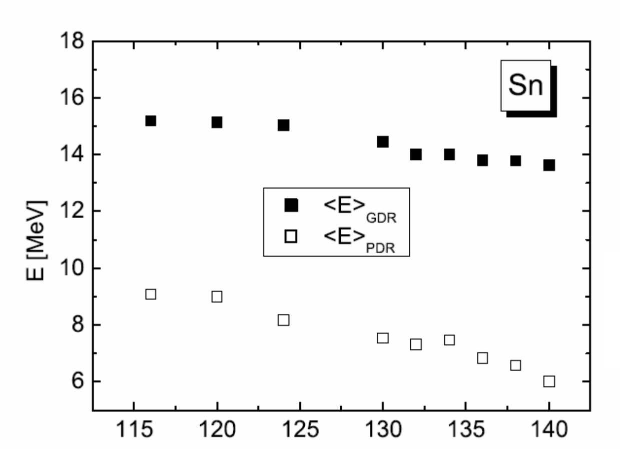
Induced p-h interaction amplitude

$$\mathcal{U} = \tilde{\mathcal{U}} + \mathcal{U}^{e}$$

$$\mathcal{U}^{e}_{12,34}(\omega,\,\varepsilon,\,\varepsilon') = \sum_{\eta,m}\frac{\eta\, g^{m(\eta)*}_{31}\, g^{m(\eta)}_{42}}{\varepsilon - \varepsilon' + \eta\left(\omega_m - i\cdot 0\right)}$$







centroid energies for
GDR and PDR

Litvinova, P.R. Tselyaev, PRC 78, 14312 (2008)
Litvinova, P.R. Tselyaev, Langanke, PRC 79, 054312 (2009)

Parameters of Lorentz distribution* (GDR)

		<E> (MeV)	Γ (MeV)	EWSR (%)
^{208}Pb	RRPA	12.9	2.0	128
	RRPA-PC	13.7	4.3	134
	Exp. [1]	13.4	4.1	
^{132}Sn	RRPA	14.5	2.6	126
	RRPA-PC	15.1	4.4	131
	Exp. [2]	16.1(7)	4.7(2.1)	
^{48}Ni	RRPA	17.9	3.1	119
	RRPA-PC	18.6	5.1	125
^{46}Fe	RRPA	17.9	3.2	122
	RRPA-PC	18.7	5.5	128

*Averaging interval: 0-30 MeV

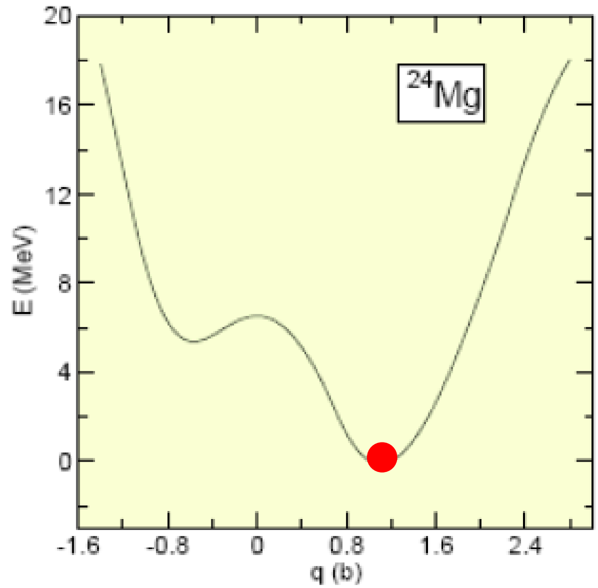
[1] Reference Input Parameter Library, Version 2

[2] Adrich et al., PRL **95**, 132501 (2005).

Generator Coordinate Method (GCM)

$$\langle \delta\Phi | \hat{H} - q\hat{Q} | \Phi \rangle = 0$$

$$\rightarrow \quad | q \rangle = | \Phi(q) \rangle$$



Constraint Hartree Fock produces
wave functions depending on a generator coordinate q

$$|\Psi\rangle = \int dq\, f(q) |q\rangle$$

GCM wave function is a
superposition of Slater determinants

$$\int dq' \left[\langle q|H|q'\rangle - E\langle q|q'\rangle \right] f(q') = 0$$

Hill-Wheeler equation:

