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Covariant density functional theory for excitated states in nuclei

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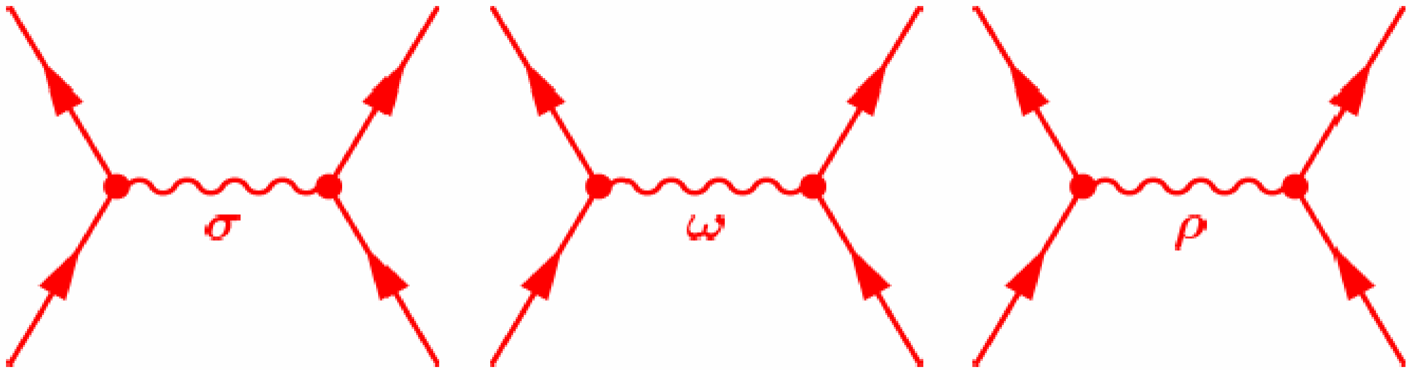
D. Vretenar, A. V. Afanasjiev, G. A. Lalazissis, P. Ring, Phys. Rep. 409 (2005) 101

Covariant density functional theory

Nucleons are coupled by exchange of mesons through an effective Lagrangian (EFT)



$(J^\pi,T)=(0^+,0)$ $(J^\pi,T)=(1^-,0)$ $(J^\pi,T)=(1^-,1)$

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

Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive

Rho-meson: isovector field

Relativistic Hartree Bogoliubov (RHB)

Ground-state properties of weakly bound nuclei far from stability

→ Unified description of mean-field and pairing correlations

chemical potential

Dirac hamiltonian

quasiparticle energy

$$\begin{pmatrix} \hat{h}_D - m - \lambda & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{h}_D + m + \lambda \end{pmatrix} \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} = E_k \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix}$$

pairing field

Gogny D1S

quasiparticle wave function

$$\Delta_{ab}(\vec{r},\vec{r}\,') = \frac{1}{2}\sum_{c,d} V^{pp}_{abcd}(\vec{r},\vec{r}\,')\kappa_{cd}(\vec{r},\vec{r}\,')$$

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Effective density dependence:

non-linear potential:

NL1,NL3..

Boguta and Bodmer, NPA. 431, 3408 (1977)

$$\frac{1}{2}m_\sigma^2\sigma^2 \quad \Rightarrow \quad U(\sigma)=\frac{1}{2}m_\sigma^2\sigma^2+\frac{1}{3}g_2\sigma^3+\frac{1}{4}g_3\sigma^4$$

density dependent coupling constants:

R.Brockmann and H.Toki, PRL 68, 3408 (1992)
S.Typel and H.H.Wolter, NPA 656, 331 (1999)

new

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

$$\mathbf{g} \;\rightarrow\; \mathbf{g}(\rho(r))$$

DD-ME1,DD-ME2

Niksic et al, PRC 66, 024306 (2002)
Lalazissis et al Niksic, PRC 71, 024312 (2005)

Nuclei used in the fit for DD-ME2

Nucleus	B.E (MeV)	r_c (fm)	$r_n - r_p$ (fm)	dE	dr_c	dr_{np}
^{16}O	127.801 (127.619)	2.727 (2.730)	-0.03	0.1	-0.1	
^{40}Ca	342.741 (342.052)	3.464 (3.485)	-0.05	0.2	-0.6	
^{48}Ca	414.770 (415.991)	3.481 (3.484)	0.18	-0.3	-0.1	
^{72}Ni	612.655 (613.173)	3.914	0.28	-0.1		
^{90}Zr	783.155 (783.893)	4.275 (4.272)	0.07	-0.1	0.1	
^{116}Sn	986.928 (988.681)	4.615 (4.626)	0.12 (0.12)	-0.2	-0.2	3.8
^{124}Sn	1048.859 (1049.962)	4.671 (4.674)	0.21 (0.19)	-0.1	-0.1	10.7
^{132}Sn	1103.469 (1102.860)	4.718	0.26	0.1		
^{204}Pb	1608.506 (1607.520)	5.500 (5.486)	0.17	0.1	0.3	
^{208}Pb	1639.826 (1636.446)	5.518 (5.505)	0.19 (0.20)	0.2	0.2	-4.7
^{214}Pb	1661.182 (1663.298)	5.568 (5.562)	0.24	-0.1	0.1	
^{210}Po	1649.695 (1645.228)	5.552	0.17	0.3		

Nuclear matter:

E/A=-16 MeV (5%), ρ_o=1,53 fm^{-1} (10%)

K = 250 MeV (10%), a_4 = 33 MeV (10%)

How many parameters ?

7 parameters

symmetric nuclear matter: E/A, ρ_0 → $\frac{g_\sigma}{m_\sigma}$ $\frac{g_\omega}{m_\omega}$

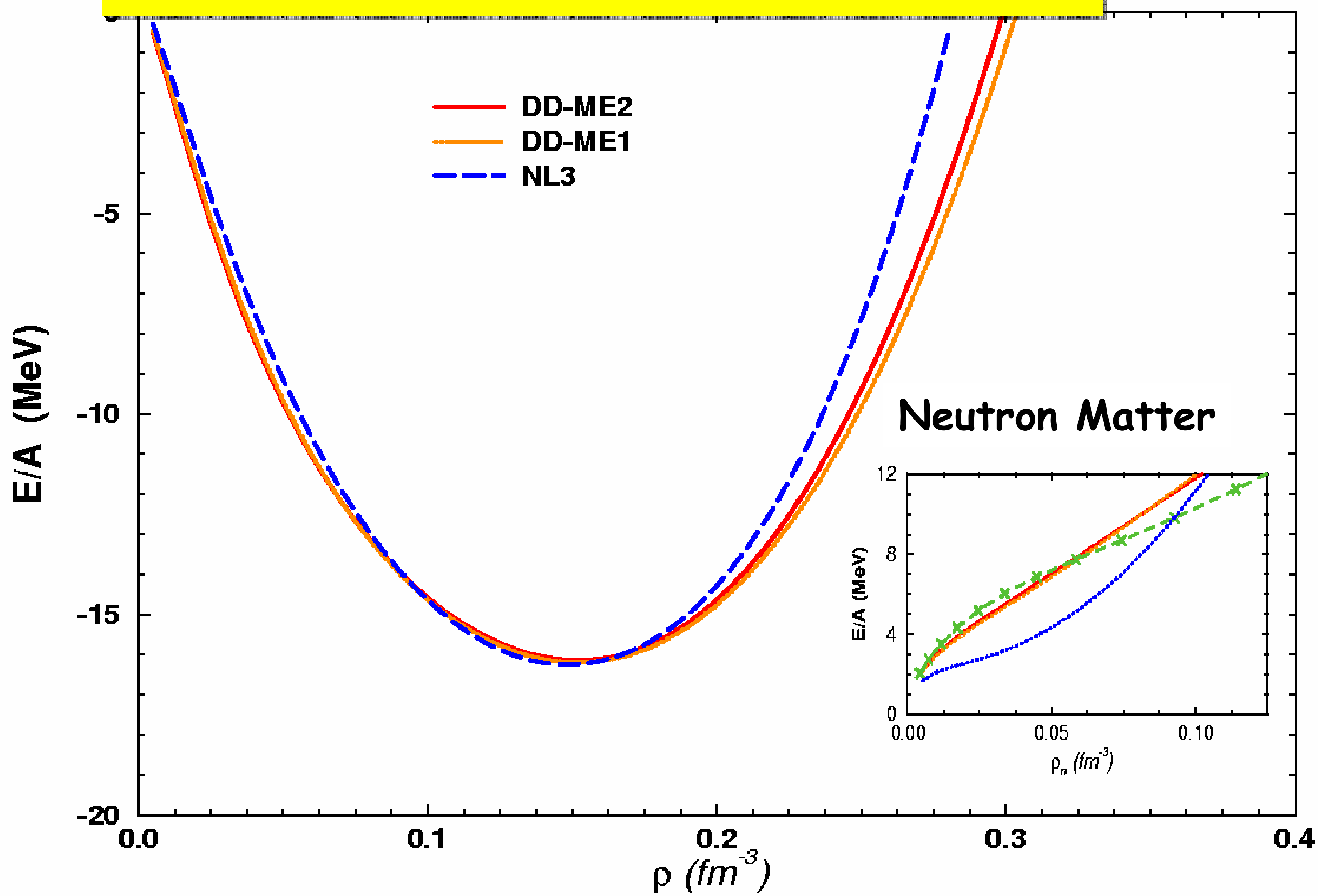
finite nuclei (N=Z): E/A, radii
spinorbit o.k. → m_σ

(N≠Z): Coulomb, symmetry energy: a_4 → $\frac{g_\rho}{m_\rho}$

density dependence: T=0 K_∞ → g_2 g_3

T=1 r_n - r_p → a_ρ

Nuclear matter equation of state



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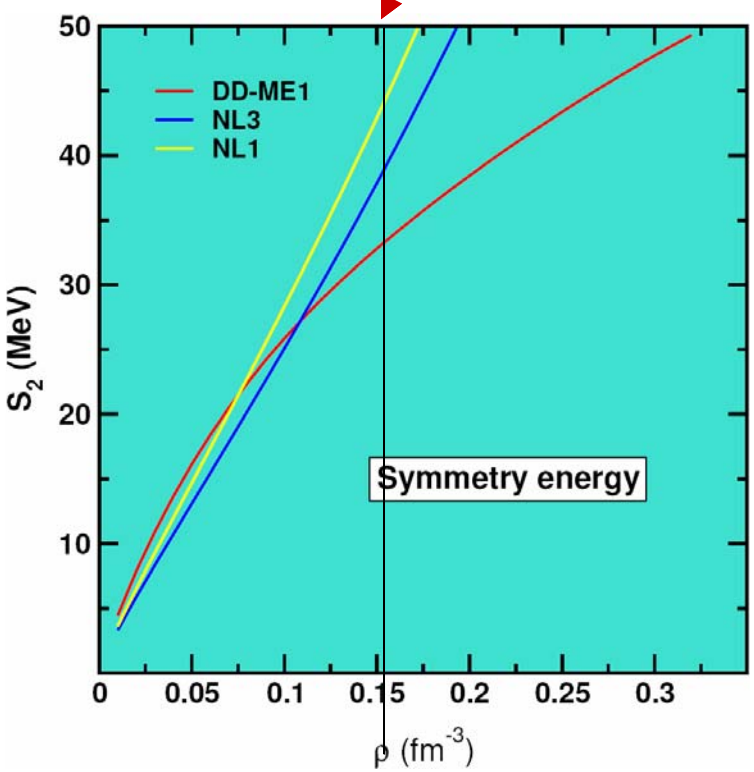
Symmetry energy

saturation density



	DD-ME1	NL3	NL1
$a_4(MeV)$	33.1	37.9	43.7
$p_0(MeV/fm^3)$	3.26	5.92	7.0
$\Delta K_0(MeV)$	-128.5	52.1	67.3

$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + S_4(\rho)\alpha^4 + \cdots$$

$$\alpha \equiv \frac{N-Z}{N+Z}$$

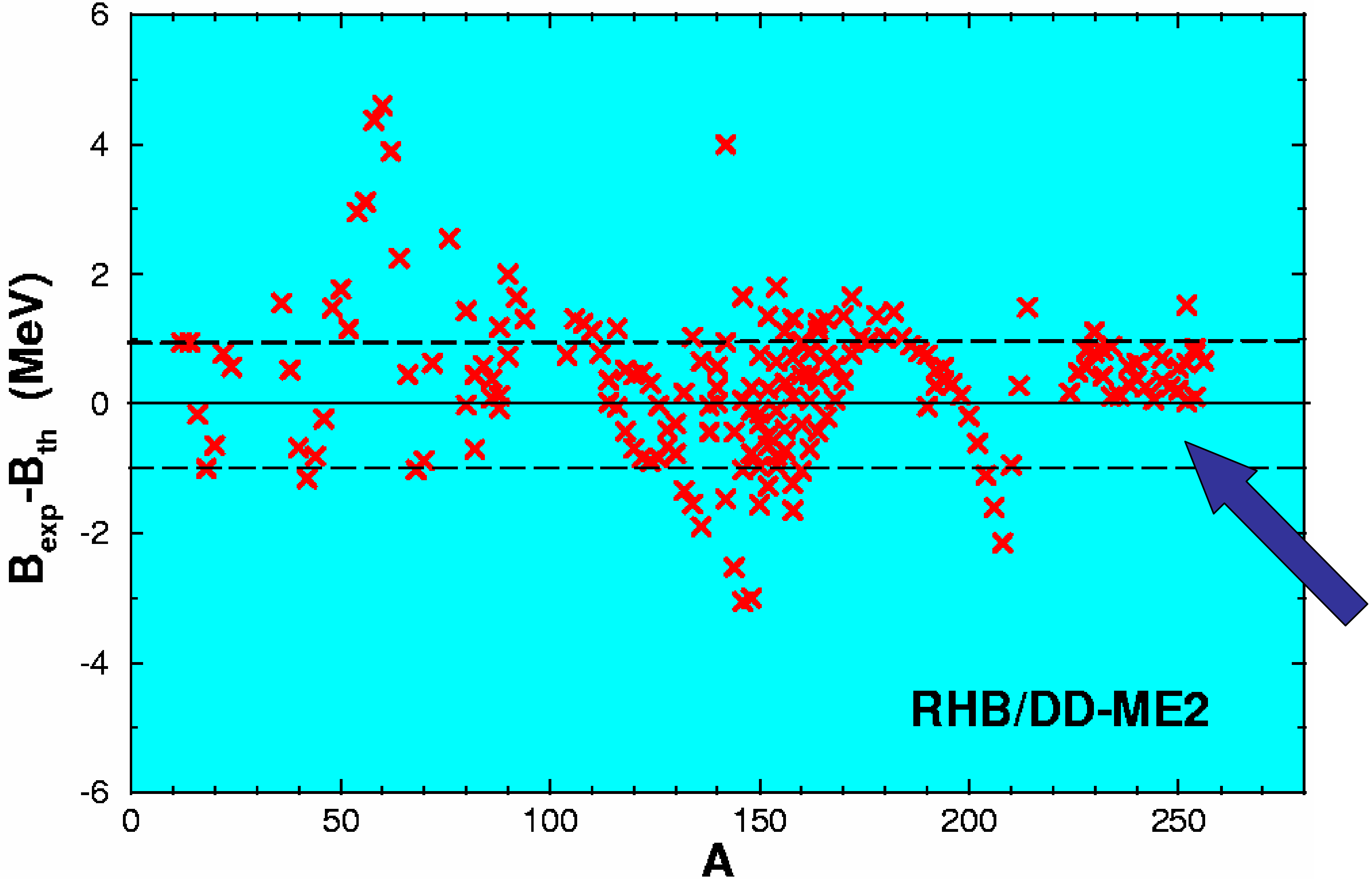
$$S_2(\rho) = a_4 + \frac{p_0}{\rho_{sat}^2}(\rho - \rho_{sat}) + \frac{\Delta K_0}{18\rho_{sat}^2}(\rho - \rho_{sat})^2 + \cdots$$

empirical values:

30 MeV < a_4 < 34 MeV
2 MeV/fm^3 < p_0 < 4 MeV/fm^3
-200 MeV < ΔK_0 < -50 MeV

Furnstahl, NPA 705 (2002) 85

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



Excited States: Time dependence:

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

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

Rotational Motion:

$$\rho(t) = e^{-i\vec{\Omega} t \cdot \vec{j}} \rho_\Omega \, e^{i\vec{\Omega} t \cdot \vec{j}}$$

$$\left[h - \vec{\Omega} \cdot \vec{j}, \rho_\Omega \right] = 0$$

Vibrational Motion:

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

A,B ~ $\delta^2 E / \delta\rho\delta\rho$

ground-state density

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

$\delta\rho_{ph}$

$\delta\rho_{hp}$

Cranked relativistic Hartree+Bogoliubov theory

CRHB equations for the fermions in the rotating frame

$$\begin{pmatrix} \hat{h}_D - \lambda_\tau - \Omega \hat{J}_x & \hat{\Delta} \\ -\hat{\Delta}^* & \hat{h}_D + \lambda_\tau + \Omega \hat{J}_x \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

Coriolis term

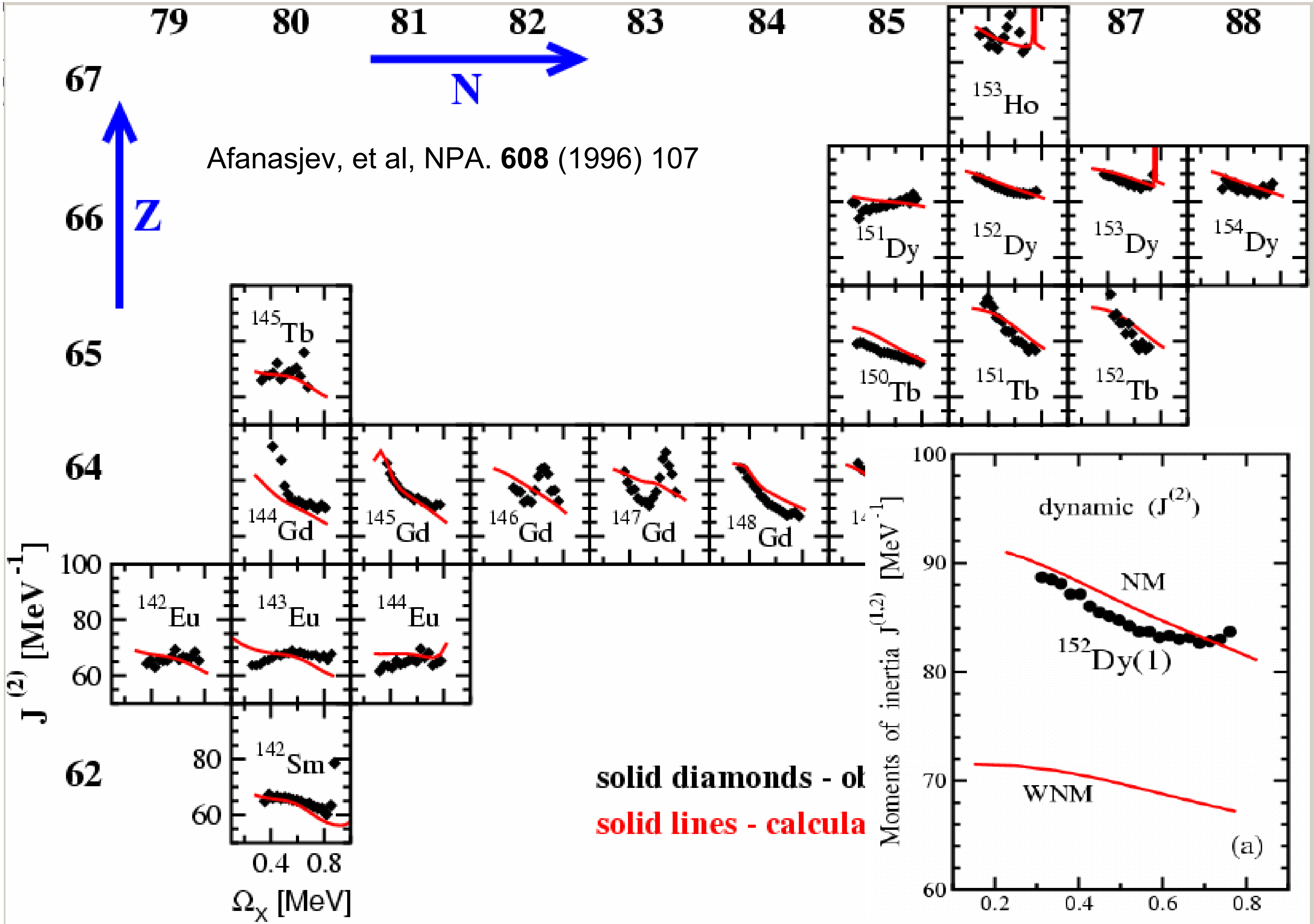
$$\hat{h}_D = \alpha(-i\vec{\nabla} - \vec{V}(\vec{r})) + V_0(\vec{r}) + \beta(m - S(\vec{r}))$$

