Covariant Density Functional Theory for isospin properties in nuclei far from stability

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in collaboration with:

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Content

- **Density-dependent meson-couplings**

  * Properties of **asymmetric nuclear matter**
  * Grundstate propterties of **finite nuclei**
  * New a-chain in **superheavy elements with Z=115**
  * **Relativistic QRPA** for excited states
    - giant resonances **GMR** and **GDR**
    - spin-Isospin modes: **IAR, GTR**
    - pygmy modes
    - torroidal modes

- **Conclusions**

Density functional theory

$$E = \left\langle \Psi \middle| \hat{H} \middle| \Psi \right\rangle = \left\langle \Phi \middle| \hat{H}_{eff} \middle| \Phi \right\rangle = E[\hat{\rho}]$$

$|\Phi\rangle$ **Slater determinant** $\Leftrightarrow$ $\hat{\rho}$ **density matrix**

$$|\Phi\rangle = \mathcal{A}(\varphi_1(\mathbf{r}_1)\cdots\varphi_A(\mathbf{r}_A)) \qquad \hat{\rho}(\mathbf{r},\mathbf{r}') = \sum_{i=1}^{A} |\varphi_i(\mathbf{r})\rangle\langle\varphi_i(\mathbf{r}')|$$

Mean field:

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

Eigenfunctions:

$$\hat{h}|\varphi_i\rangle = \varepsilon_i|\varphi_i\rangle$$

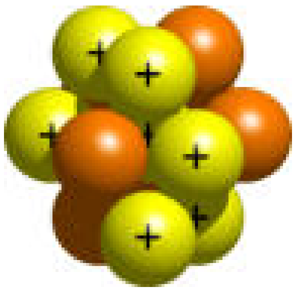
Interaction:

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

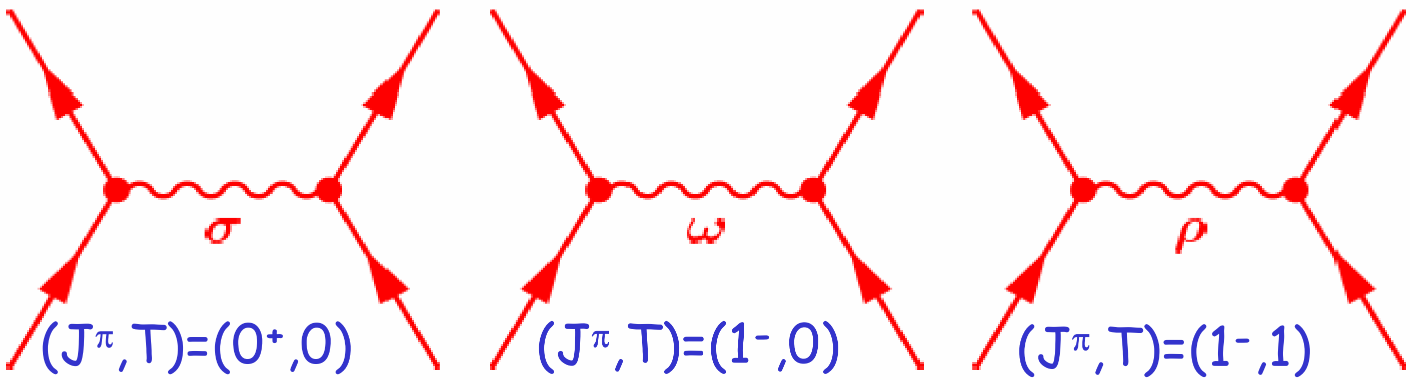
Extensions: Covariance, Pairing correlations
Relativistic Hartree Bogoliubov (RHB)

Covariant density functional theory

NL3/D1S



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



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

Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive

Rho-meson: isovector field

Effective density dependence:

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)