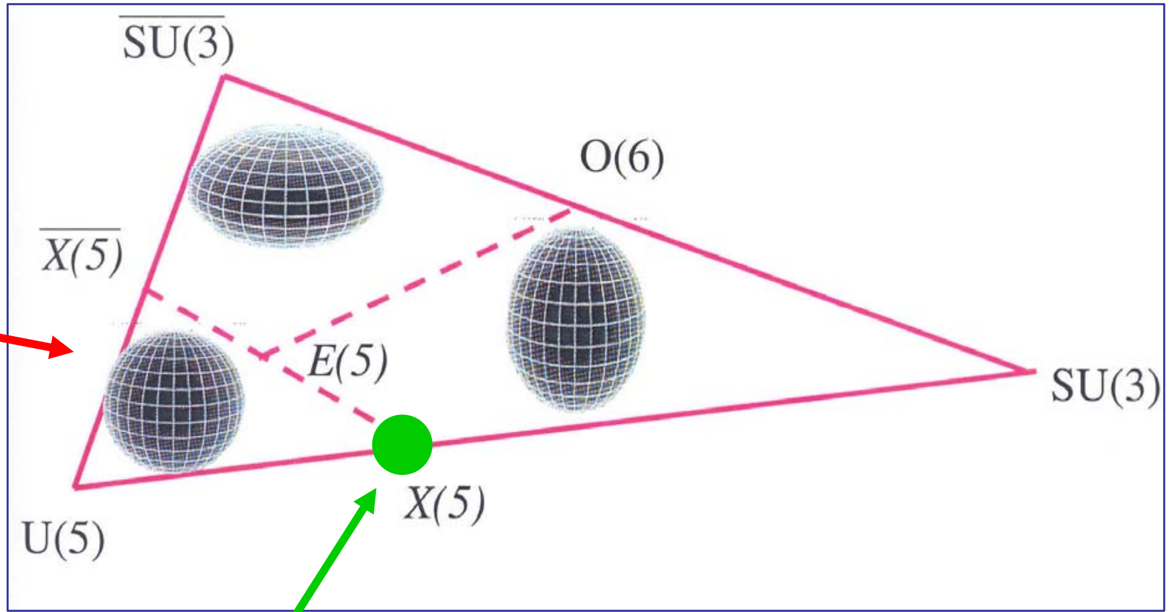
$$|\Psi\rangle = \int dq\, f(q) \hat{P}^N \hat{P}^I |q\rangle$$

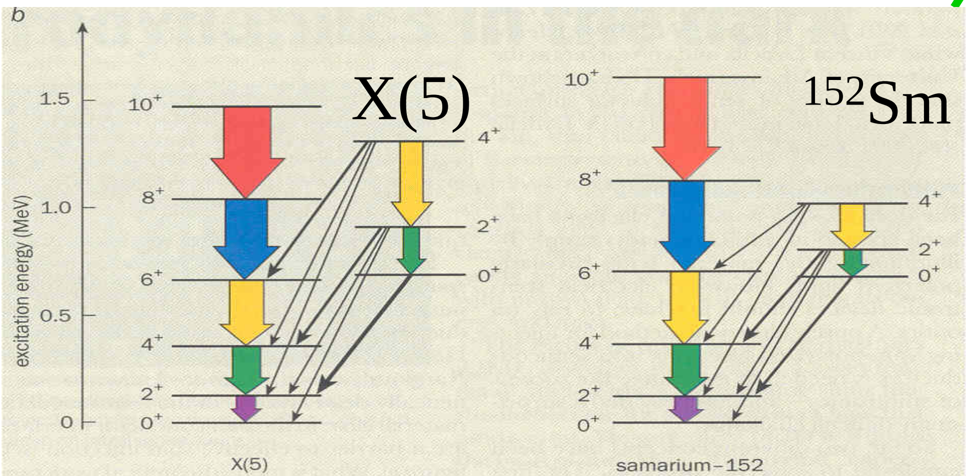
with projection:

Quantum phase transitions and critical symmetries

Interacting Boson Model

Casten Triangle



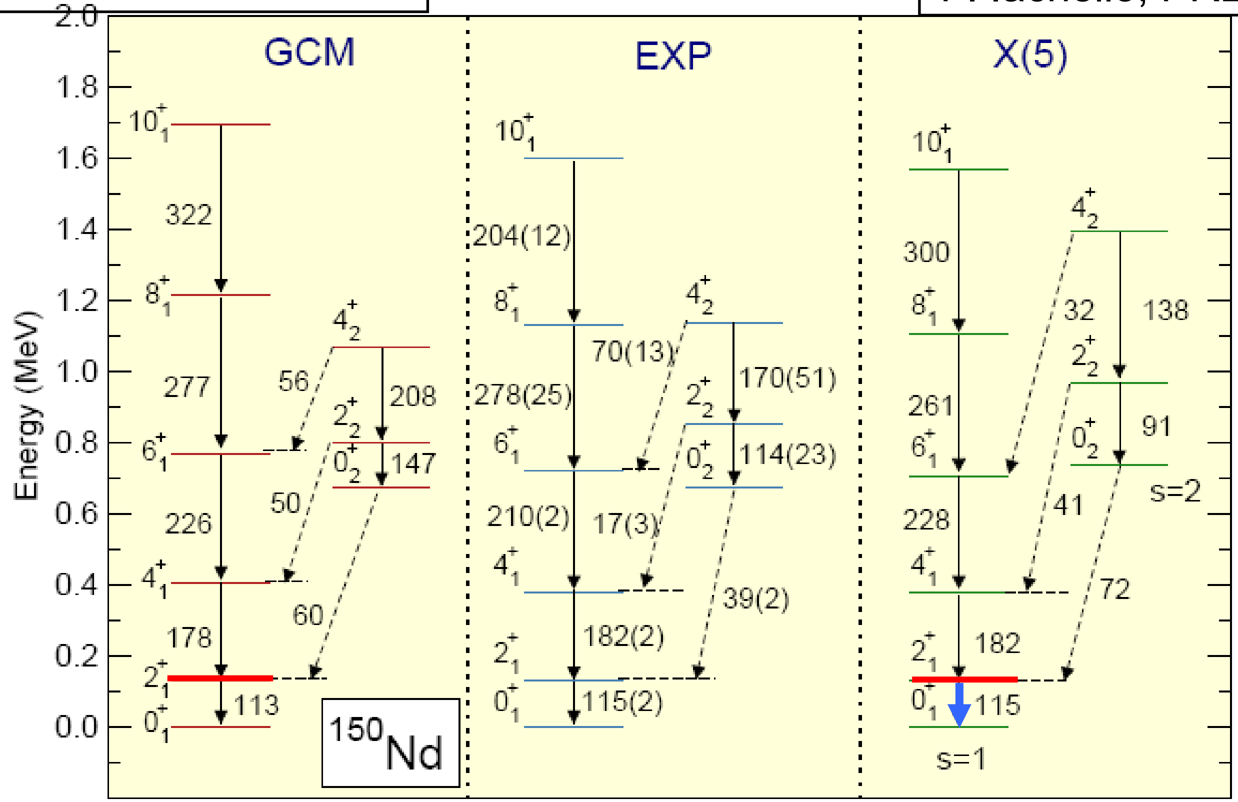


E(5): F. Iachello, PRL 85, 3580 (2000)
X(5): F. Iachello, PRL 87, 52502 (2001)

R.F. Casten, V. Zamfir, PRL 85 3584, (2000) Niksic *et al* PRL 99, 92502 (2007)

R. Krücken *et al*, PRL 88, 232501 (2002)

F. Iachello, PRL 87, 52502 (2001)



GCM: only one scale parameter: **$E(2_1)$**

X(5): two scale parameters: **$E(2_1)$,** **$BE2(2_2 \rightarrow 0_1)$**

Problem of GCM at this level: **restricted to $\gamma=0$**

AGP and number projected HFB:

AGP is equivalent to number projected HFB
(variation after projection: VAP)

$$|AGP\rangle = (C^\dagger)^{\frac{N}{2}}|0\rangle = \hat{P}^N e^{C^\dagger}|0\rangle = \hat{P}^N|\Phi\rangle$$

with

$$C^\dagger = \sum_{ik} C_{ik} a_i^\dagger a_k^\dagger$$

The coefficients C_{ik} are variational parameters and Φ is a generalized Slater determinant.

The AGP-energy it the number projected HFB-energy.

$$E_{AGP}[\mathcal{R}] = E^N[\mathcal{R}] = \frac{\langle\Phi|H\hat{P}^N|\Phi\rangle}{\langle\Phi|\hat{P}^N|\Phi\rangle}$$

where $\mathcal{R}$ is the Valatin density. This is an intrinsic density. The corresponding projected HFB-Field is

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

i.e. we need the analytic dependence of $E^N[\mathcal{R}]$ on $\mathcal{R}$

projected density functionals:

$$E^I[\rho] = \langle\Phi|H\hat{P}^I|\Phi\rangle$$

where H is an effective Hamiltonian.