Magnetic potential

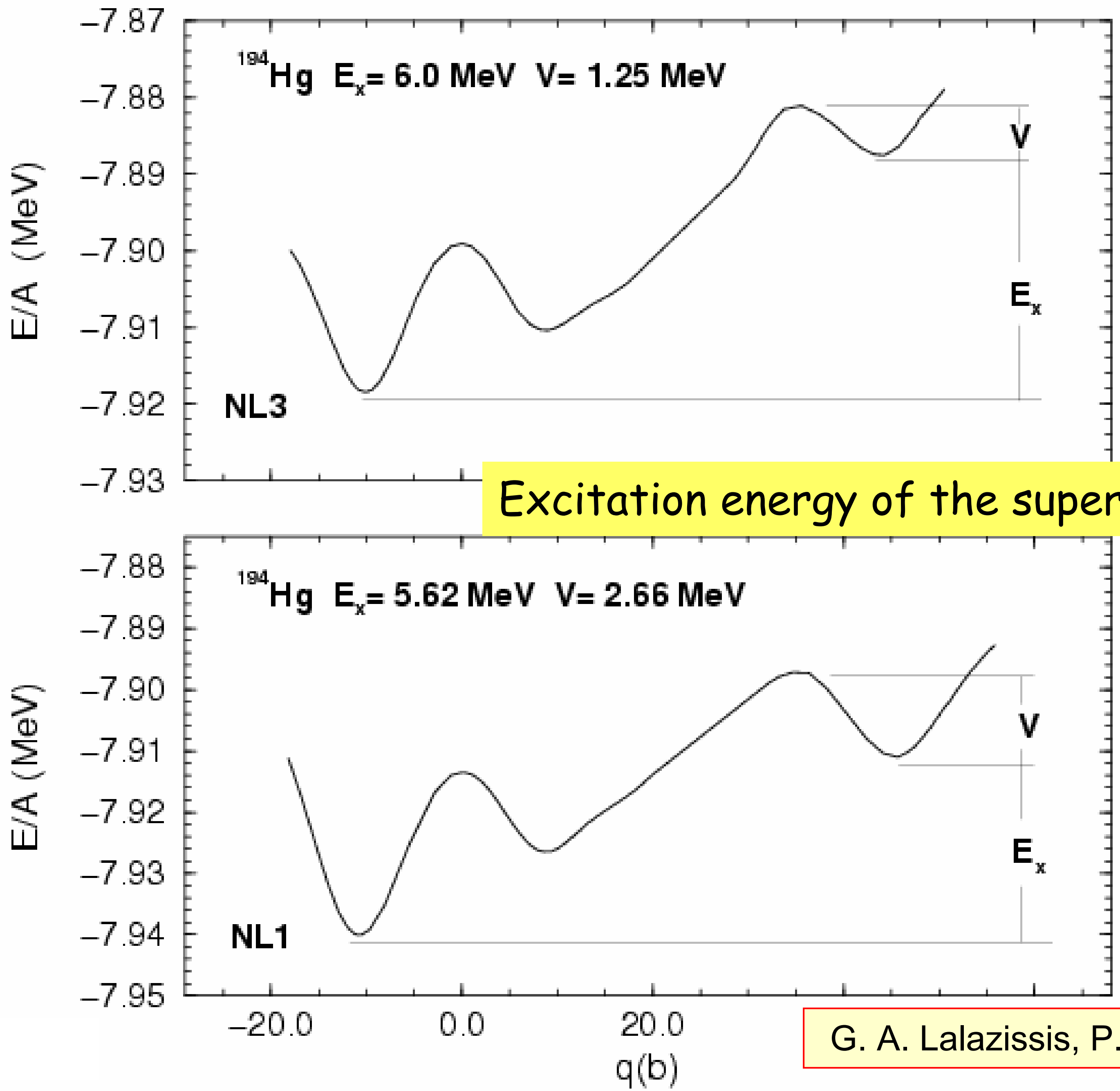
$$\vec{V}(\vec{r}) = g_\omega \vec{\omega}(\vec{r}) + g_\rho \tau_3 \vec{\rho}(\vec{r}) + e\frac{1-\tau_3}{2}\vec{A}(\vec{r})$$

space-like components of vector mesons
behaves in Dirac equation like a magnetic field

Nuclear magnetism



79 80 81 82 83 84 85 87 88
67
66
65
64
62
N
Z
Afanasjev, et al, NPA. **608** (1996) 107
153Ho
151Dy 152Dy 153Dy 154Dy
145Tb
150Tb 151Tb 152Tb
144Gd 145Gd 146Gd 147Gd 148Gd
142Eu 143Eu 144Eu
142Sm
J (2) [MeV -1]
100
80
60
0.4 0.8
Ωx [MeV]
solid diamonds - ol
solid lines - calcula
dynamic (J(2))
NM
152Dy(1)
WNM
(a)
Moments of inertia J(1,2) [MeV-1]
100 90 80 70 60
0.2 0.4 0.6 0.8



^{194}Hg

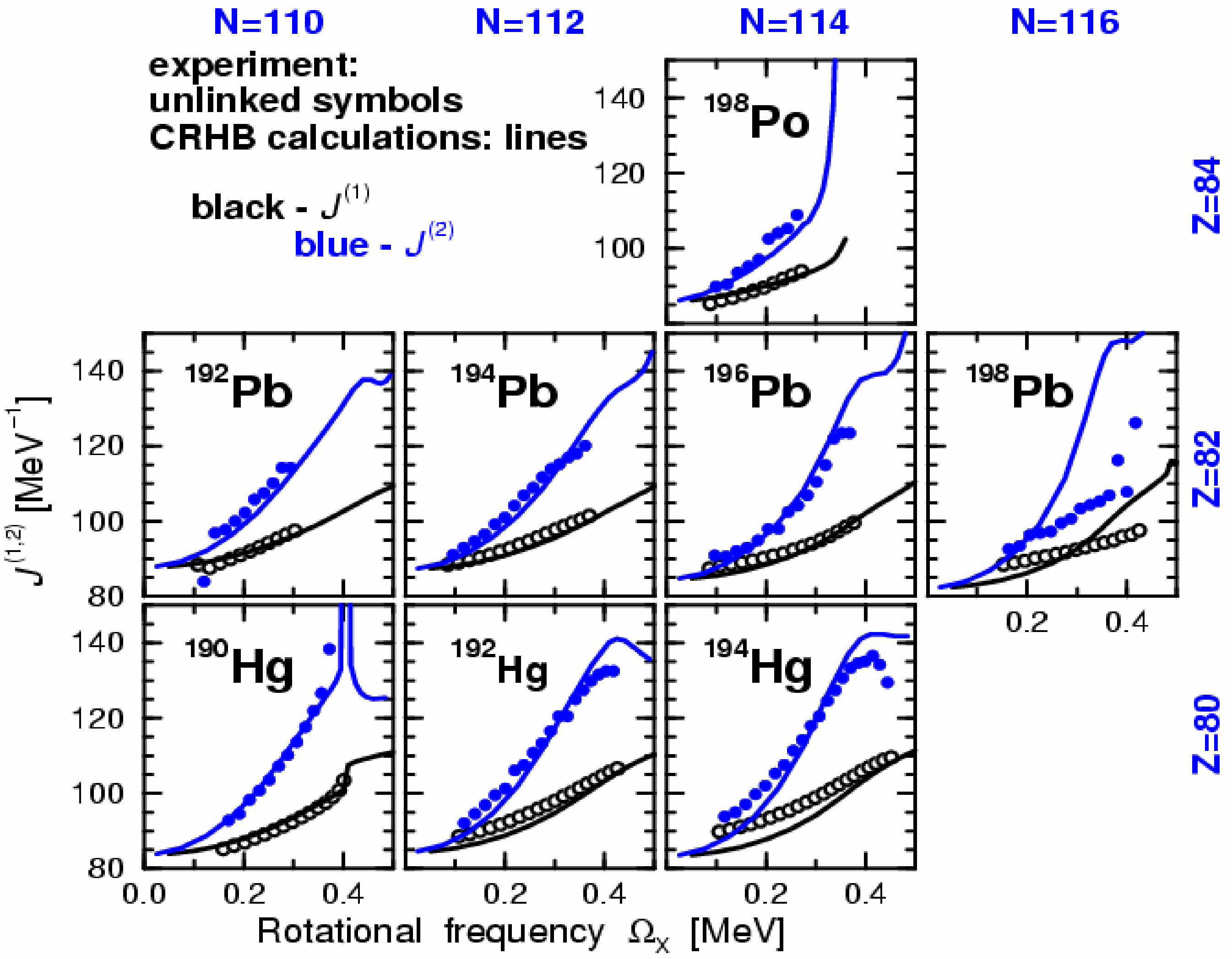
Excitation energy of the superdeformed minimum:

Exp: E_x = 6.02
NL3: = 6.0
NL1: = 5.6
Gogny: = 6.9
Skyrme: = 5.0
WS: = 4.6

G. A. Lalazissis, P. Ring, PLB 427 (1998) 225

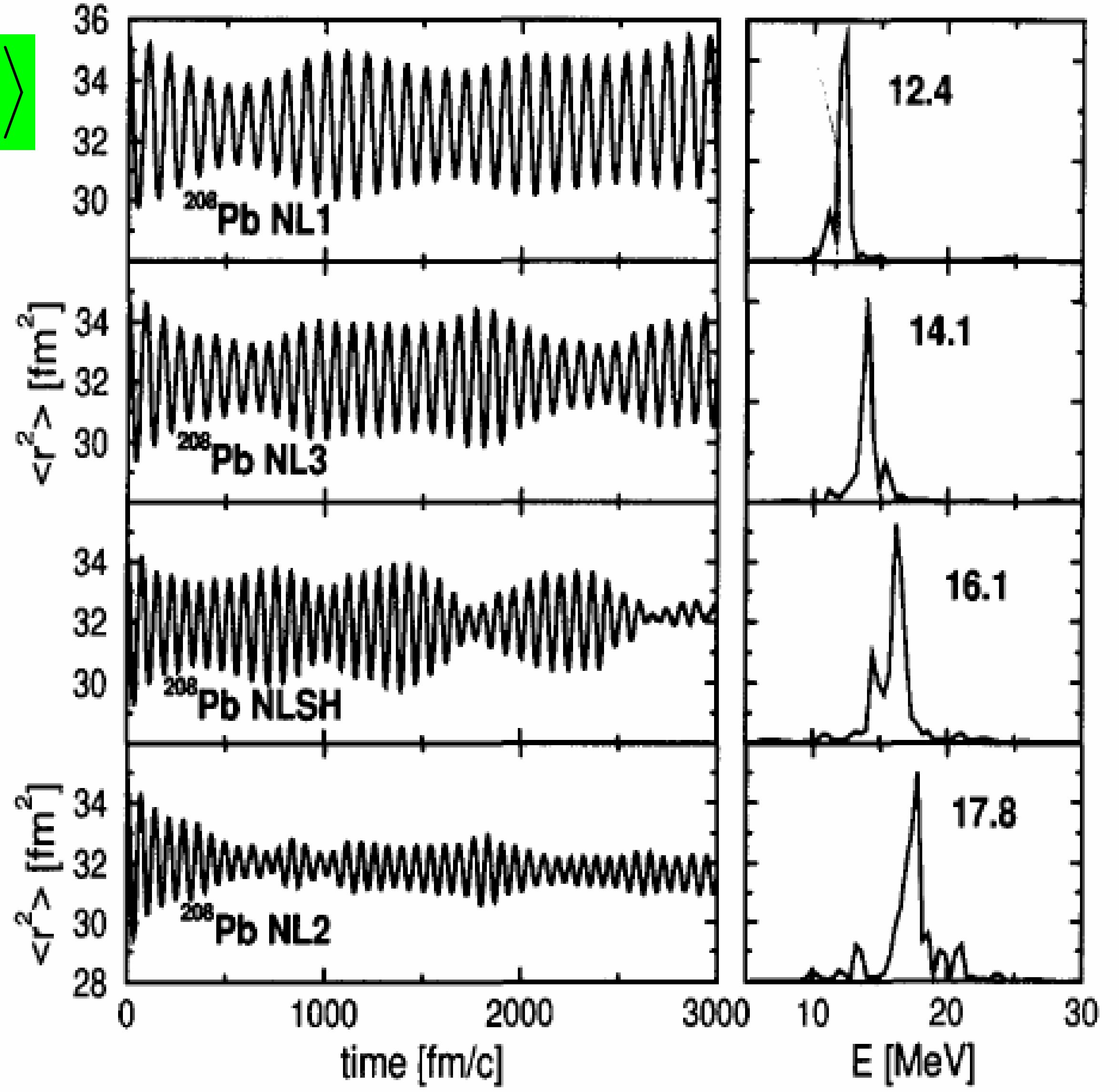
Cranked RHB

A.V.Afanasjev, P. Ring, J. Konig
Phys. Rev. C60 (1999) 051303; Nucl. Phys. A 676 (2000) 196



Time-dependent RMF: breathing mode, ^{208}Pb:

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



K_∞=211

K_∞=271

K_∞=355

Pb: lowlying discrete spectrum

Calculated and experimental excitation energies, and $B(EL)$ values for the low-lying vibrational states in ^{208}Pb

L^π	E_{th}	E_{exp}	$B(EL)_{th}$	$B(EL)_{exp}$
3^-	2.76	2.61	499×10^3	$(540 \pm 30) \times 10^3$
5^-	3.26	3.71	201×10^6	330×10^6
2^+	4.99	4.07	2816	2965
4^+	4.95	4.32	998×10^4	1287×10^4

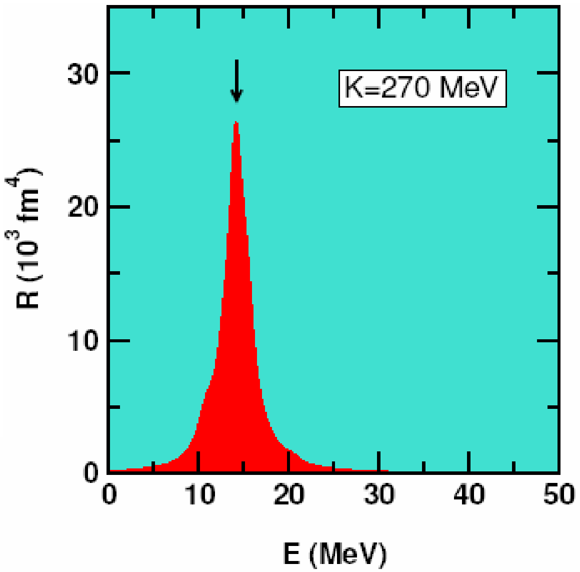
The calculated values correspond to NL3 parameterization, the data are from Ref. [29]. Energies are in MeV, $B(EL)$ values in e^2 fm^{2L}.

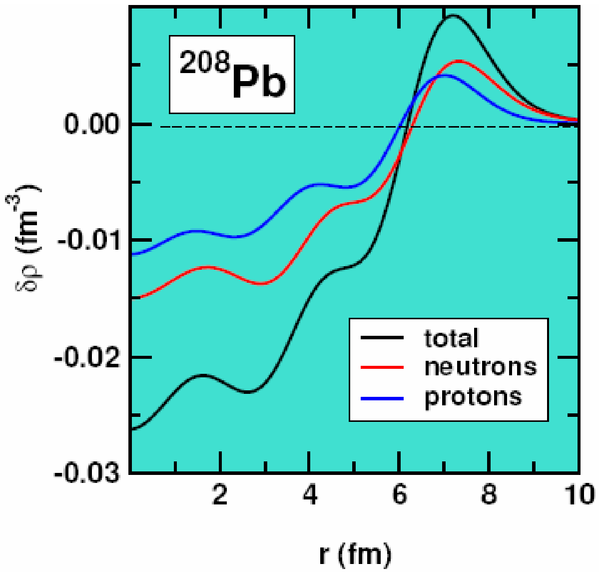
Z.Y. Ma, A. Wandelt et al., NPA 694 (2001) 249

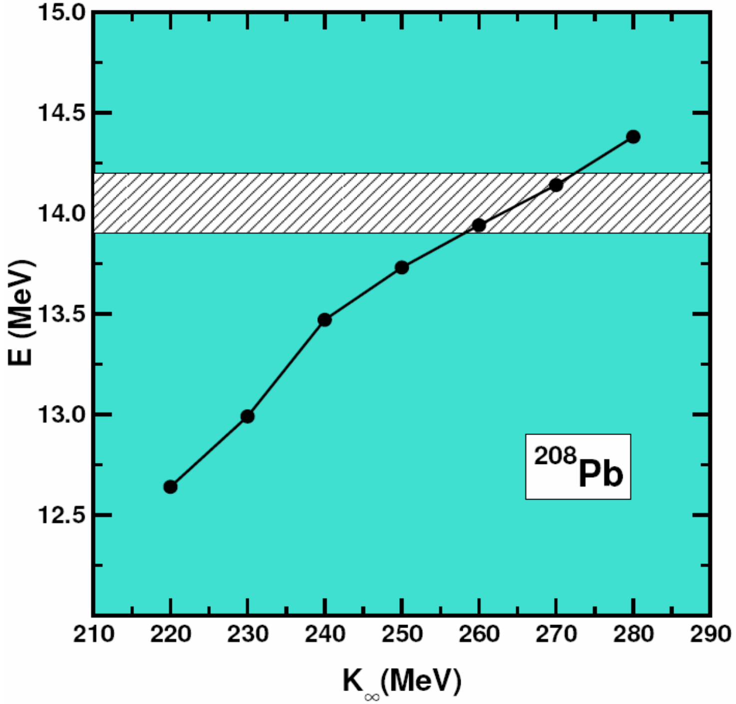
Isoscalar Giant Monopole Resonance: IS-GMR

The ISGMR represents the essential source of experimental information on the nuclear incompressibility

$$K_0 = p_f^2 \frac{d^2 E/A}{dp_f^2}\bigg|_{p_{f0}}$$







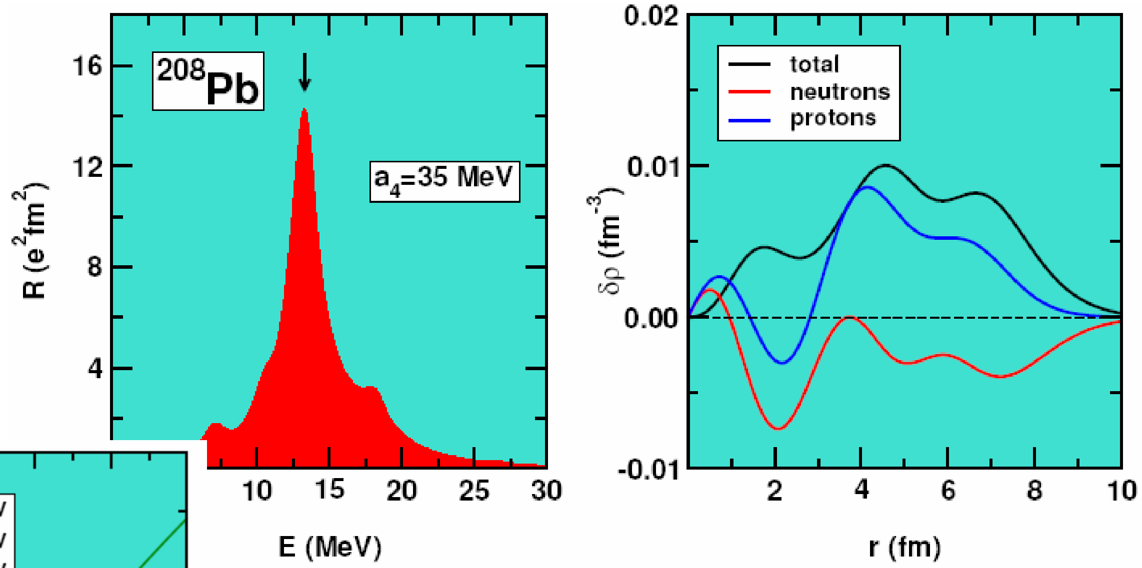
constraining the nuclear matter compressibility

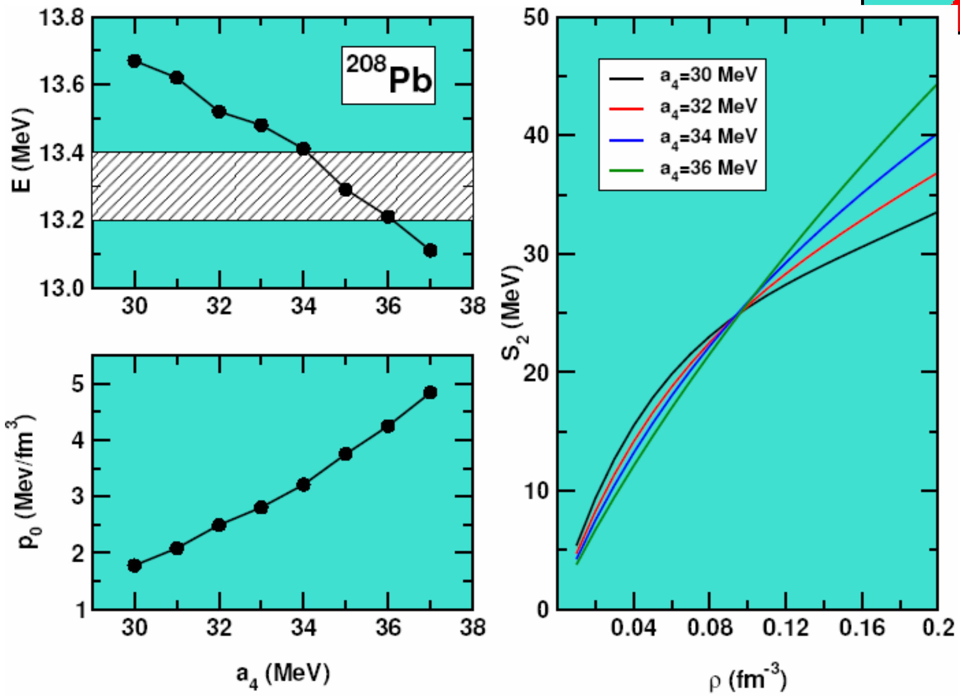
→ RMF models reproduce the experimental data only if

$$250\ \text{MeV} \le K_0 \le 270\ \text{MeV}$$

Isovector Giant Dipole Resonance: IV-GDR

the IVGDR represents one of the sources of experimental informations on the nuclear matter symmetry energy