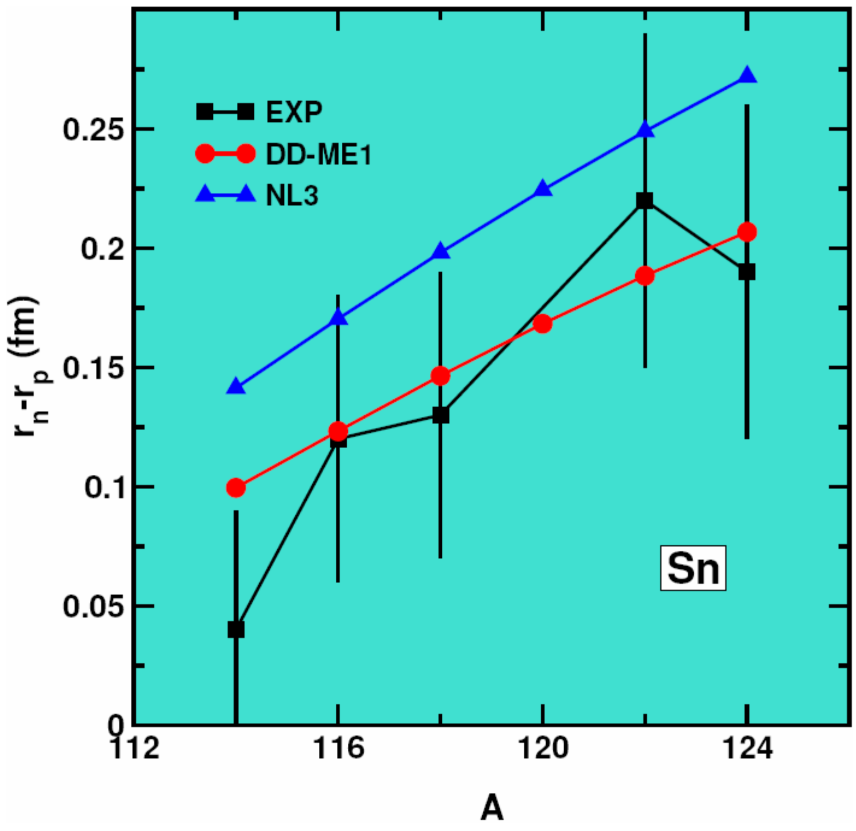
$$g_\sigma, g_\omega, g_\rho \Rightarrow g_\sigma(\rho), g_\omega(\rho), g_\rho(\rho)$$

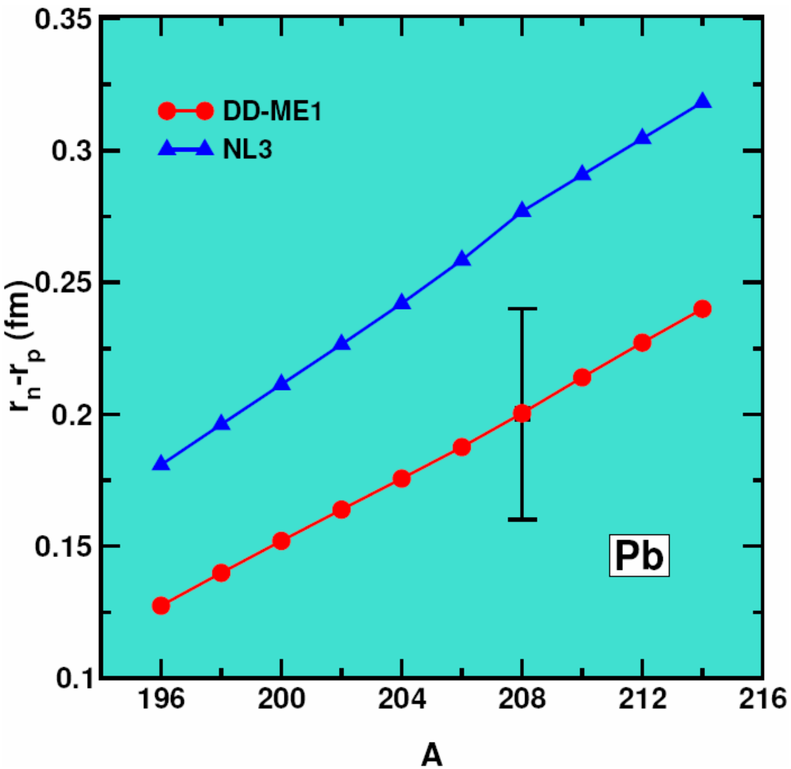
$\mathbf{g} \rightarrow \mathbf{g}(\rho(r))$

DD-ME1,DD-ME2

Why again an new parameterization ?

standard RMF interactions overestimate the neutron skins





Parameterization of denstiy dependence

MICROSCOPIC: Dirac-Brueckner calculations

PHENOMENOLOGICAL:

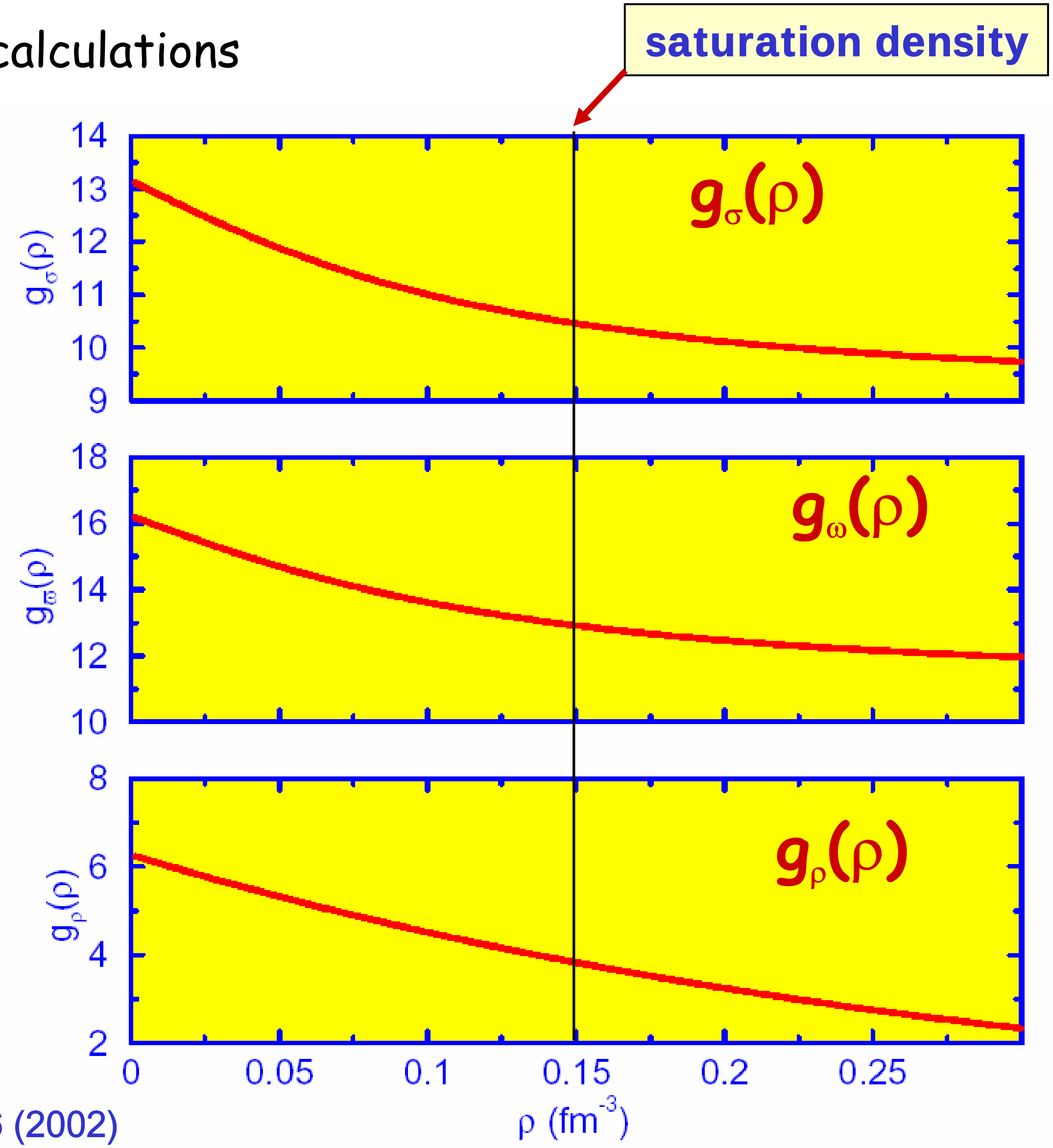
$$g_i(\rho) = g_i(\rho_{\text{sat}}) f_i(x)$$