The projected HF (or KS) field is given by

$$h^I_{KS} = \frac{\delta E^I}{\delta\rho}$$

The generalized Wick theorem shows, that $E^I[\rho]$ is an integral over the rotational angle α and it depends on the mixed density

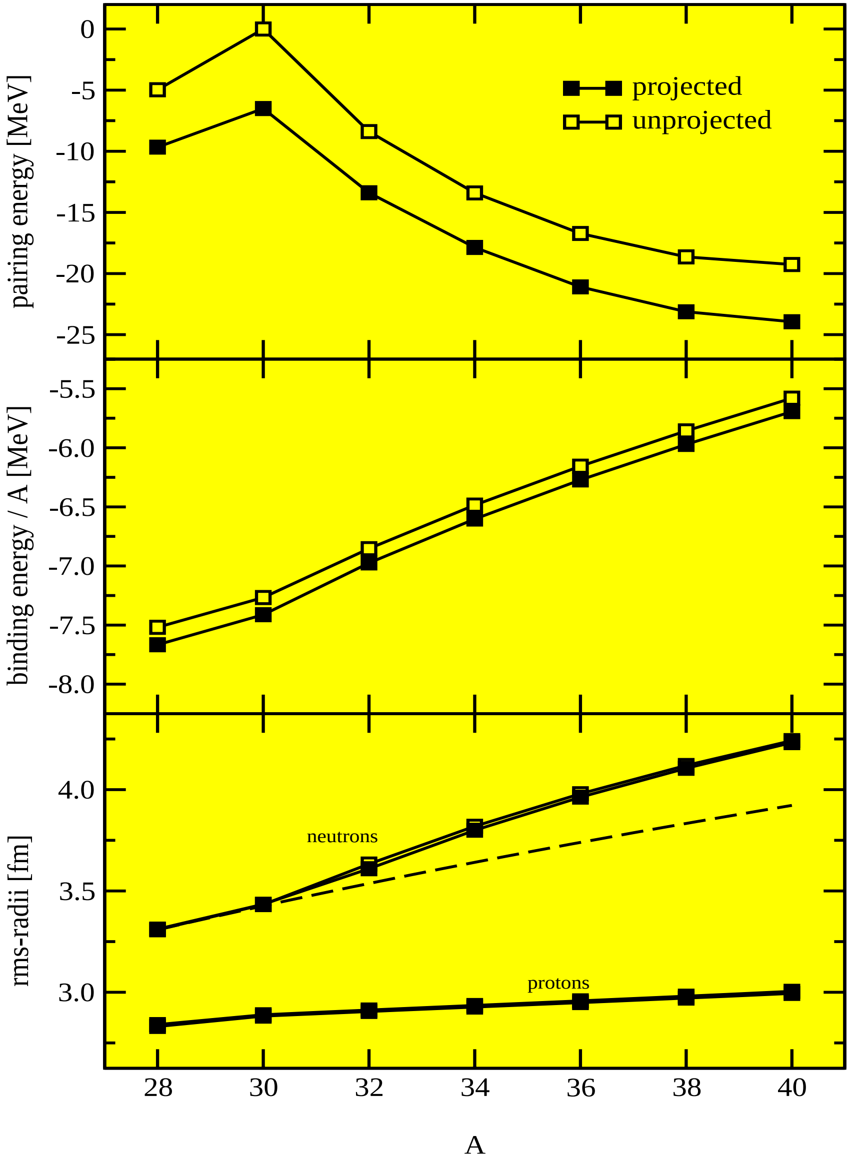
$$\rho(\alpha) = \langle\Phi|a^\dagger a e^{i\alpha\hat{J}}|\Phi\rangle.$$

It can be shown that the mixed density can be expressed analytically by the intrinsic density

$$\rho(\alpha) = e^{i\alpha J}\rho(1 + (e^{i\alpha J} - 1)\rho)^{-1}$$

Sheikh, P.R., PRC 78, 14312 (2008)

pes



airing energies

inding energies

rms-radii

L. Lopes, PhD Thesis, TUM, 2002

Conclusions:

Phenomenological DFT in nuclei produces exellent results

- static: binding energies, radii, deformations, ….
- quasistatic: treatment of rotational excitations in the rotating frame
- dynamic: QRPA reproduces positions collective excitations and the response of the nuclear systems to external fields

Beyond mean field:

- energy dependence of the self energy reduces the shell gap
- and allows to calculate the width of giant resonances
- configuration mixing of def. states describes fluctuations and phase transitions
- restoration of symmetries allows to calculate spectroscopic properties

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