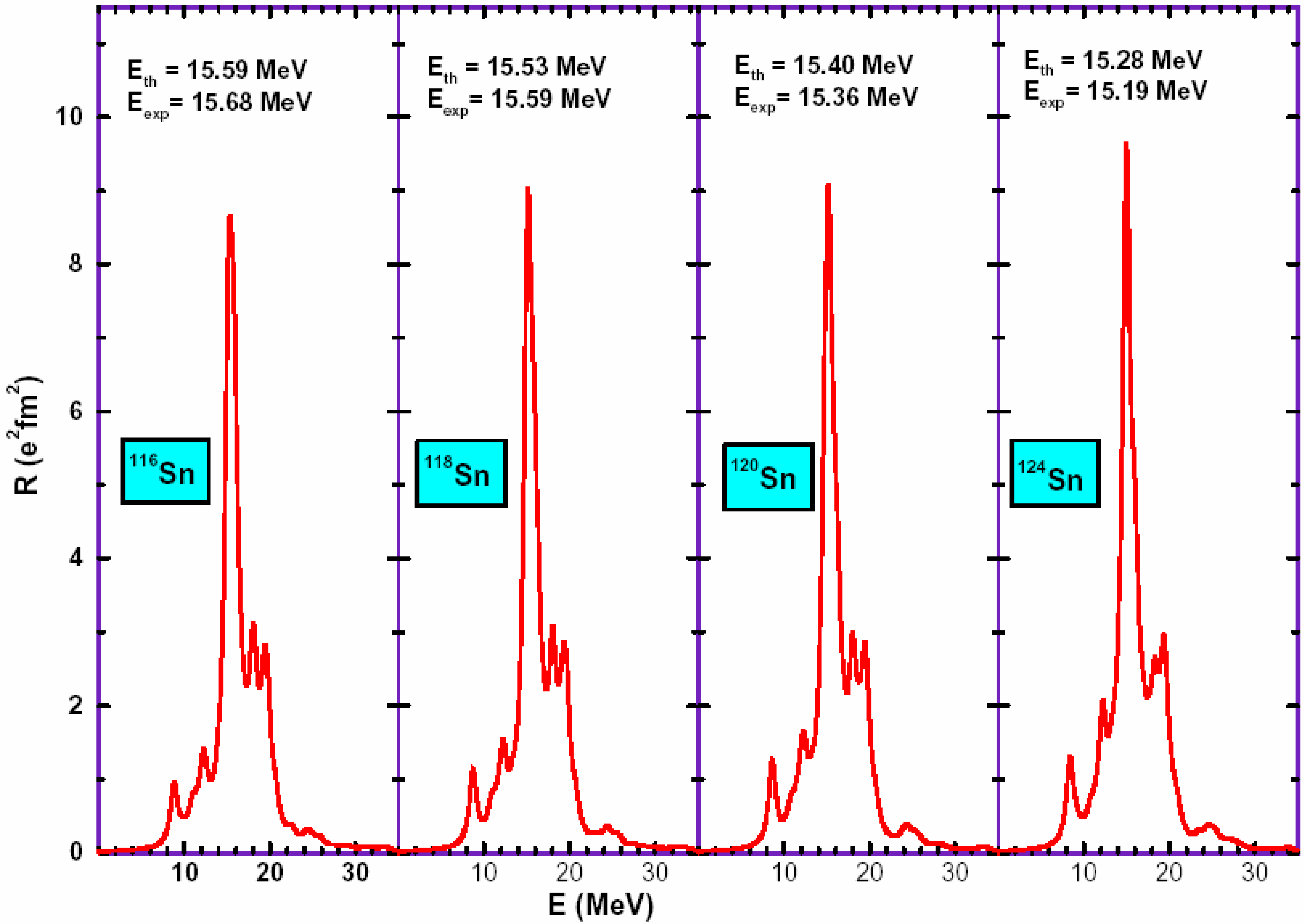
constraining the nuclear matter symmetry energy

→ the position of IVGDR is reproduced if

$$34 \text{ MeV} \leq a_4 \leq 36 \text{ MeV}$$

IV-GDR in Sn-isotopes

DD-ME2



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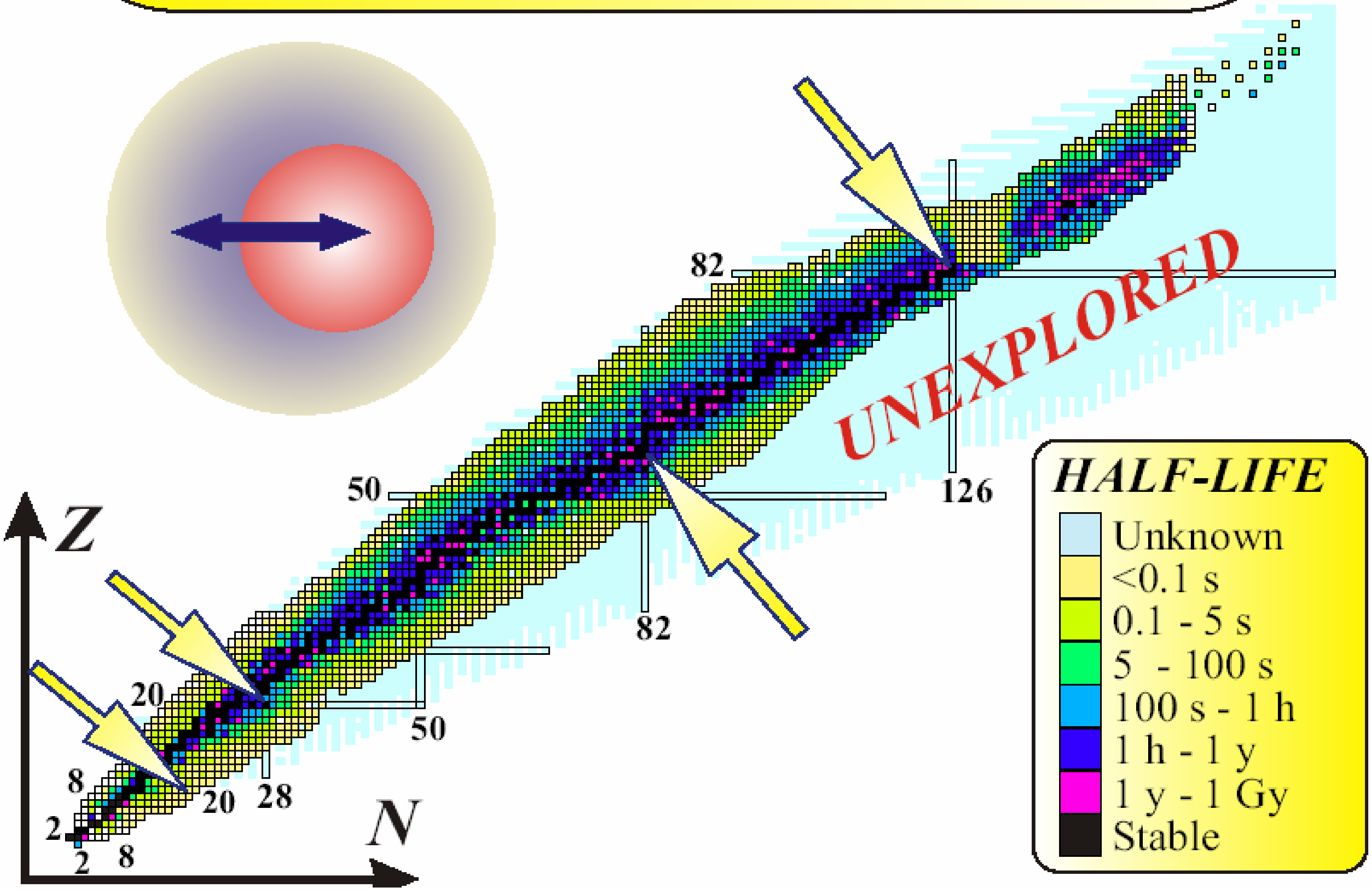
Experimental indications of the soft dipole mode



VOLUME 86, NUMBER 24 PHYSICAL REVIEW LETTERS 11 JUNE 2001

Photoneutron Cross Sections for Unstable Neutron-Rich Oxygen Isotopes

A. Leistenschneider, T. Aumann, K. Boretzky, D. Cortina, J. Cub, U. Datta Pramanik, W. Dostal, Th. W. Elze, H. Emling, H. Geissel, A. Grünschloß, M. Hellstr, R. Holzmann, S. Ilievski, N. Iwasa, M. Kaspar, A. Kleinböhl, J. V. Kratz, R. Kulessa, Y. Leifels, E. Lubkiewicz, G. Münzenberg, P. Reiter, M. Rejmund, C. Scheidenberger, C. Schlegel, H. Simon, J. Stroth, K. Sümmerer, E. Wajda, W. Walús, and S. Wan

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Institut für Kernchemie, Johannes Gutenberg-Universität, D-55099 Mainz, Germany
Institut für Kernphysik, Technische Universität, D-64289 Darmstadt, Germany
Instytut Fizyki, Uniwersytet JagellońSki, PL-30-059 Kraków, Poland
Sektion Physik, Ludwig-Maximilians-Universität, D-85748 Garching, Germany

(Received 19 December 2000)

The dipole response of stable and unstable neutron-rich oxygen nuclei of masses A=17 to A=22 Has been investigated experimentally utilizing electromagnetic excitation in heavy-ion collisions at beam energies about 600 MeV/ nucleon. A kinematically complete measurement of the neutron decay channel in inelastic scattering of the secondary beam projectiles from a Pb target was performed. Differential electromagnetic excitation cross sections dσ/dE were derived up to 30 MeV excitation energy. In contrast to stable nuclei, the deduced dipole strength distribution appears to be strongly fragmented and systematically exhibits a considerable fraction of low-lying strength.

DOI: 10.1103/PhysRev ... 25.60.−t, 27.20.+n

The study of the response of ...
clear or electromagneticeld is ...
the properties of the nuclear ...
citation energies above the par...
response of stable nuclei is dor...
tions of various multipolarities,...
the giant resonance strength ...
stable to exotic weakly bound n...
to-proton ratios is presently un...
For neutron-rich nuclei, mode...
nounced effects, in particula...
strength towards lower excitati...
giant resonance region. The p...
depend strongly on the effectiv...
lations. In turn, measurements ...
response of exotic nuclei can...
tion on the isospin depende...
nucleon-nucleon interaction [7...
Systematic experimental inf...
response of exotic nuclei, how...
For some light halo nuclei, low...
observed in electromagnetic ...
[8–11]. For the one-neutron h...
C [11], the observed dipole ...
tation energies was interpreted...
threshold effect, involving nor...
valence neutron into the contin...
He and Li, a coherent dipol...
neutrons against the core was ...
The appearance of a collectiv...
general was predicted for hea...
[19,20], located at excitation ...
dipole resonance (GDR) [19].

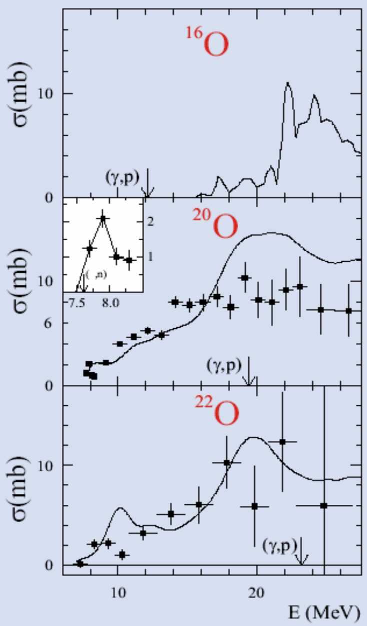

FIG. 2. Photoneutron cross sections for O16 (upper panel) and for the unstable isotopes 20,22O (lower panels) as extracted from the measured electromagnetic excitation cross section (symbols). The inset displays the cross section for near the neutron threshold on an expanded energy scale. The thresholds for decay channels involving protons (which were not observed in the present experiment) are indicated by arrows.

...gmy resonance, may arise
...e neutrons vibrate against
...passing that a systematic
...le strength in neutron-rich
...sical aspects, e.g., calcu-
...es in the -process of the
...21].
...t resonances and lower ly-
... investigated systematically
...s of all neutron-rich oxygen
...ongly bound doubly magic
...pes, one may expect a de-
...ns from the inert O core.
...st neutron is 7–8 MeV for
..., and about 4 MeV for the
...16 MeV for O. Thus the
...ight be good candidates for
...ion.
...ve use the electromagnetic
... high targets. Similar to
...s mostly sensitive to electric
...mall E2 contributions. For
...weighted sum rule for E1
...rbitrarily at an excitation
...electromagnetic excitation
...nb, respectively (calculated
...a Pb target). It was demon-
...] that the dipole strength
...ntitatively from a measure-
...magnetic dissociation cross
...ee parameters by applying
...24]. The high secondary
...eV nucleon allows for the

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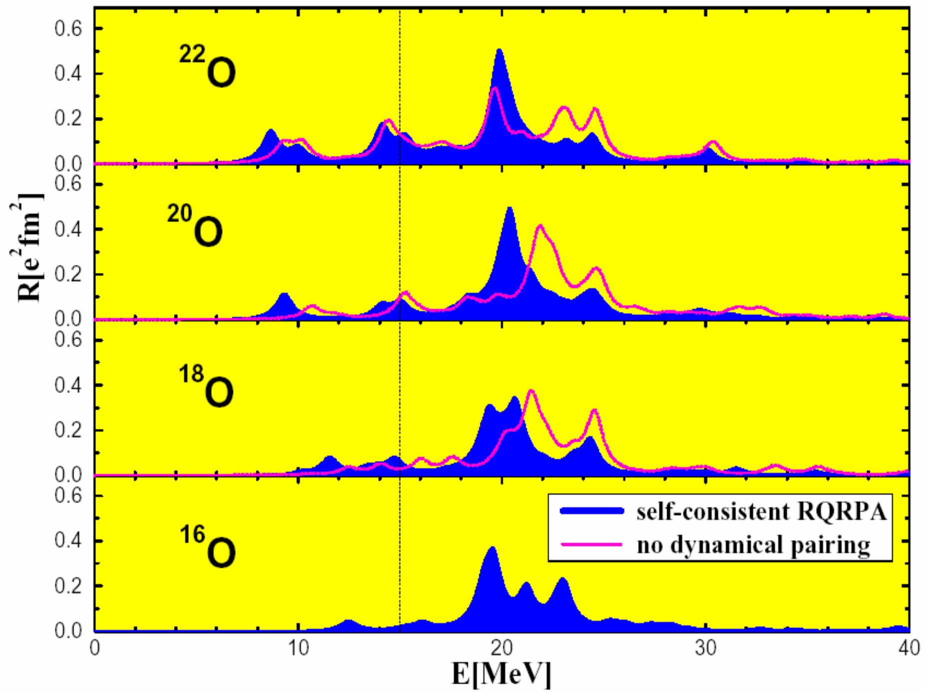
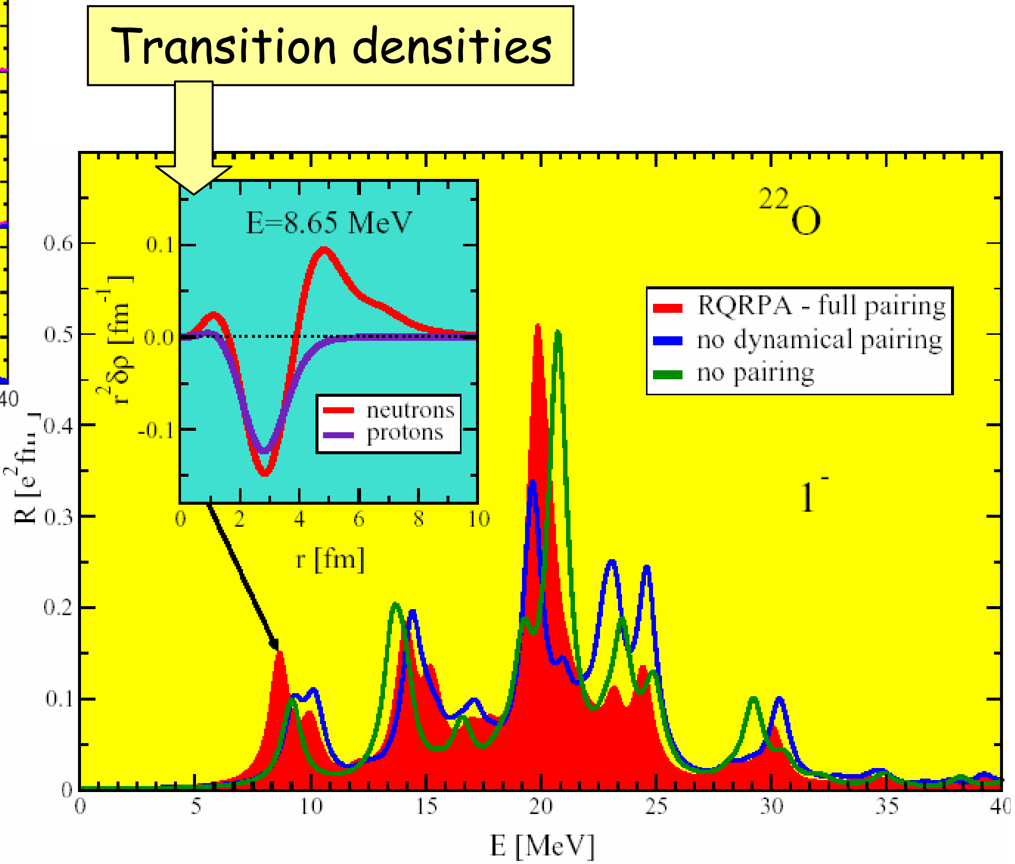
Evolution of IV dipole strength in Oxygen isotopes

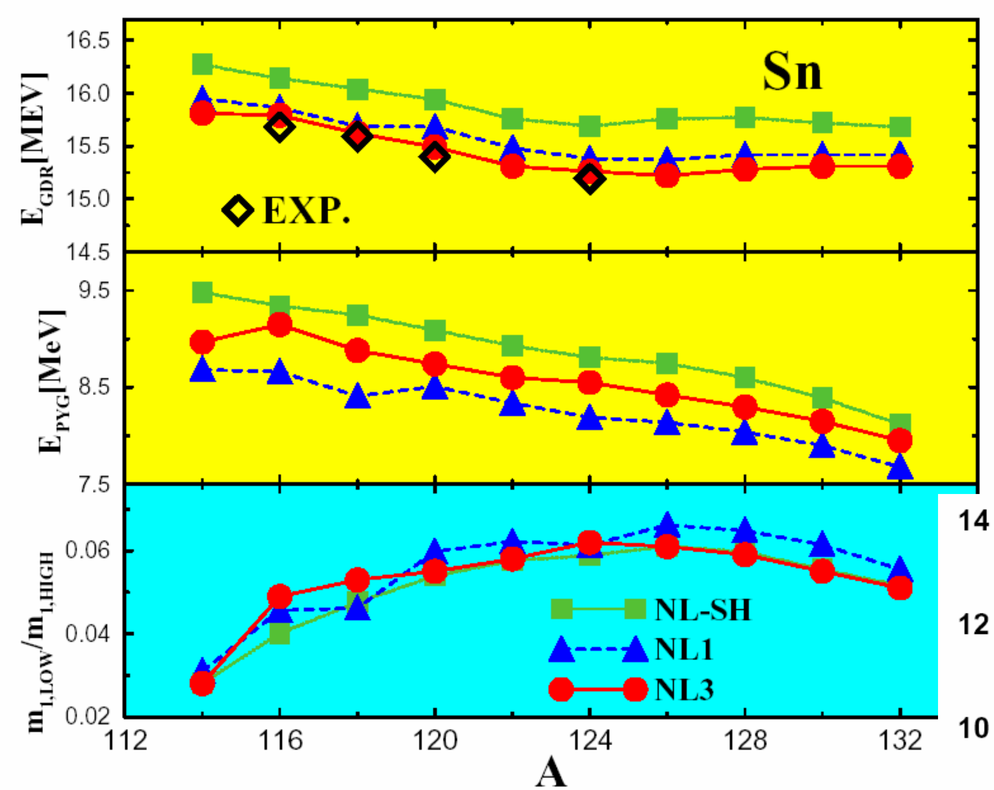


RHB + RQRPA calculations with the NL3 relativistic mean-field plus D1S Gogny pairing interaction.



What is the structure of low-lying strength below 15 MeV ?

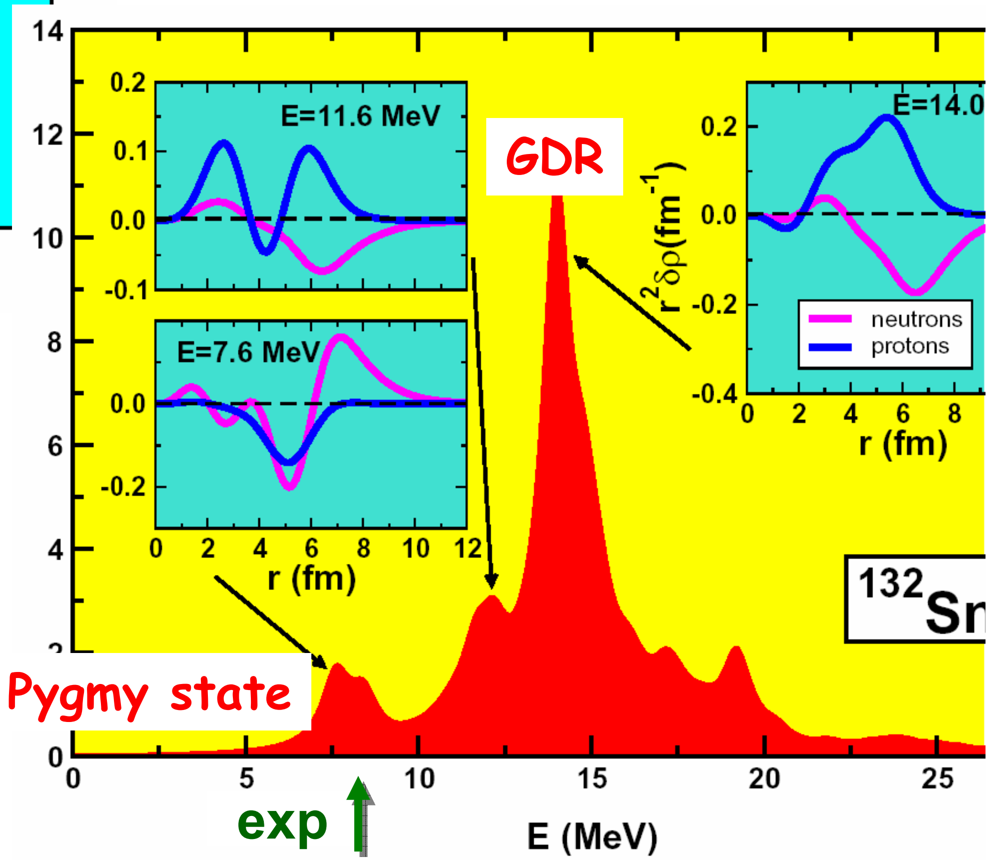
Effect of pairing correlations on the dipole strength distribution



Mass dependence of GDR and Pygmy dipole states in Sn isotopes. Evolution of the low-lying strength.

Isovector dipole strength in ^{132}Sn.

Nucl. Phys. A692, 496 (2001)



Distribution of the neutron particle-hole configurations for the peak at 7.6 MeV (1.4% of the EWSR)

^{132}Sn at 7.6 MeV	
28.2%	$2d_{3/2} \rightarrow 2f_{5/2}$
21.9%	$2d_{5/2} \rightarrow 2f_{7/2}$
19.7%	$2d_{3/2} \rightarrow 3p_{1/2}$
10.5%	$1h_{11/2} \rightarrow 1i_{13/2}$
3.5%	$2d_{5/2} \rightarrow 3p_{3/2}$
1.9%	$1g_{7/2} \rightarrow 2f_{5/2}$
1.5%	$1g_{7/2} \rightarrow 1h_{9/2}$
0.6%	$1g_{7/2} \rightarrow 2f_{7/2}$
0.6%	$2d_{3/2} \rightarrow 3p_{3/2}$

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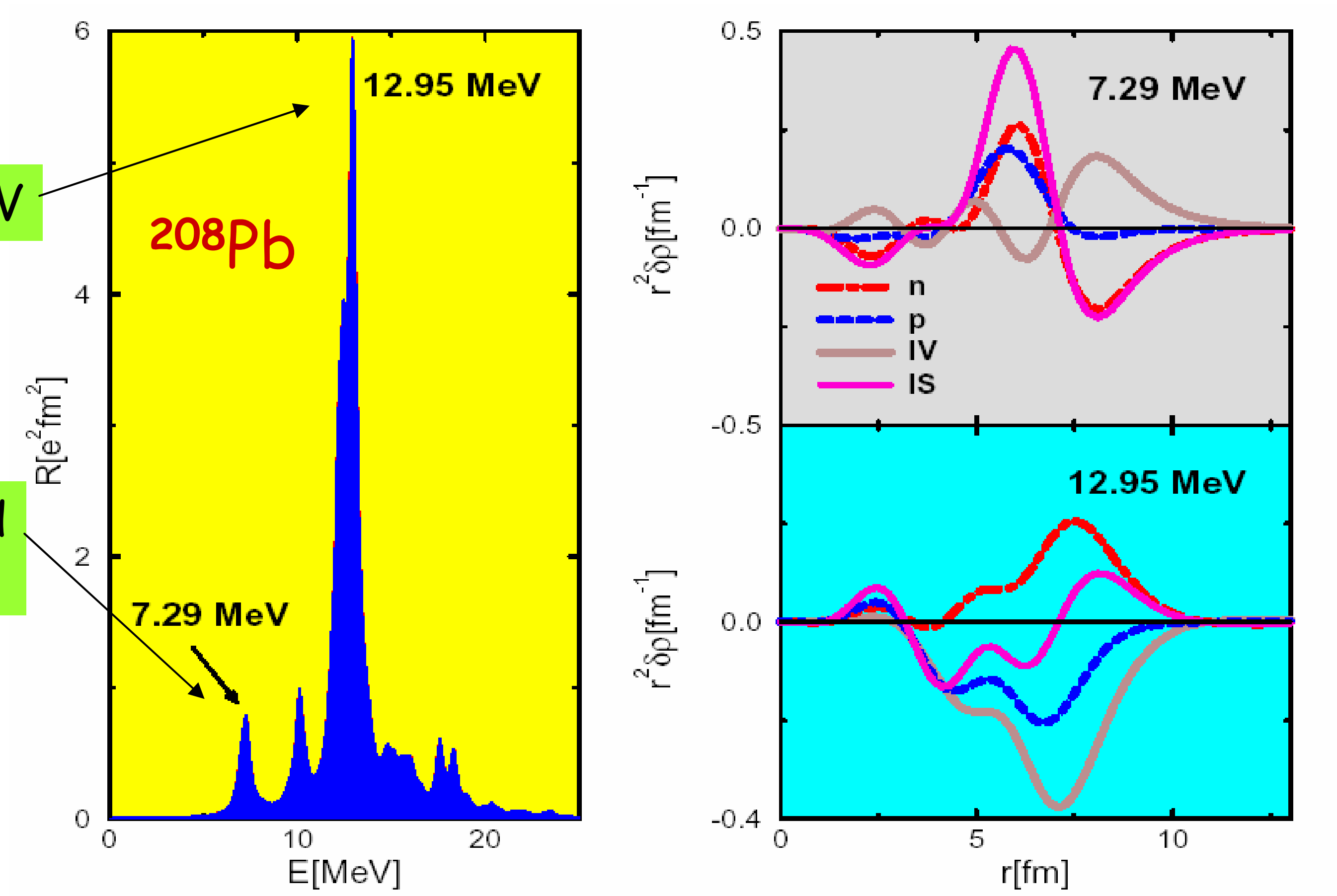
IV Dipole Strength for ^{208}Pb and transition densities for the peaks at 7.29 MeV and 12.95 MeV PRC 63, 047301 (2001)

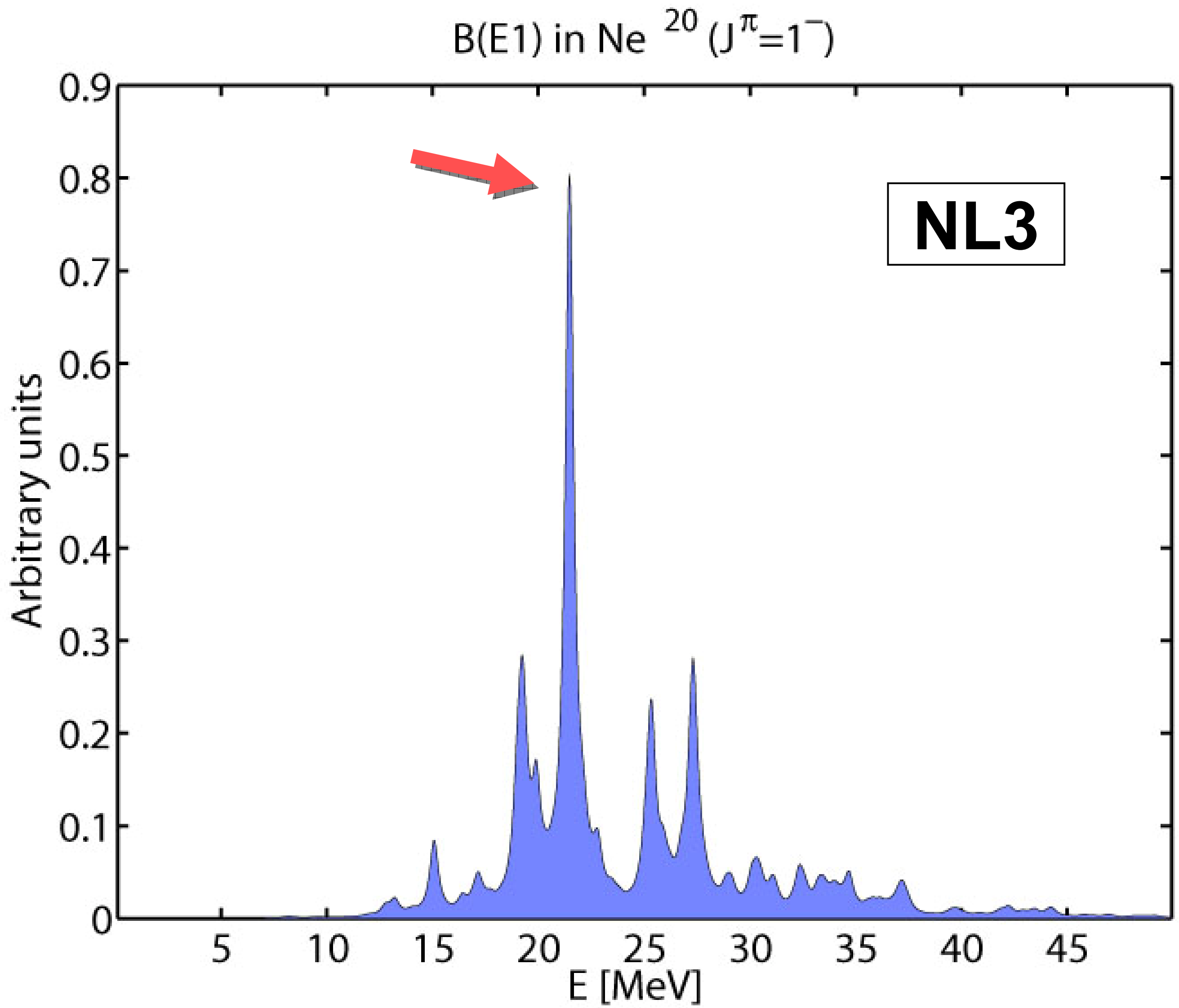
Exp GDR at 13.3 MeV

Exp PYGMY centroid at 7.37 MeV

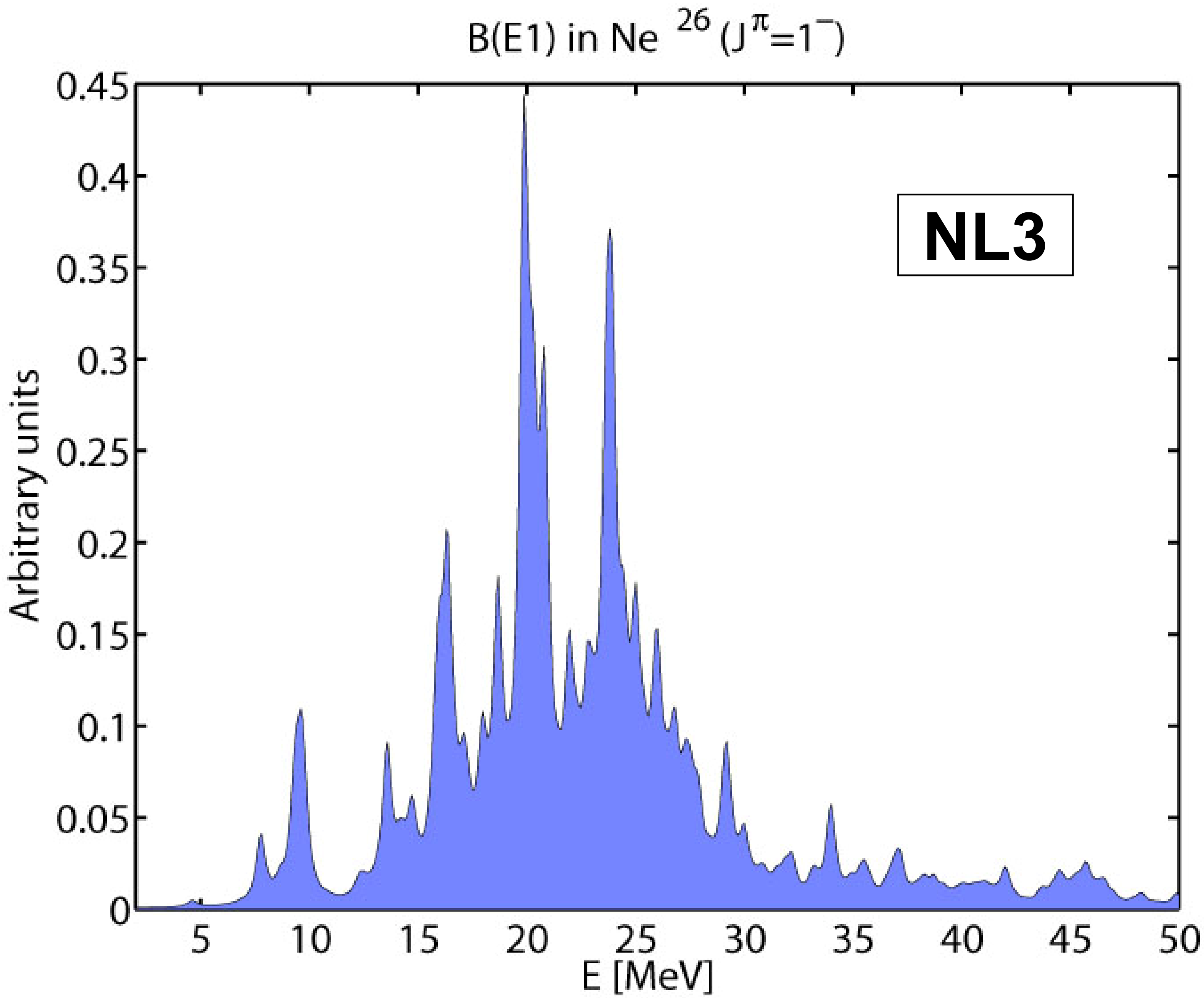


In heavier nuclei low-lying dipole states appear that are characterized by a more distributed structure of the RQRPA amplitude.

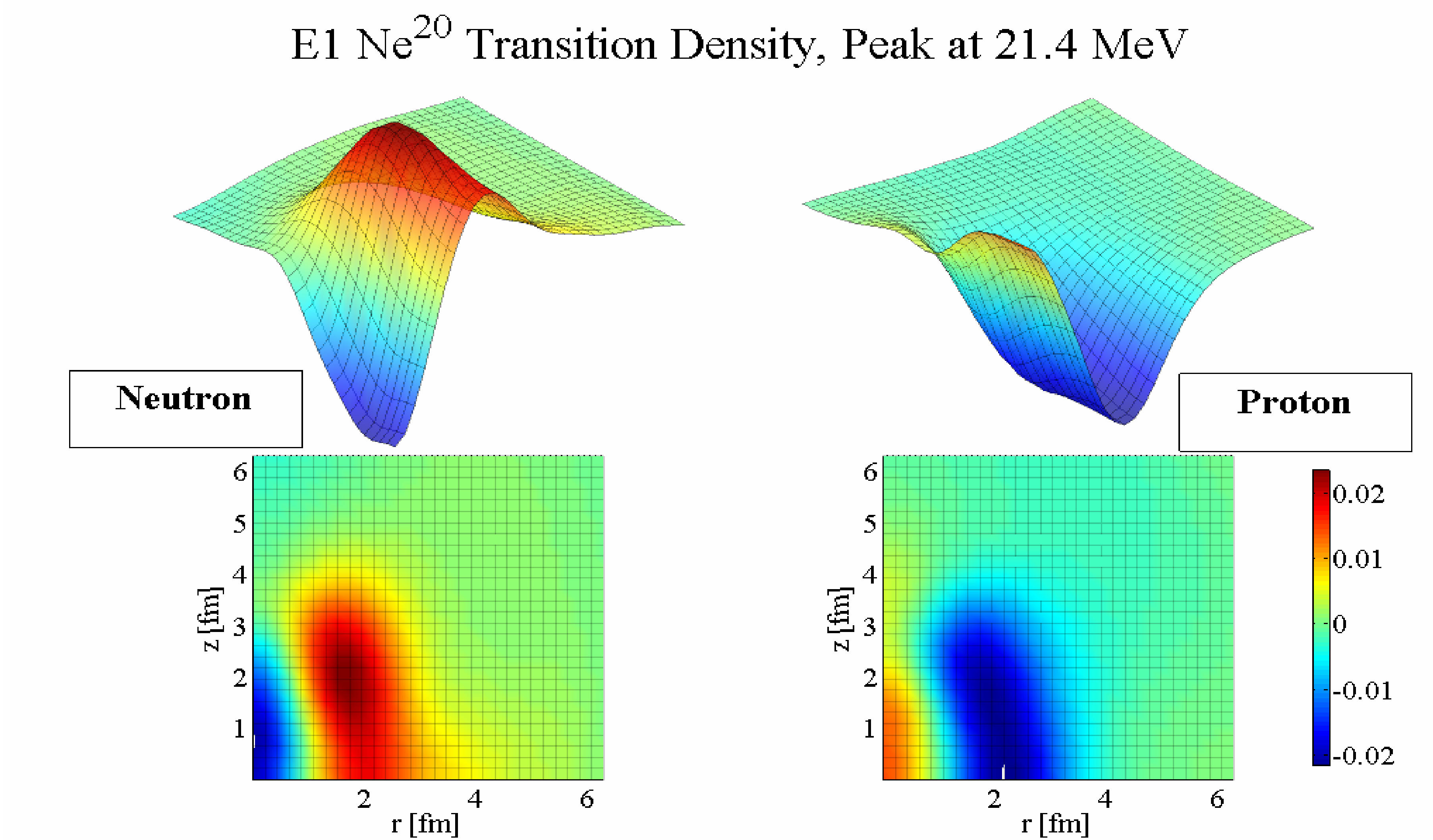
E1-strength distribution in deformed ^{20}Ne



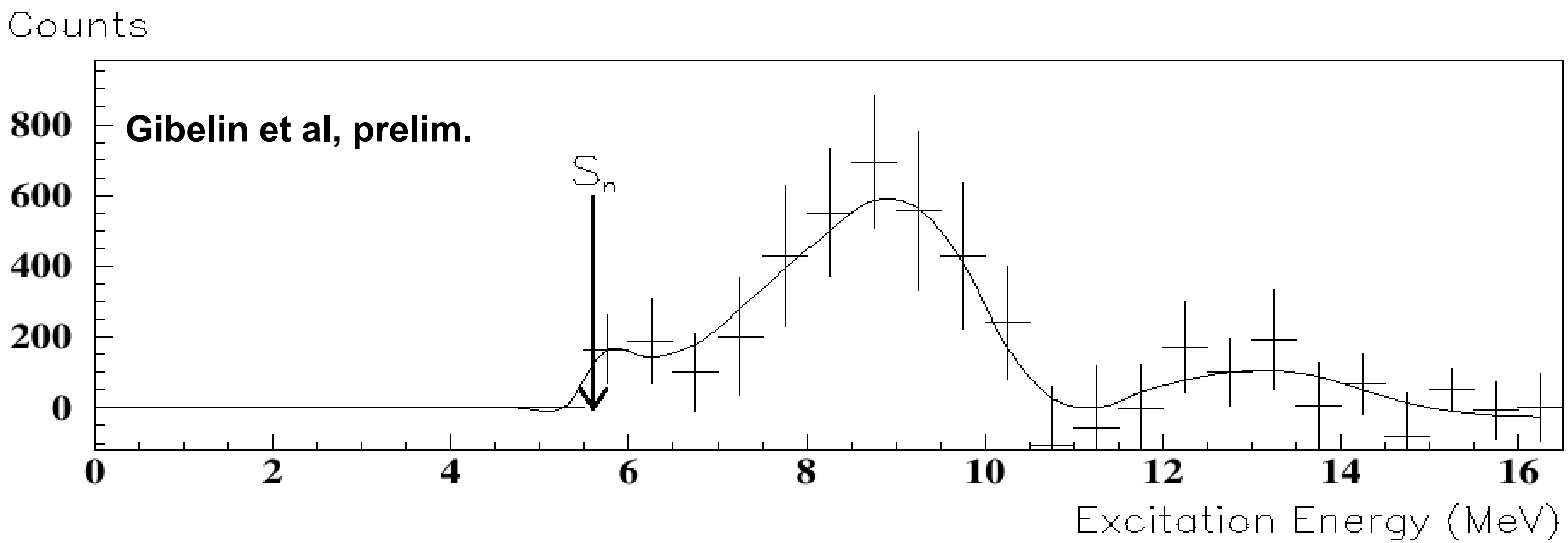
IV-E1-Resonances in deformed ^{26}Ne

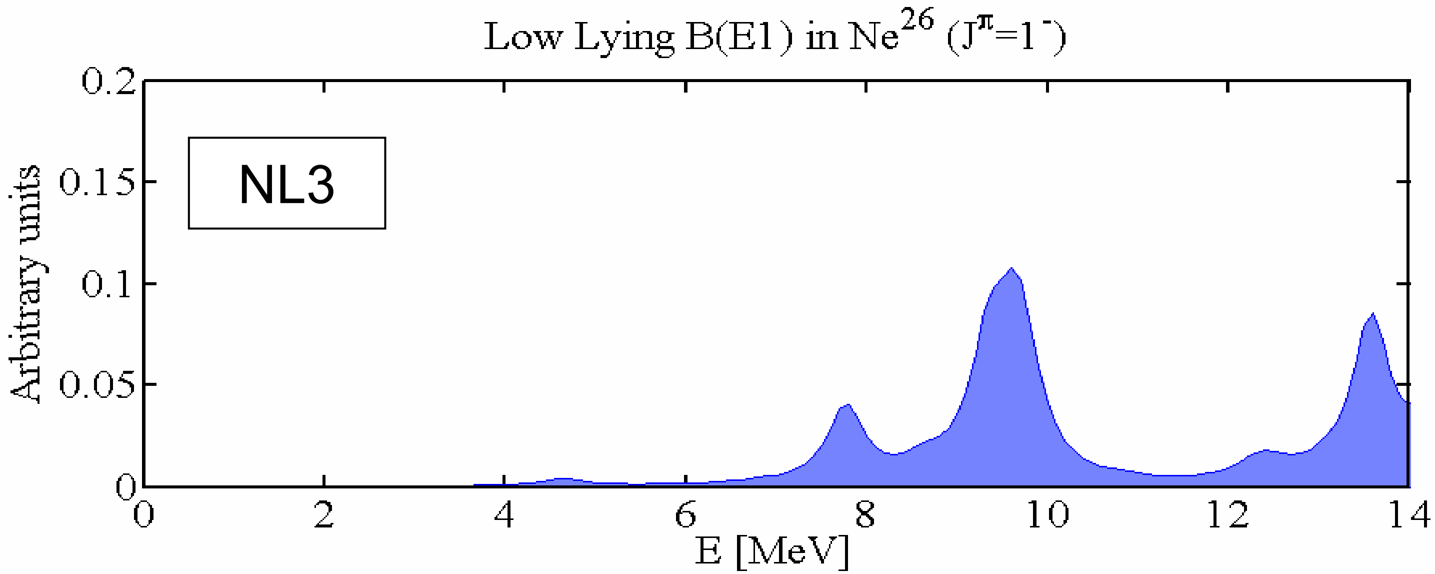


Transition density of the upper E1-peak



Pygmy-Resonance in deformed ^{26}Ne





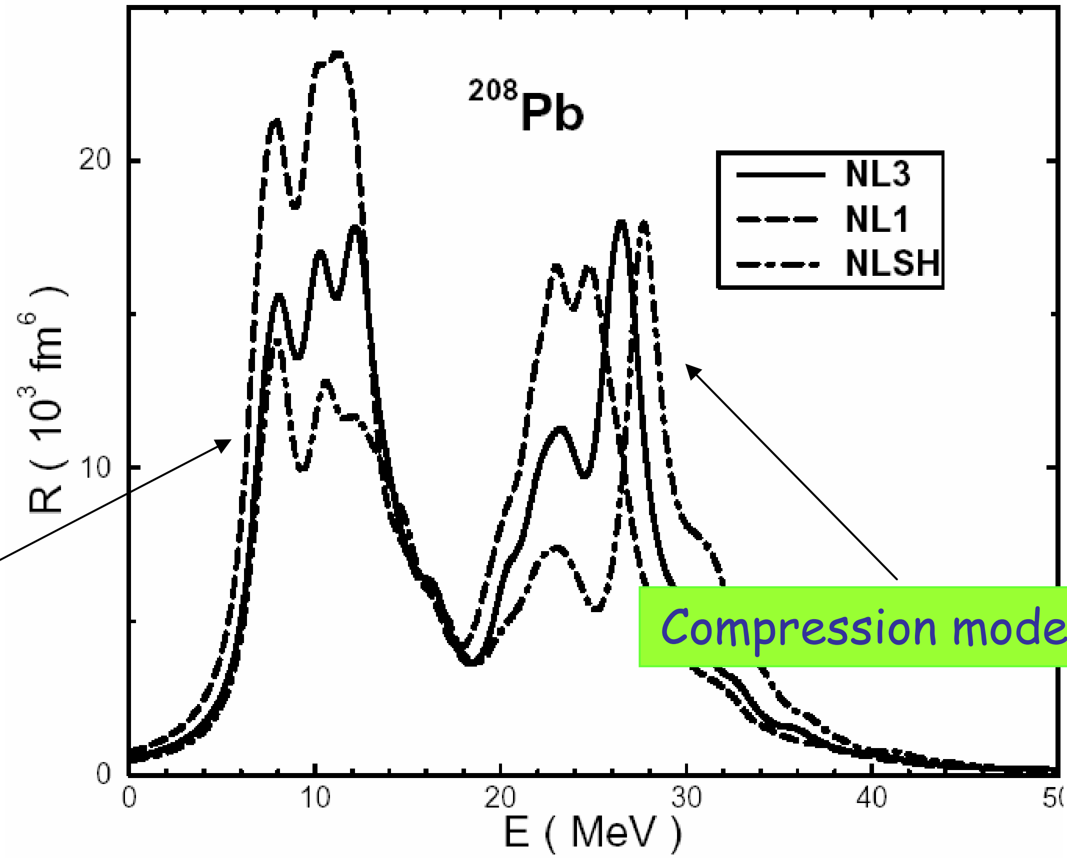
Isoscalar dipole compression - toroidal modes

Isoscalar GMR in spherical nuclei -> nuclear matter compression modulus K_{nm}.

Giant isoscalar dipole oscillations -> additional information on the nuclear incompressibility.

$$\hat{Q}_{1\mu}^{T=0} = \sum_{i=1}^{A} \gamma_0 \left(r^3 - \eta r\right) Y_{1\mu}(\theta_i, \varphi_i)$$

ISGDR strength distributions
Effective interactions
with different K_{nm}.

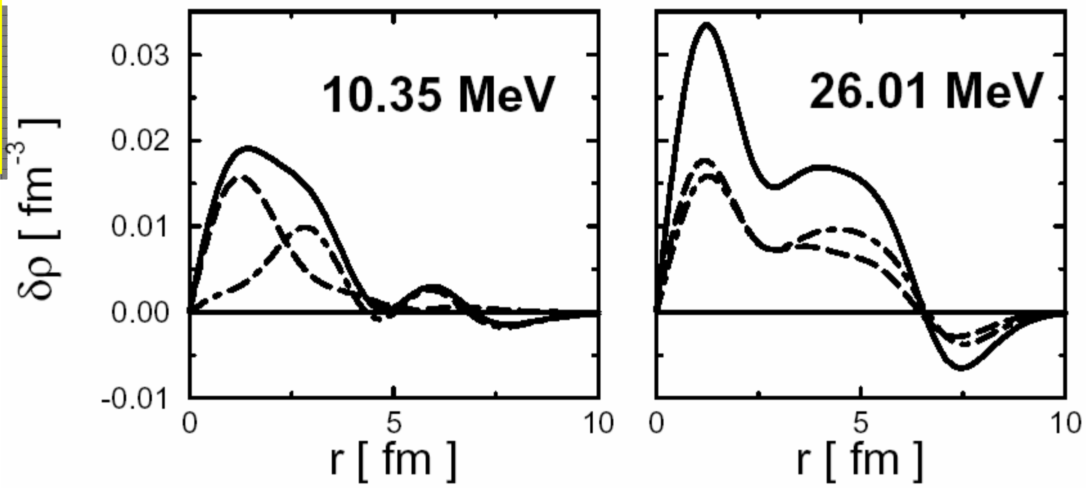


The low-energy strength does not depend on K_{nm} !

Phys. Lett. B487, 334 (2000)

Toroidal motion:

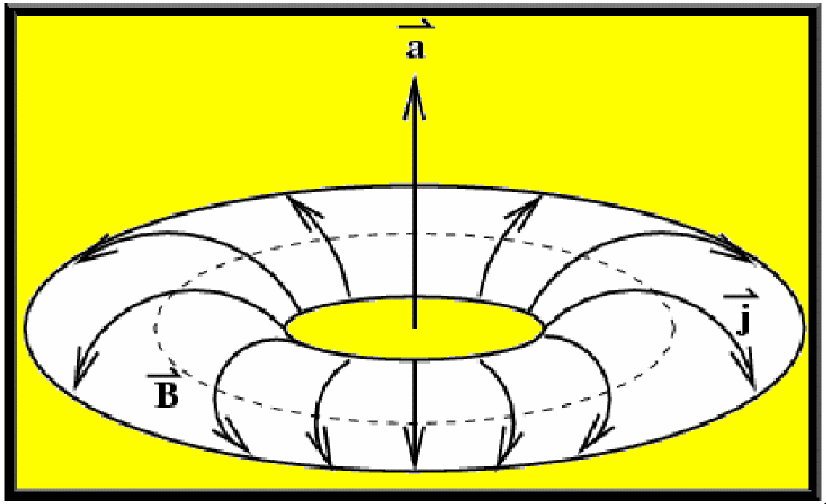
ISGDR transition densities for ^{208}Pb (NL3 interaction)



multipole expansion of a four-current distribution:

- charge moments
- magnetic moments
- electric transverse moments -> toroidal moments

toroidal dipole moment: poloidal currents on a torus



isoscalar toroidal dipole operator:

$$\hat{T}^{T=0}_{1\mu} \sim \int [r^2 \left(\vec{Y}^{*}_{10\mu} + \frac{\sqrt{2}}{5}\vec{Y}^{*}_{12\mu}\right) - < r^2 >_0 \vec{Y}^{*}_{10\mu}] \cdot \vec{J}(\vec{r}) d^3 r$$

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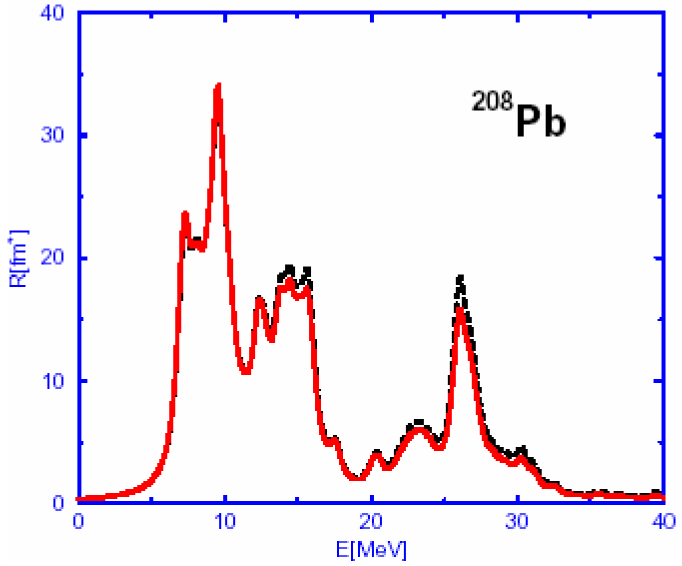
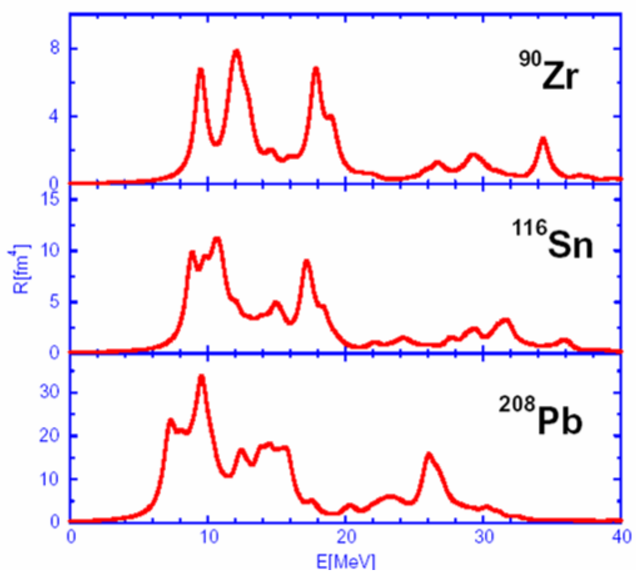
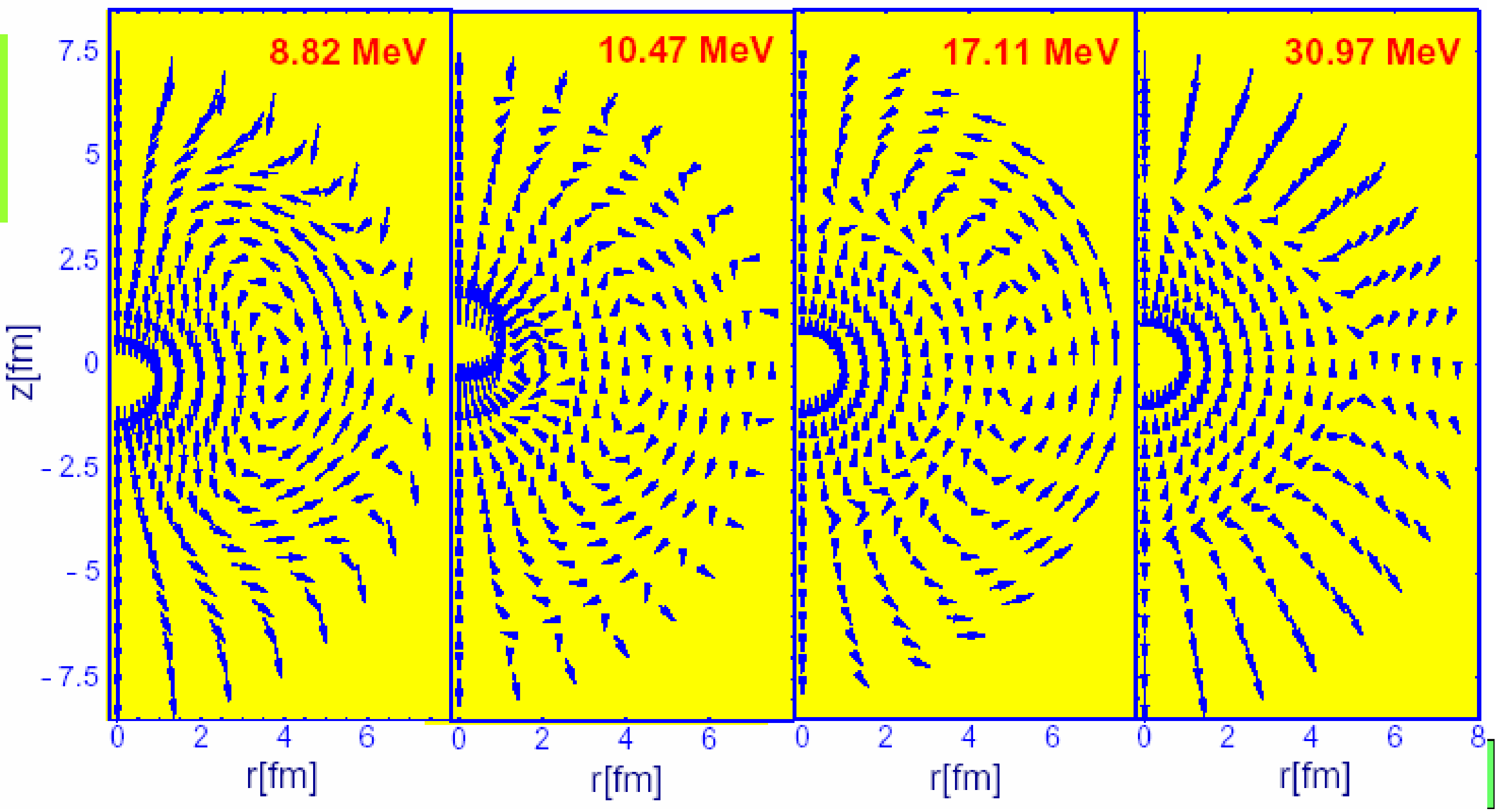
Toroidal dipole strength distributions.

Vretenar, Paar, Niksic, Ring, Phys. Rev. C65, 021301 (2002)





Velocity distributions in ^{116}Sn



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Spin-Isospin Resonances: IAR - GTR

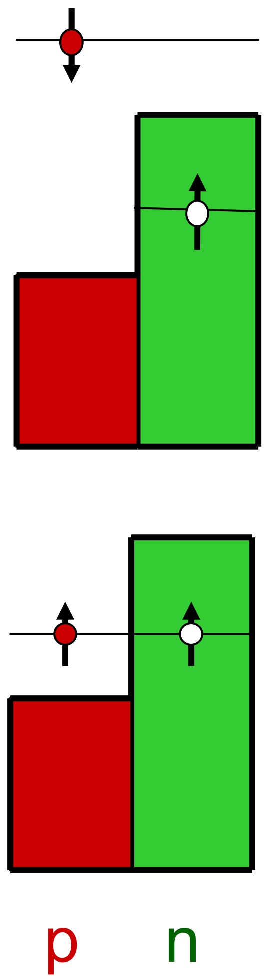
Z,N **Z+1,N-1**

$$|\mathbf{GTR}\rangle = \mathbf{S_- T_-}|\mathbf{Z,N}\rangle$$

spin flip σ

$$|\mathbf{Z,N}\rangle \longrightarrow |\mathbf{IAR}\rangle = \mathbf{T_-}|\mathbf{Z,N}\rangle$$

isospin flip τ



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

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Spin-Isospin Resonances: IAR and GTR

charge-exchange excitations → **proton-neutron relativistic QRPA**

π and ρ-meson exchange generate the spin-isospin dependent interaction terms

$$\mathcal{L}_{\pi N} = -\frac{f_\pi}{m_\pi}\bar{\psi}\gamma_5\gamma_\mu\partial^\mu\vec{\pi}\vec{\tau}\psi$$

the Landau-Migdal zero-range force in the spin-isospin channel

$$V(1,2) = g_0'\left(\frac{f_\pi}{m_\pi}\right)^2 \vec{\tau}_1\cdot\vec{\tau}_2\ \Sigma_1\cdot\Sigma_2\ \delta(\boldsymbol{r}_1-\boldsymbol{r}_2)$$

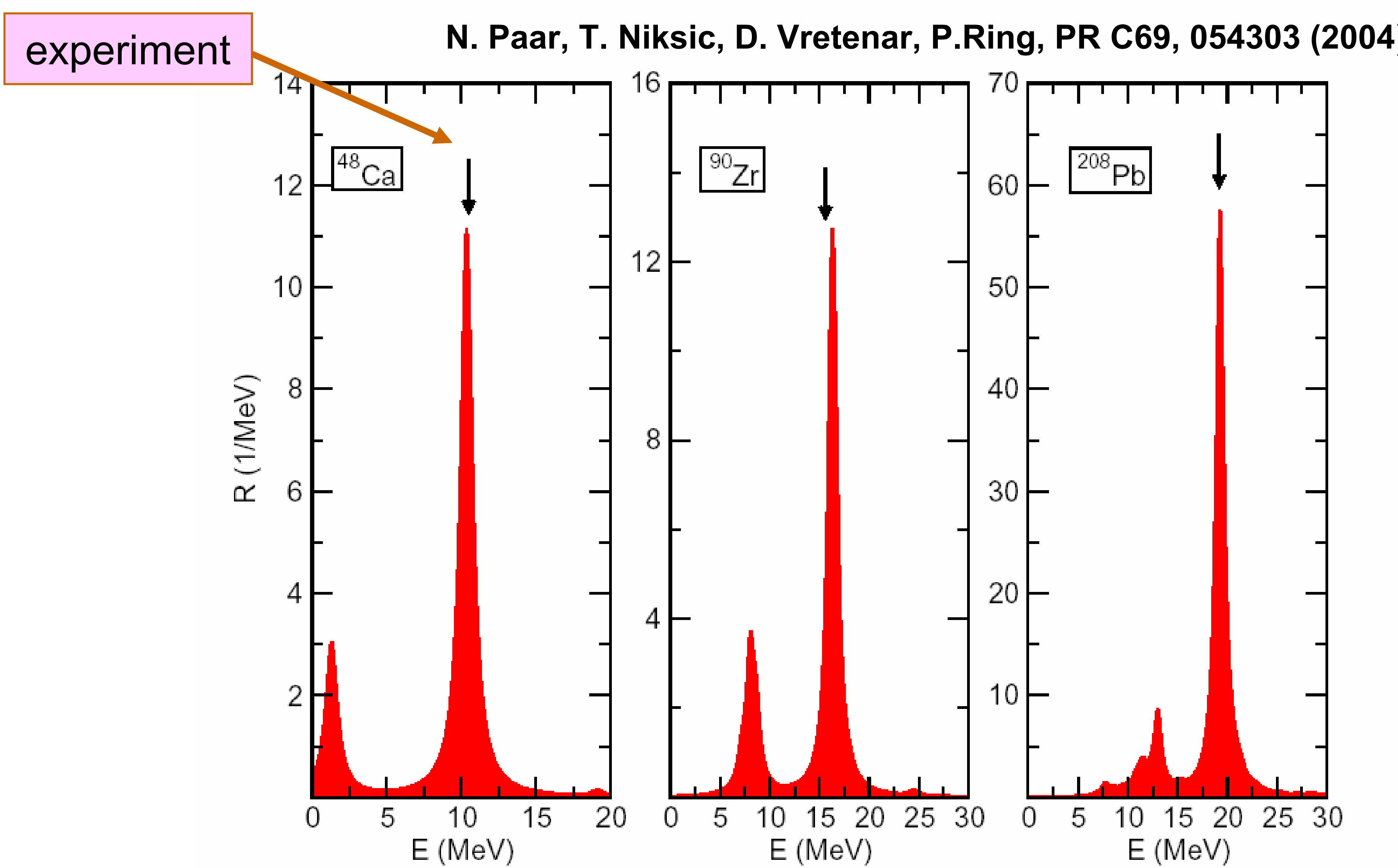
(g'_0=0.55)

GAMOW-TELLER RESONANCE: S=1 T=1 $J^\pi = 1^+$

ISOBARIC ANALOG STATE: S=0 T=1 $J^\pi = 0^+$

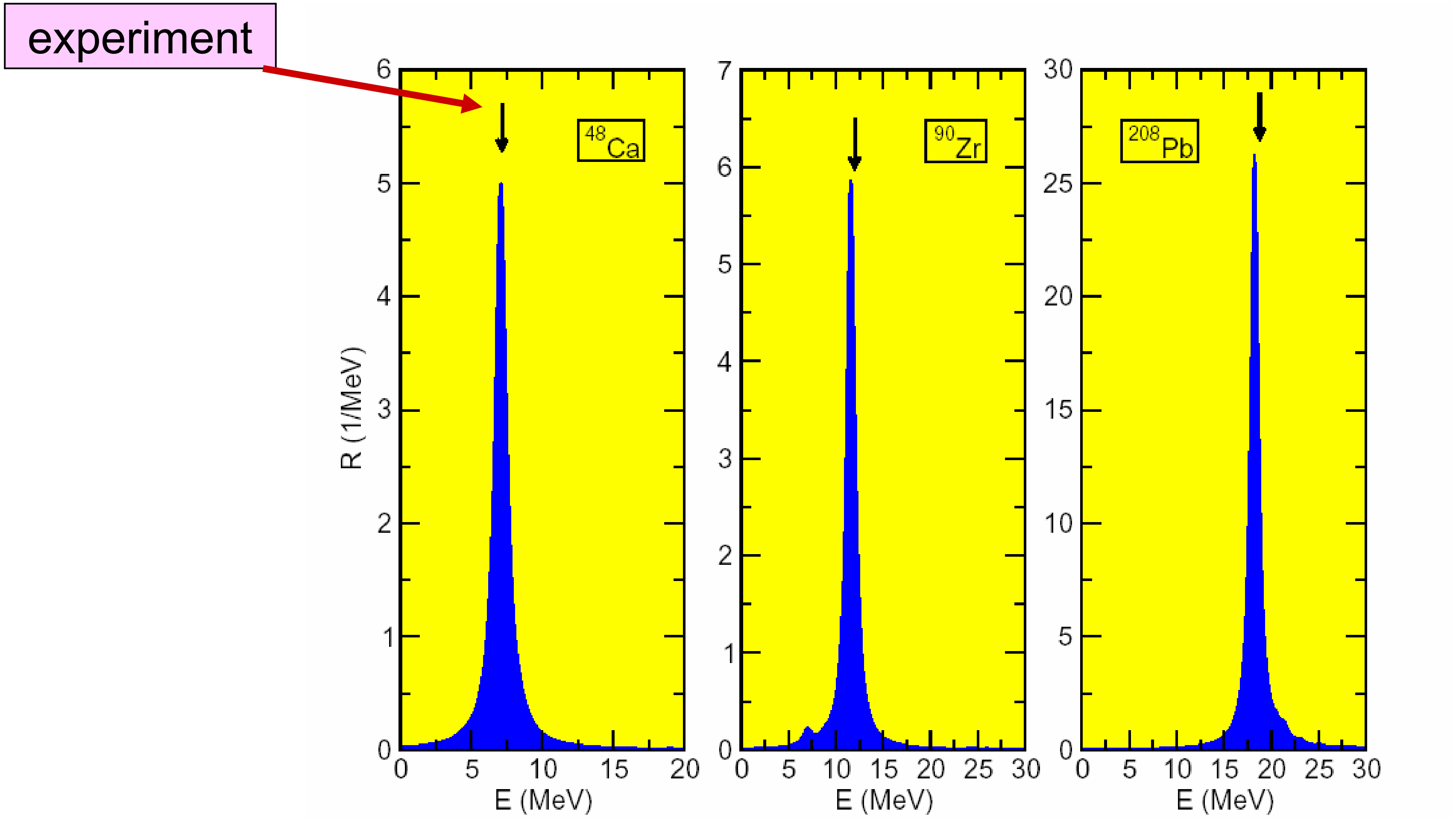
GT-Resonances

N. Paar, T. Niksic, D. Vretenar, P.Ring, PR C69, 054303 (2004)

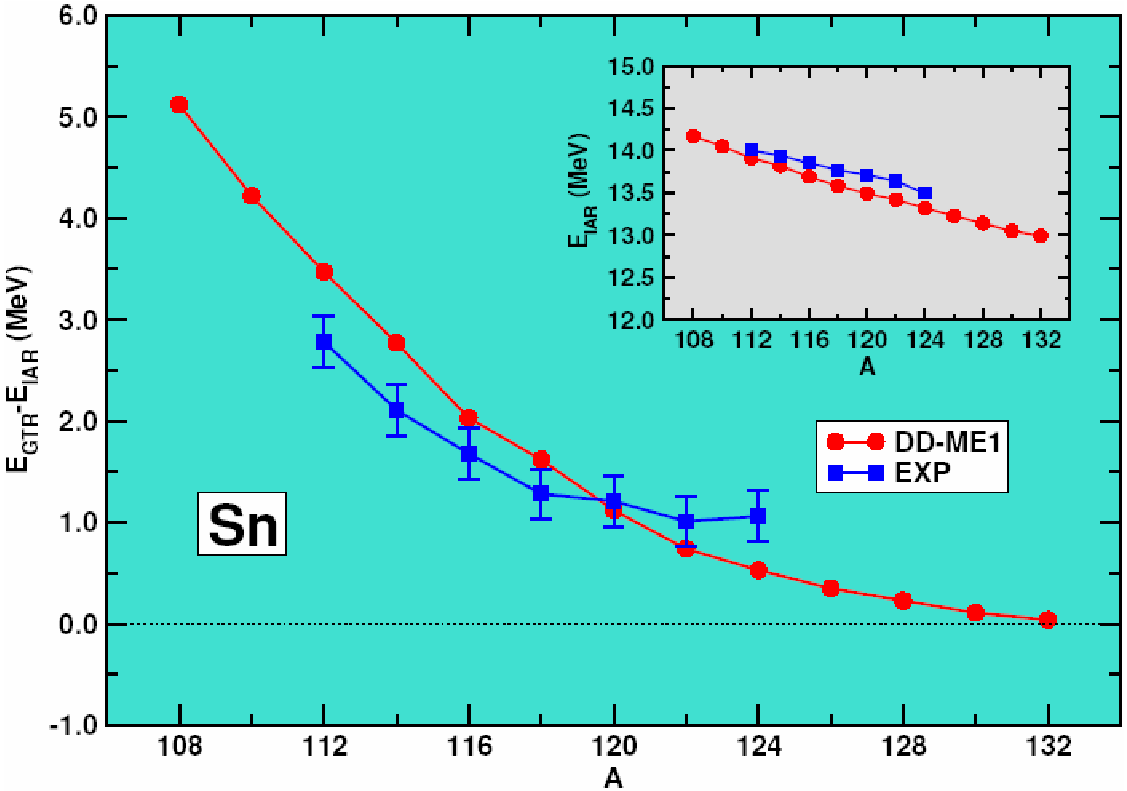


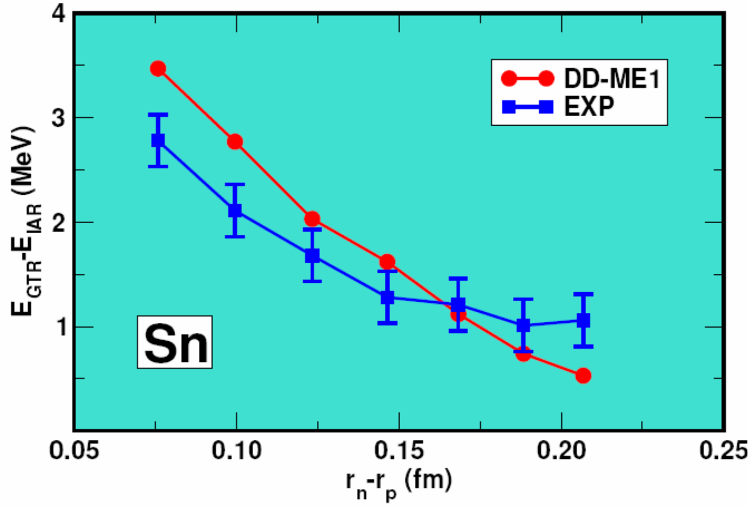
Isobaric Analog Resonance: IAR

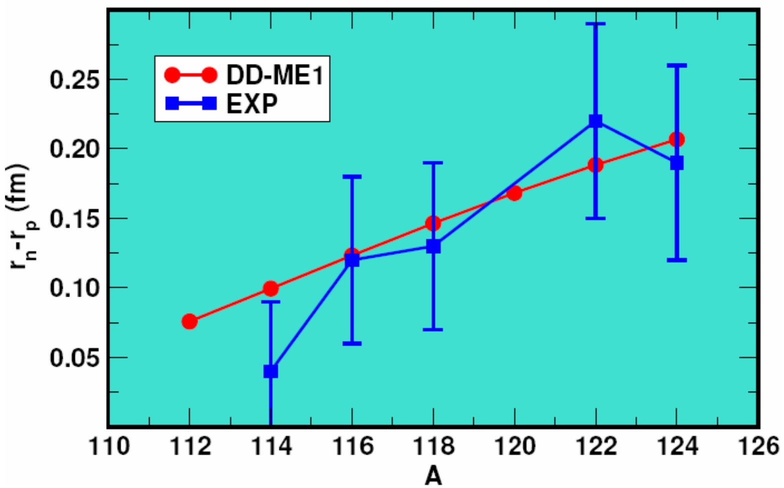
N. Paar, T. Niksic, D. Vretenar, P.Ring, PR C69, 054303 (2004)



Neutron skin and IAR/GRT



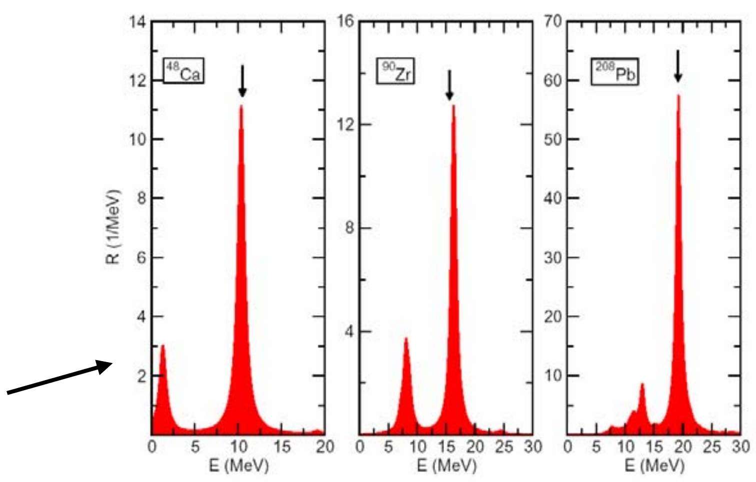




The isotopic dependence of the energy spacings between the GTR and IAS

direct information on the evolution of the neutron skin along the Sn isotopic chain

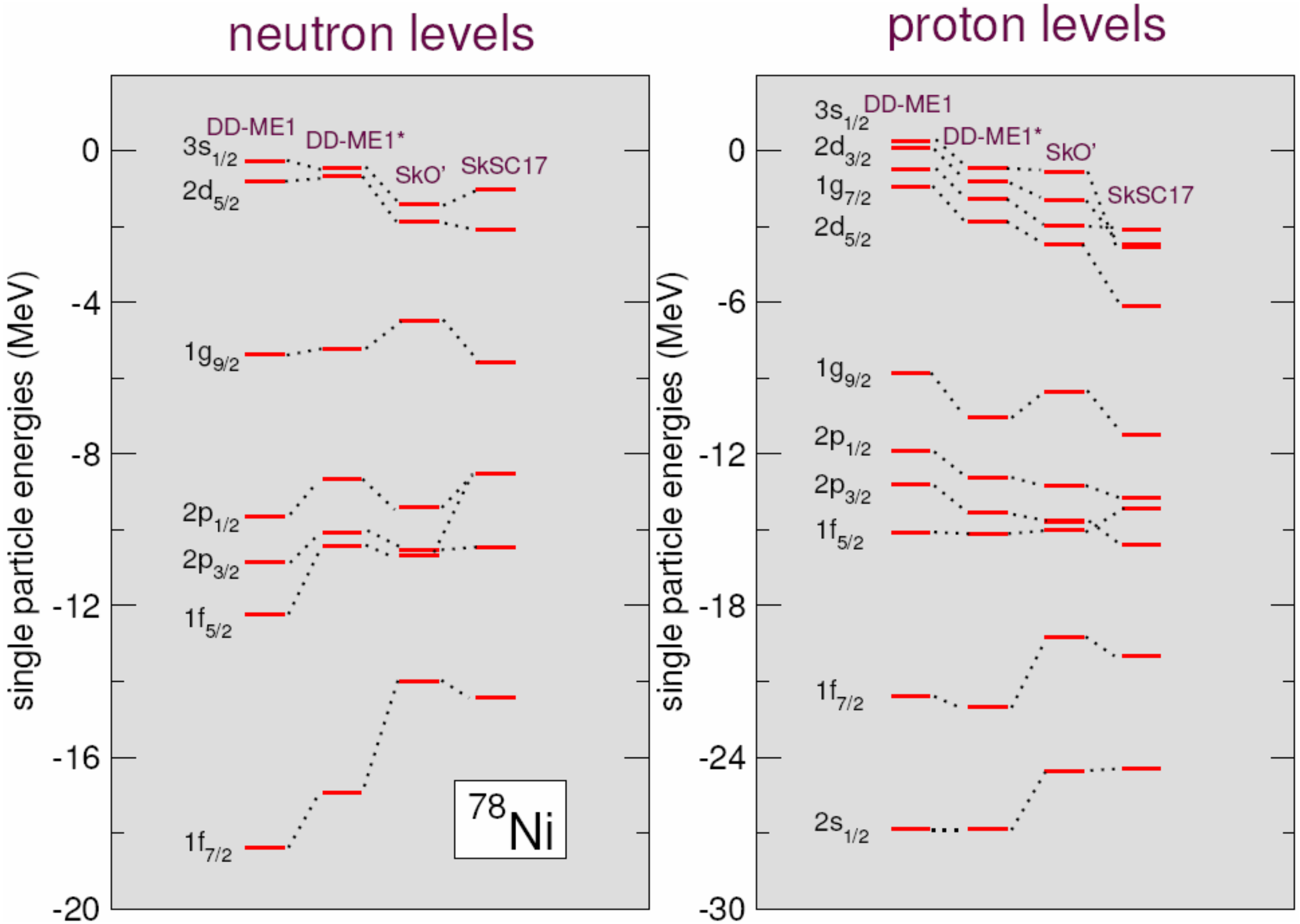
allowed β-decay :



*** Important points:**
- the tail of the GT-strength distribution at low energies
- the position of specific single particle levels (i.e. effective mass)
- effective pairing force in the T=1 and T=0 channel.
- in simple QRPA the lifetimes are too big

*** Possible methods to improve the results:**
- coupling to surface vibrations (difficult and beyond mean field)
- use of a tensor coupling in the ω-channel (one phenom. param.)
- T=0 pairing force with Gaussian character (one phen. parameter)

enhanced value of the effective mass → increased density of states around the Fermi surface



T. Niksic et al, PRC 71, 014308 (2005)

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The nucleon effective mass m*:

m^* represents a measure of the density of states around the Fermi surface

nonrelativistic mean-field models

effective mass: $m^*/m = 0.8 \pm 0.1$

relativistic mean-field models

→ Dirac mass: $m_D = m + S(r)$

→ effective mass: $m^* = m - V(r)$

conventional RMF models

spin-orbit splittings + nuclear matter binding

⇨

$0.55m \leq m_D \leq 0.60m$

$0.64m \leq m^* \leq 0.67m$

small density of states -> overestimated β-decay lifetimes

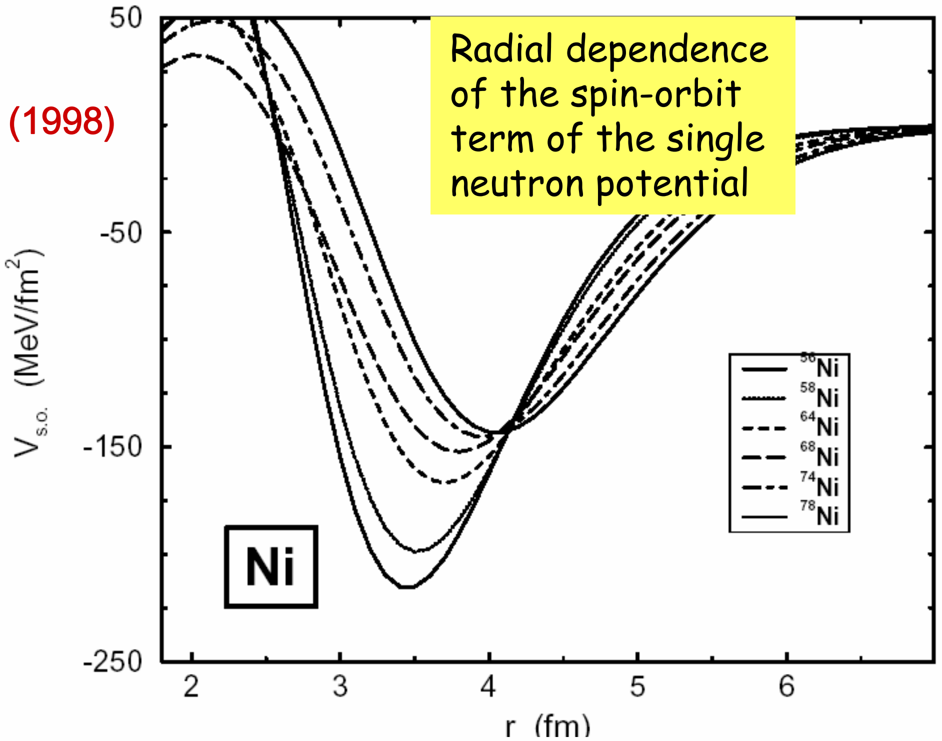
Reduction of the spin-orbit in neutron-rich nuclei

Lalazissis, Vretenar, Poeschl, Ring, Phys. Lett. B418, 7 (1998)

The spin-orbit potential originates from the addition of two large fields: the field of the vector mesons (short range repulsion), and the scalar field of the sigma meson (intermediate attraction).

$$V_{s.o.} \approx \frac{1}{r}\frac{\partial}{\partial r}V_{ls}(r)$$

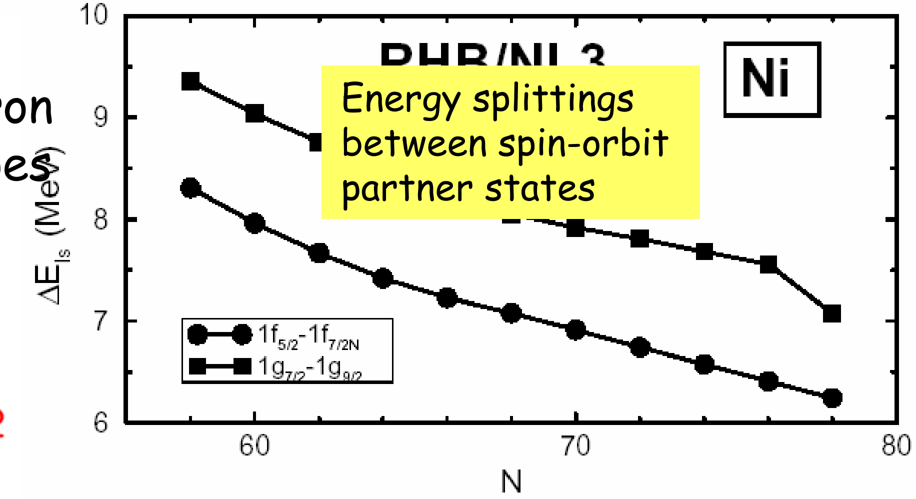
$$V_{ls} = \frac{m}{m_{eff}}(V - S)$$



weakening of the effective single-neutron spin-orbit potential in neutron-rich isotopes

reduced energy spacings between spin-orbit partners

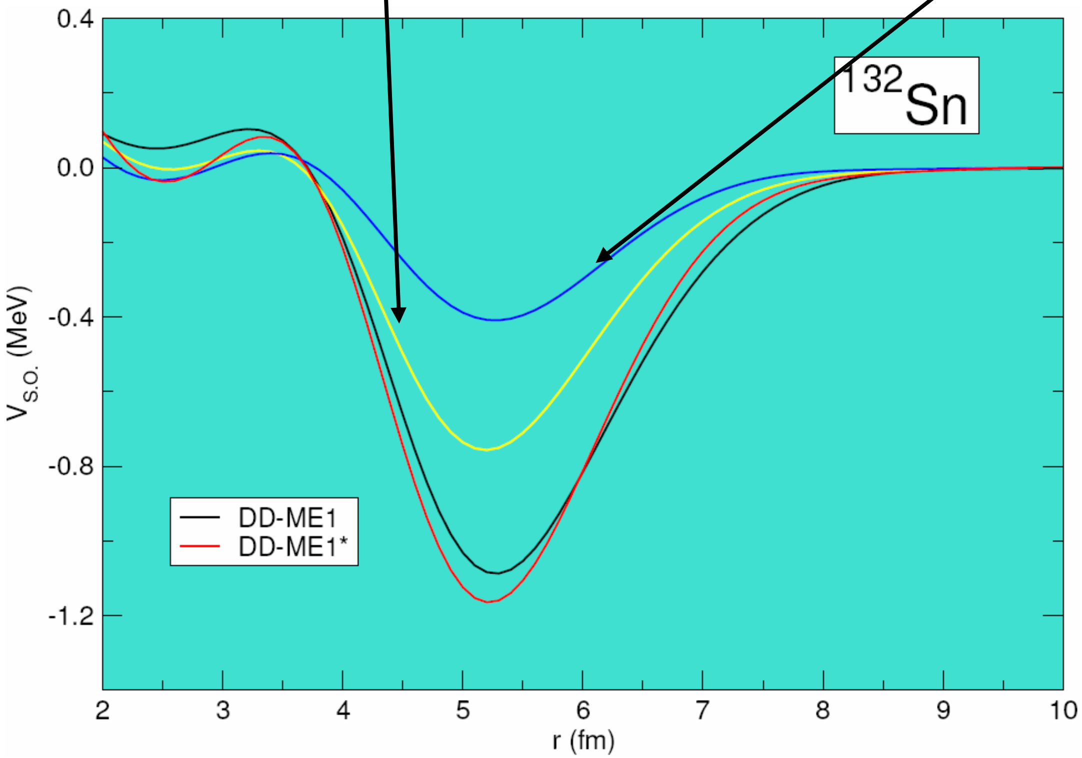
$$\Delta E_{ls} = E_{n,l,j=l-1/2} - E_{n,l,j=l+1/2}$$



tensor omega-nucleon coupling
enhances the spin-orbit interaction

⇒ scalar and vector self-energies can be reduced

$$V_{so} = \left[\frac{1}{4\bar{M}^2}\frac{1}{r}\frac{d}{dr}(V-S) + \frac{f_V}{2M\bar{M}}\frac{1}{r}\frac{d\omega}{dr}\right]\mathbf{l}\cdot\mathbf{s}$$



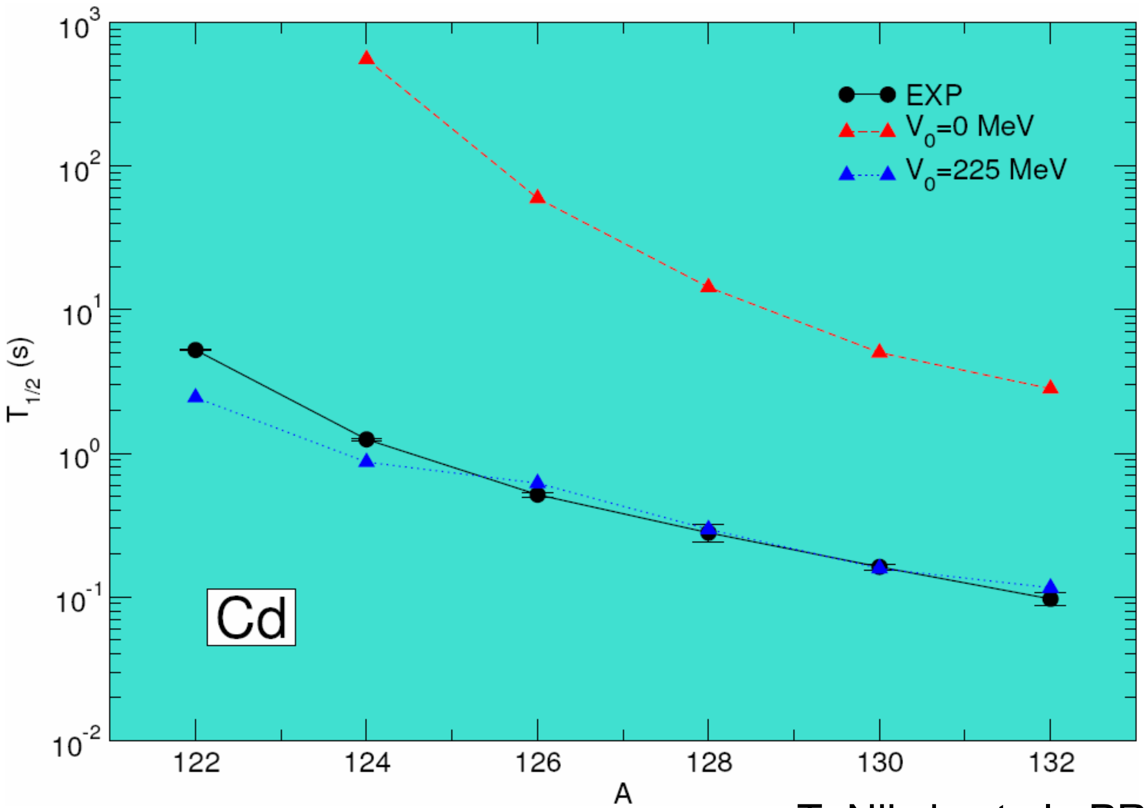
	DD-ME1	DD-ME1*
m_D/m	0.58	0.67
m^*/m	0.66	0.76

T. Niksic et al, PRC 71, 014308 (2005)

N≈82 region:

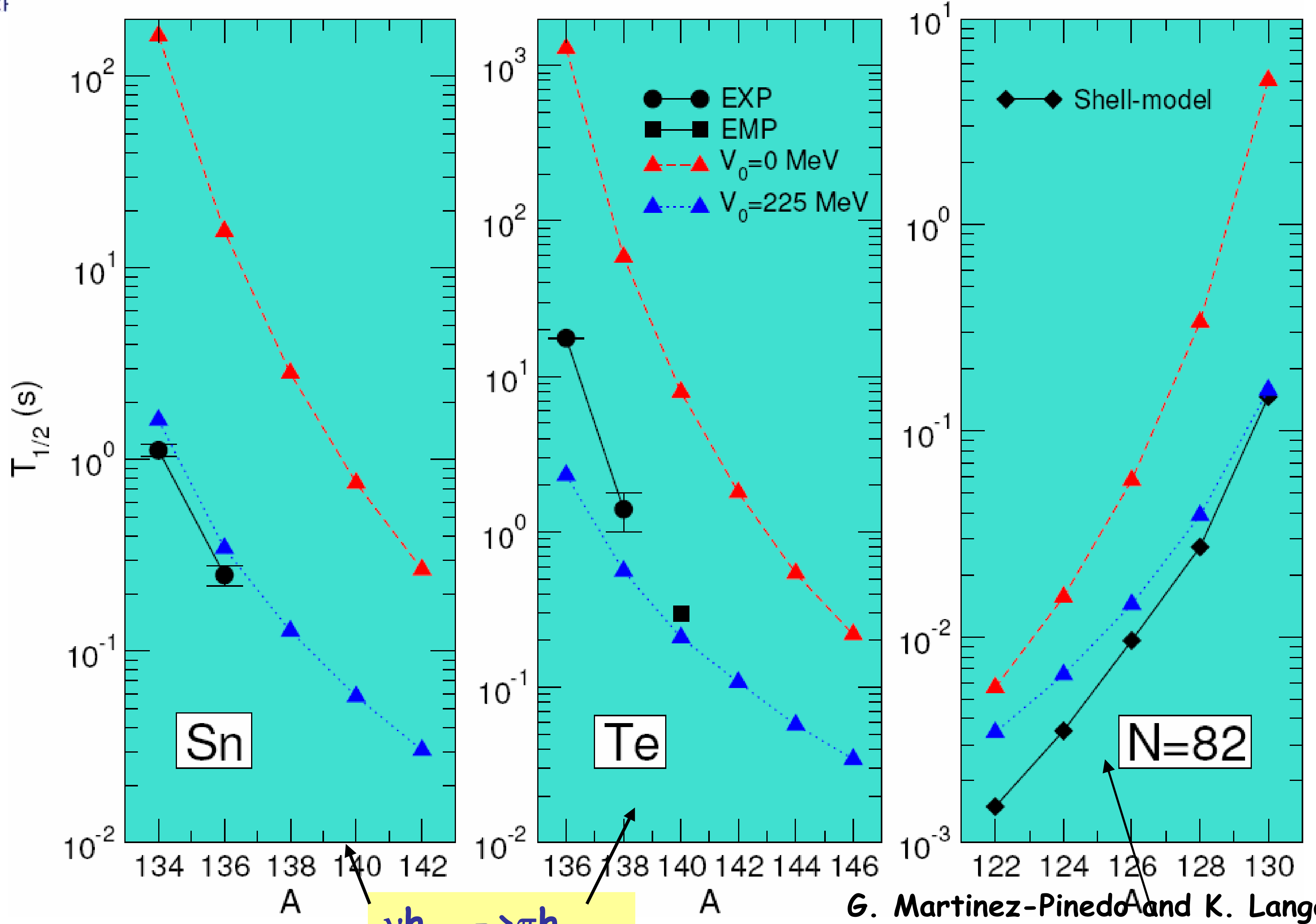
Cadmium isotopes: π1g9/2 level is partially empty

⇨ T=0 pairing has large influence on the ν1g7/2->π1g9/2 transition which dominates the β-decay process



T. Niksic et al, PRC 71, 014308 (2005)

An increase of the T=0 pairing partially compenstates for the fact that the density of states is still rather low Niksic et al, PRC 71, 014308 ('05)



$\nu h_{9/2} \to \pi h_{11/2}$

G. Martinez-Pinedo and K. Langanke, PRL 83, 4502 (1999)

Correlations beyond mean field

- Conservation of symmetries by projection before variation
- Motion with large amplitude by Generator Coordinates
- Coupling to collective vibrations
  - shifts of single particle energies
  - decay width of giant resonances

Projected Density Functionals

$$\left|\Psi^N\right\rangle = \hat{P}^N\left|\Phi\right\rangle = \delta\left(\hat{N} - N\right)\left|\Phi\right\rangle = \int \frac{d\varphi}{2\pi} e^{i\varphi\left(\hat{N}-N\right)}\left|\Phi\right\rangle$$

projected denstiy functional:

$$E^N[\hat{\rho}, \hat{\kappa}] = \frac{\left\langle\Phi\left|\hat{H}\hat{P}^N\right|\Phi\right\rangle}{\left\langle\Phi\left|\hat{P}^N\right|\Phi\right\rangle}$$

analytic expressions

projected HFB-equations (variation after projection):

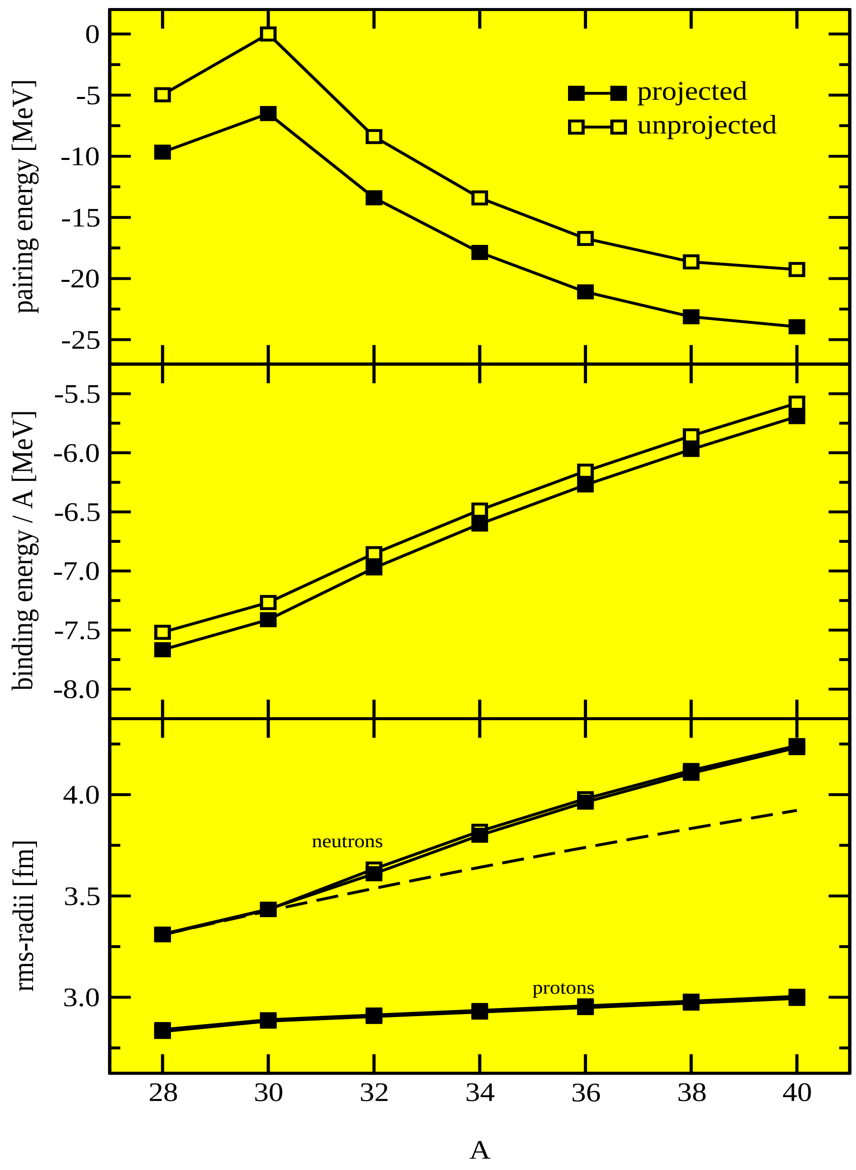
$$\begin{pmatrix} \hat{h}^N & \hat{\Delta}^N \\ -\Delta^{N*} & -\hat{h}^{N*} \end{pmatrix}\begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} = \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} E_k$$

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

$$\hat{\Delta}^N = \frac{\delta E^N}{\delta\hat{\kappa}}$$

J.Sheikh and P. Ring NPA 665 (2000) 71

Ne-isotopes



airing energies

inding energies

rms-radii

L. Lopes, PhD Thesis, TUM, 2002

Generator Coordinate Method (GCM)

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

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

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

GCM wave function is a superposition of Slaterdeterminants

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

Hill-Wheeler equation:

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

with projection:

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

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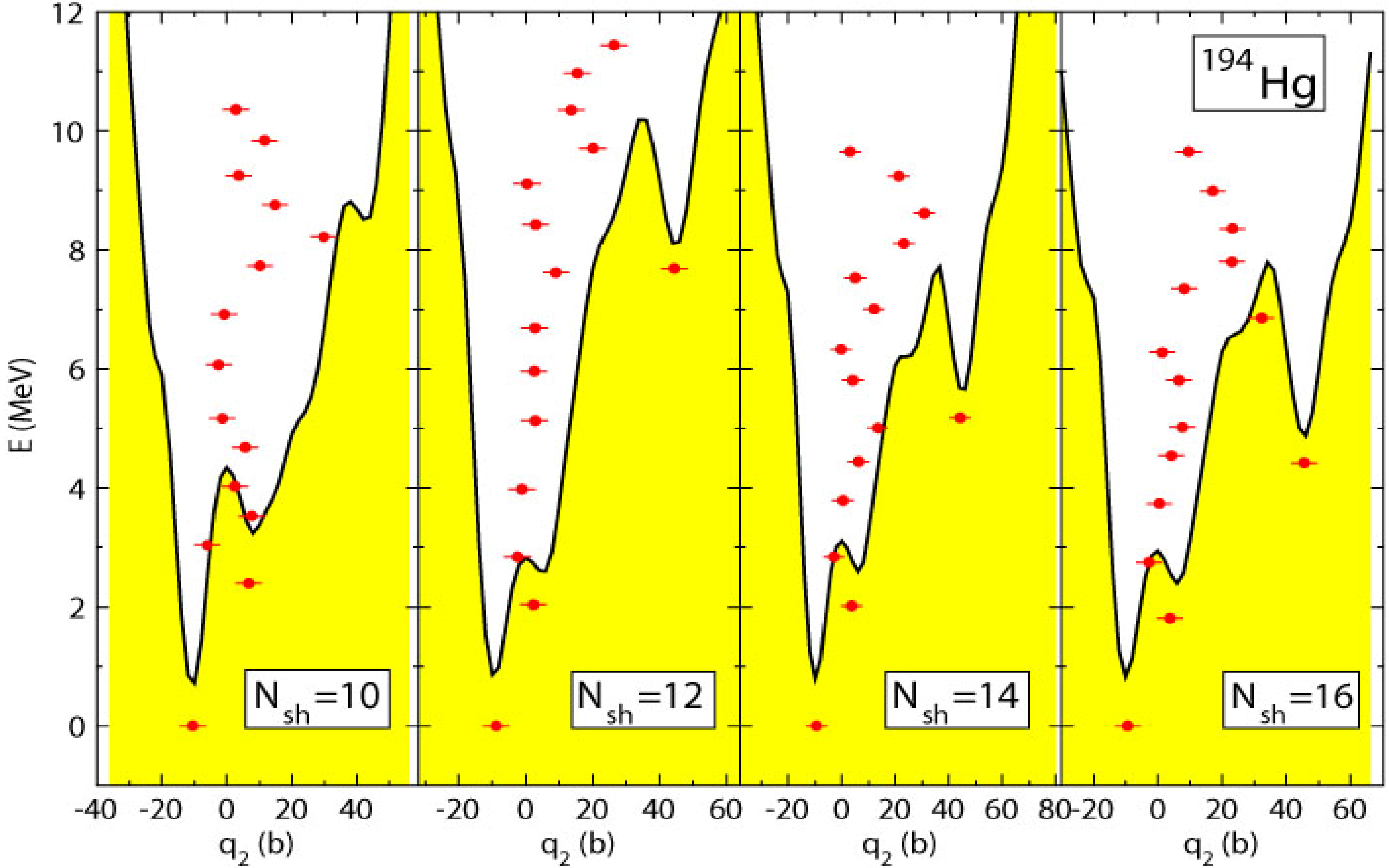
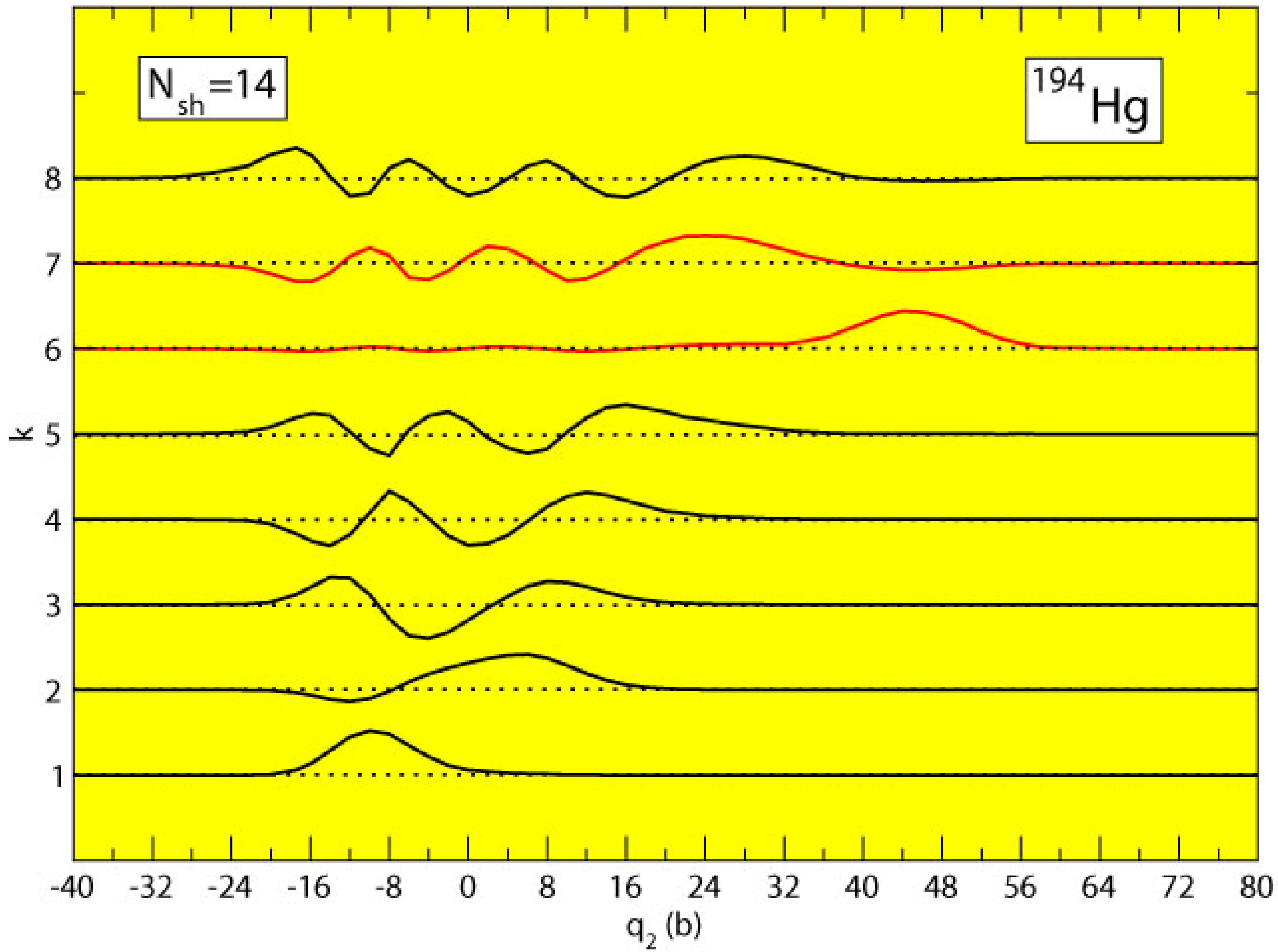
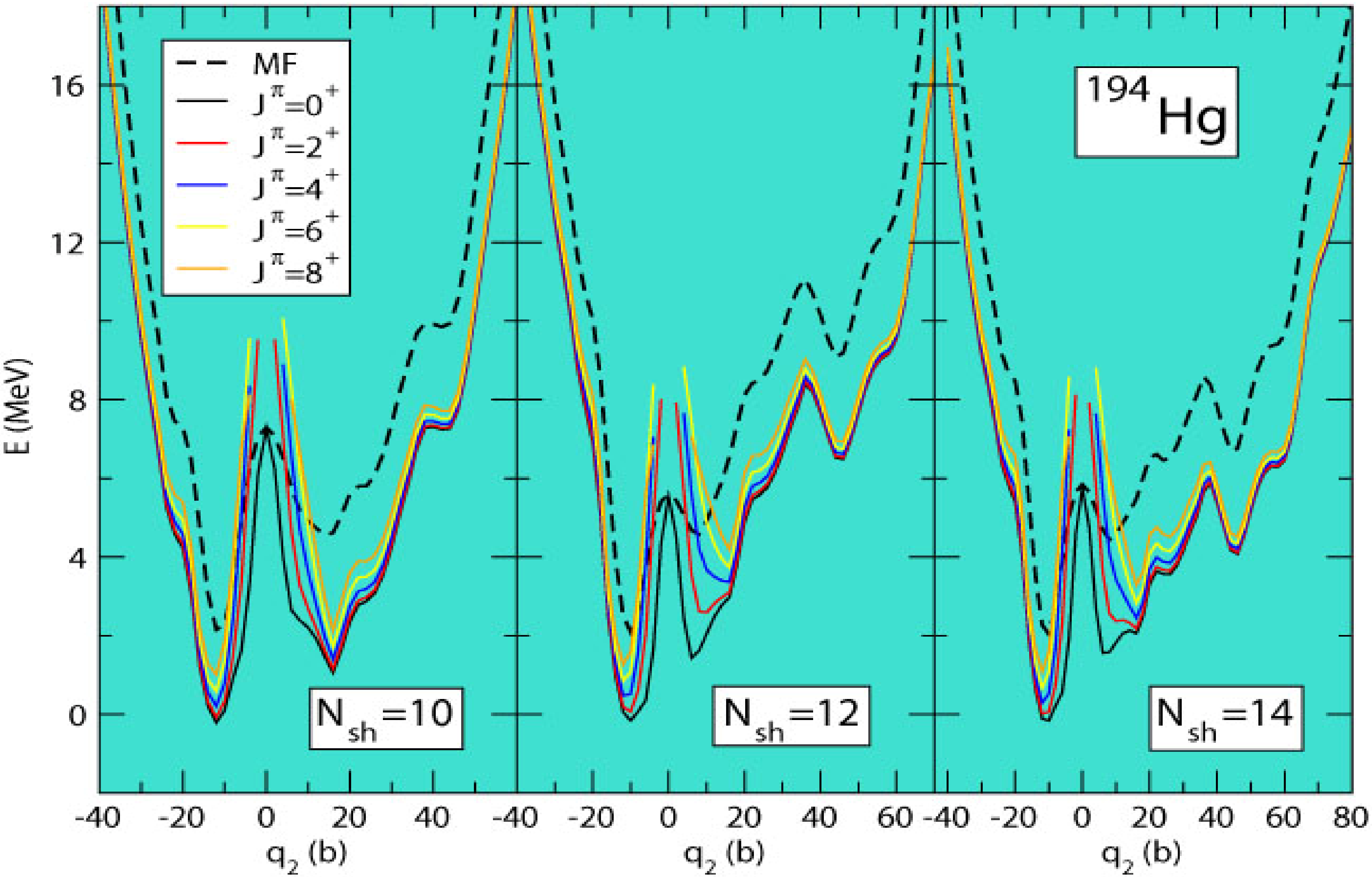
GCM without projection:



GCM-wave functions of the lowest states



Ang. momentum projected energy surfaces:

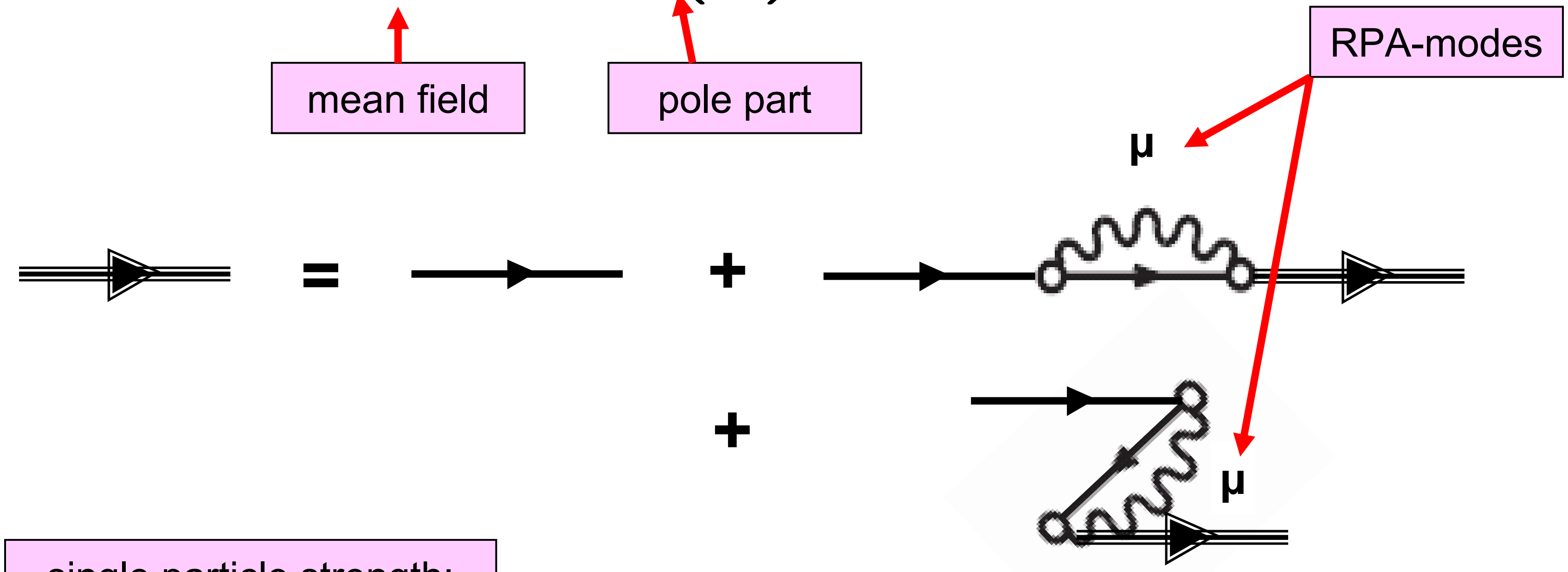


Vibrational Couplings:
energy dependent self-energy:

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

mean field

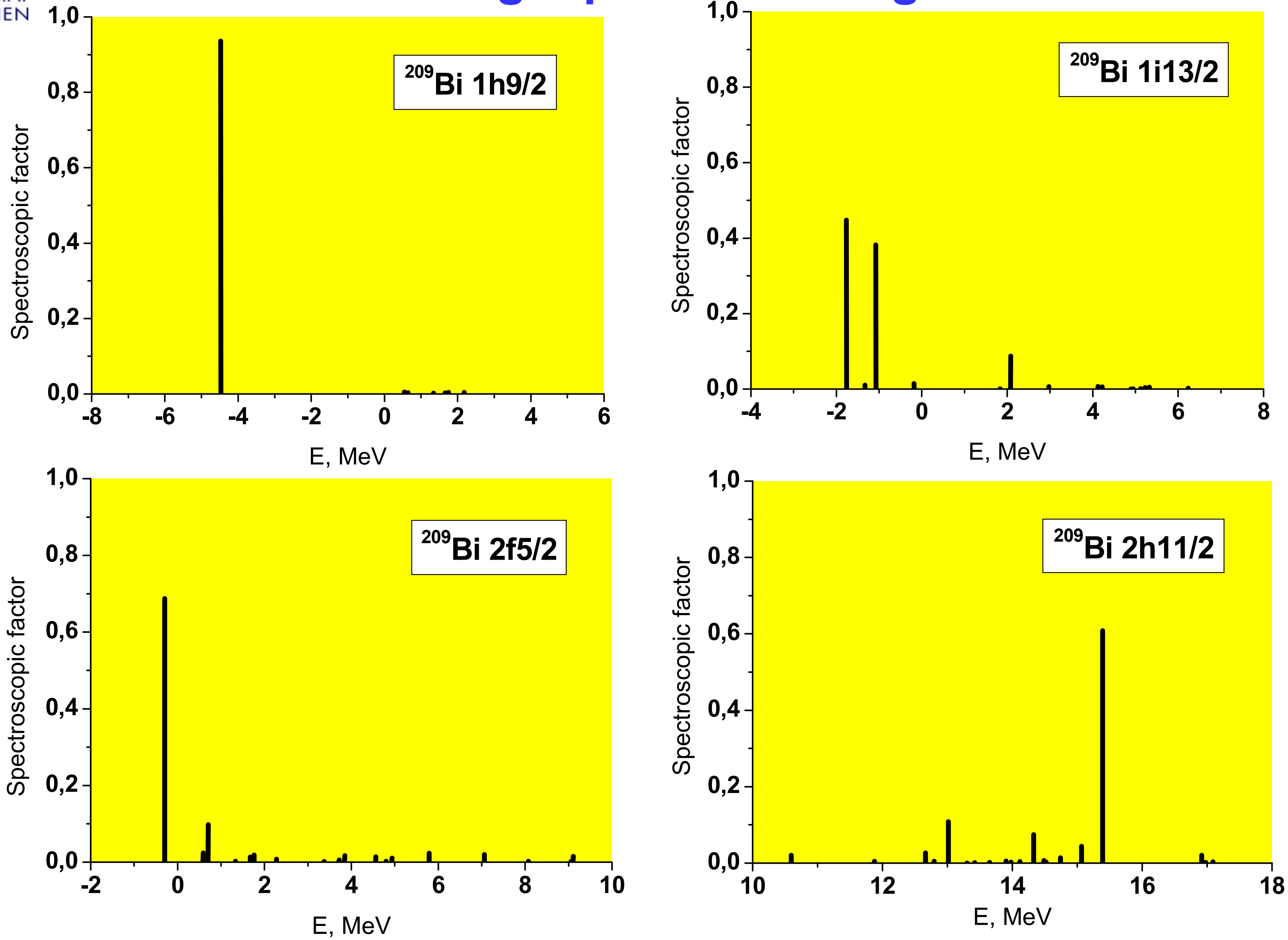
pole part

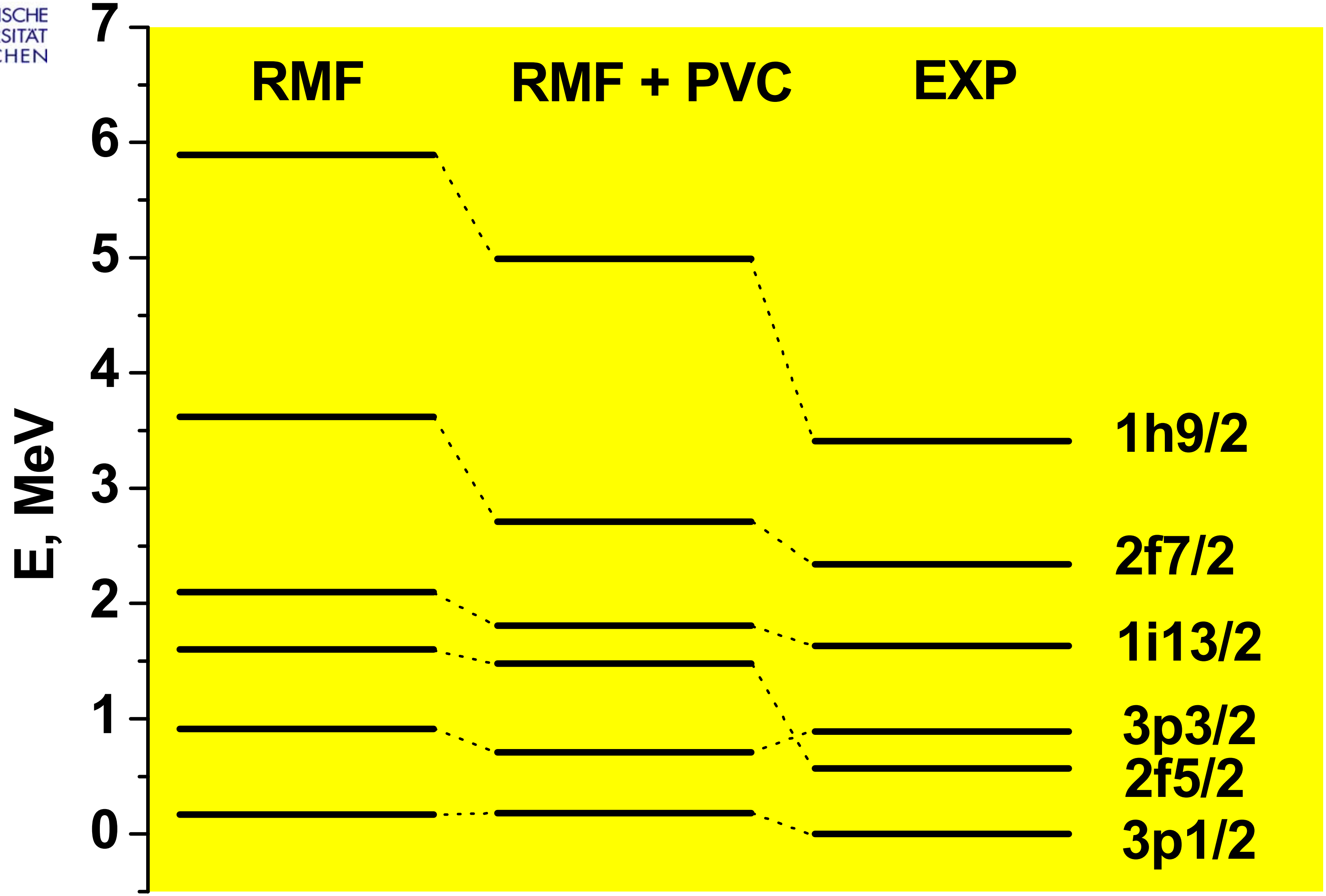


single particle strength:

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

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





Level scheme for ^{207}Pb

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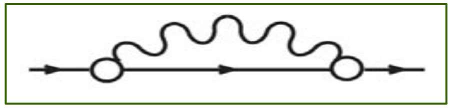
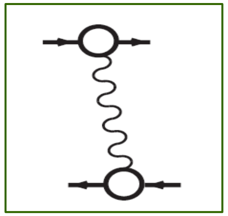
Contributions of complex cofigurations

The full response contains energy dependent parts coming from vibrational couplings.

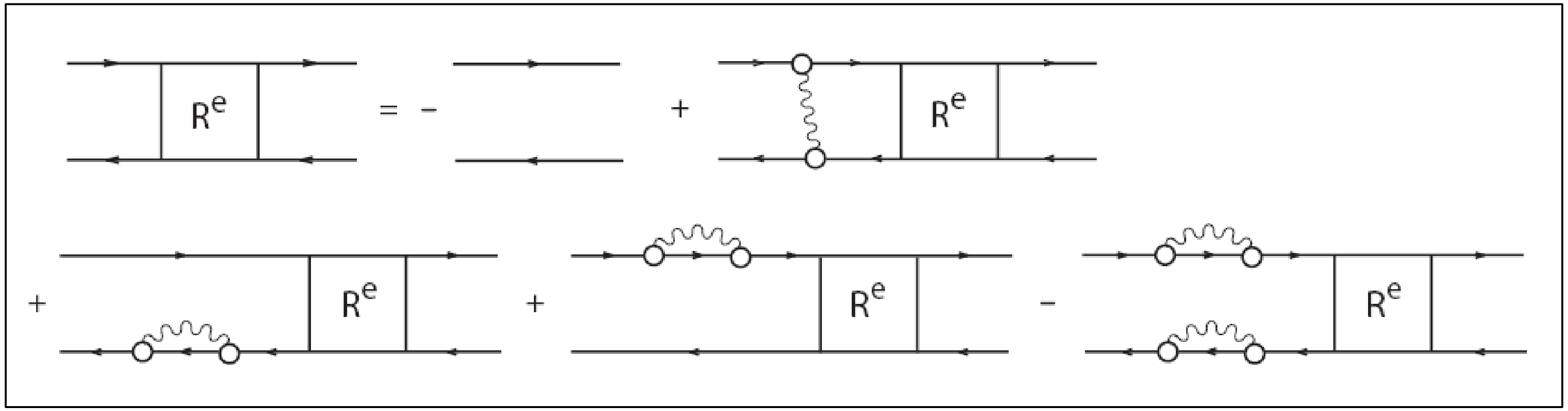


Self energy

g – phonon amplitudes (QRPA)



ph interaction amplitude

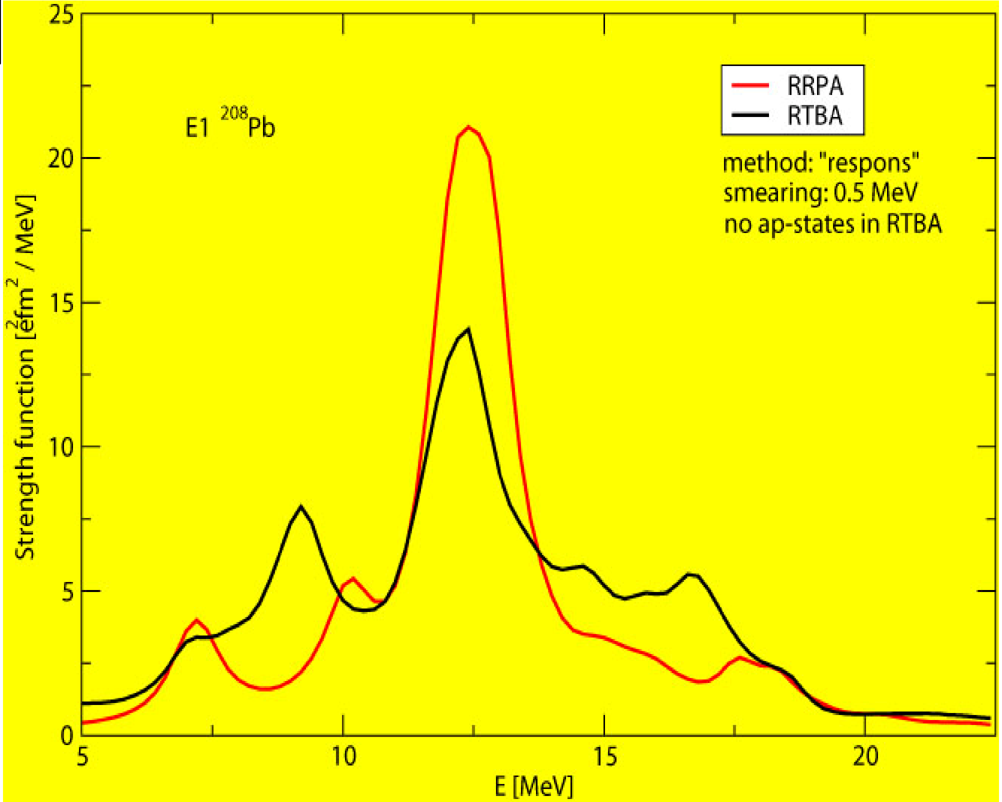


Decay-width of the Giant Resonances

$$S(E) = -\frac{1}{\pi} \operatorname{Im} \Pi(E + i\,\Delta)$$

E1 photoabsorption cross section

$$\sigma_{\mathrm{E1}}(E) = \frac{16\pi^3 e^2}{9\hbar c} E\, S_{\mathrm{E1}}(E)$$



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Conclusions

On the way to a universal covariant density functional adjustet to ground state properties of finite nuclei.

≈7 parameters necessary for high precision

Time-dependent mean field theory provides a parameter-free theory for excited states

- rotational spectra (cranked RHB-theory)
- vibrational excitations (rel. QRPA)

Method beyond mean field:

- Projected funcionals (PDFT)
- Generator Coordinate Method (GCM)
- Particle-Vibrational Coupling (PVC)

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Open Problems:

Fock terms and tensor forces:
- **why is the first order pion-exchange quenched?**

Vacuum polarization:
- **renormalization in finite systems**

Simpler parametrizations:
- **point coupling**
- **simple pairing**

Do we have to change the functional,
if we go beyond mean field?

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