$$f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}$$

$$i = \sigma, \omega$$

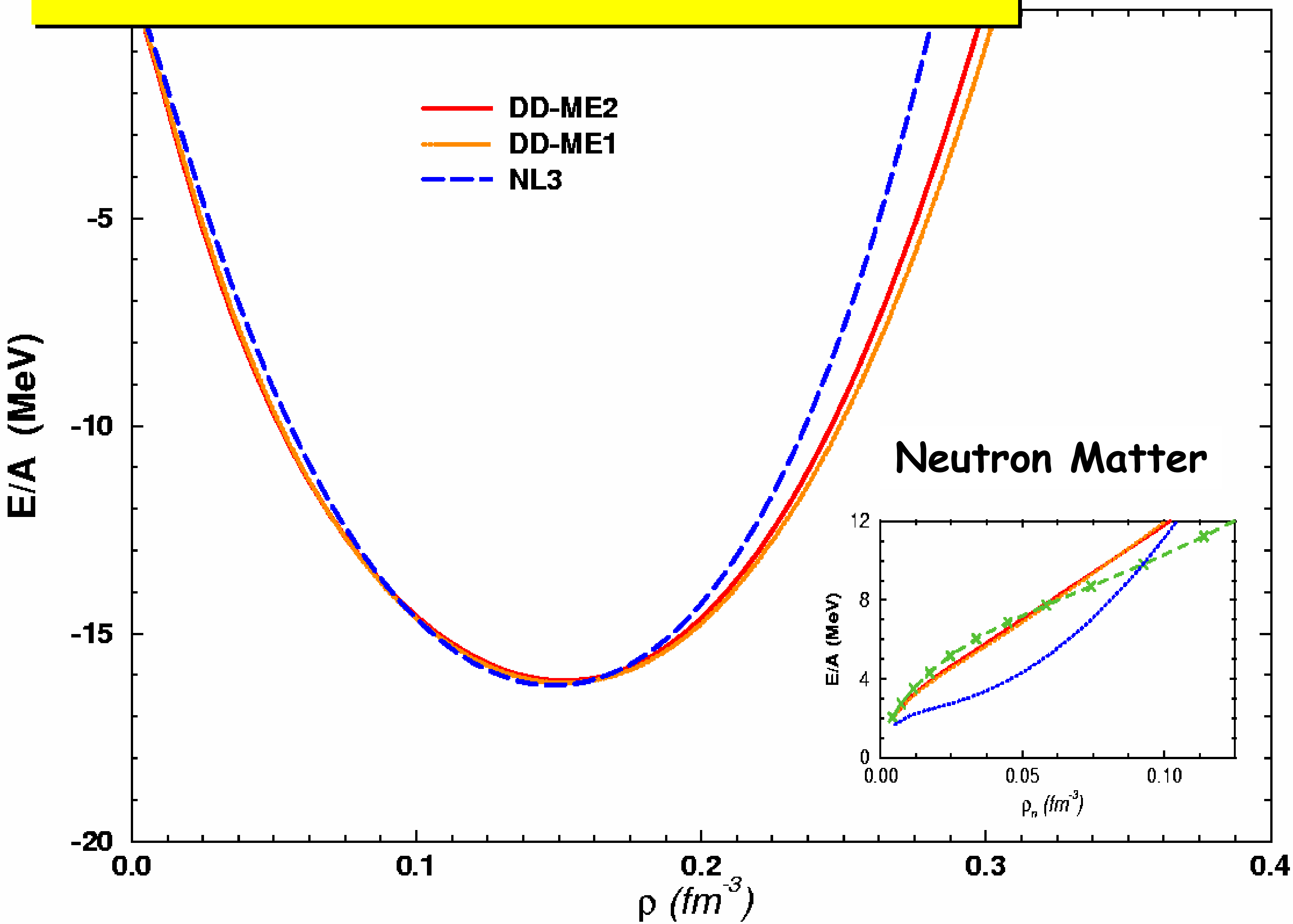
$$g_\rho(\rho) = g_\rho(\rho_{\text{sat}})\ \mathrm{e}^{-a_\rho(x-1)}$$

$$x = \rho/\rho_{\text{sat}}$$



Typel and Wolter, NPA 656, 331 (1999)
Niksic, Vretenar, Finelli, Ring, PRC 66, 024306 (2002)

Nuclear matter equation of state

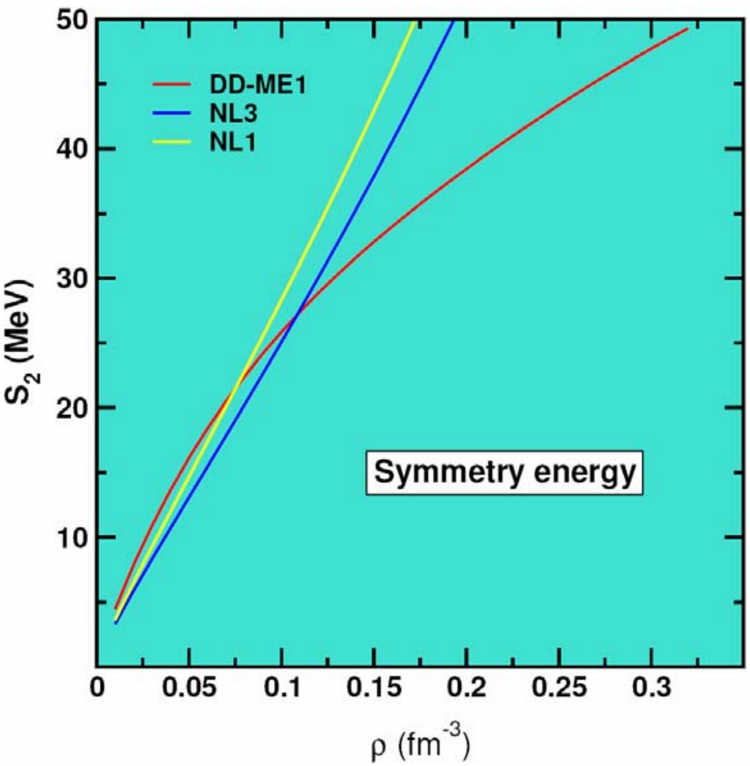


Symmetry energy

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

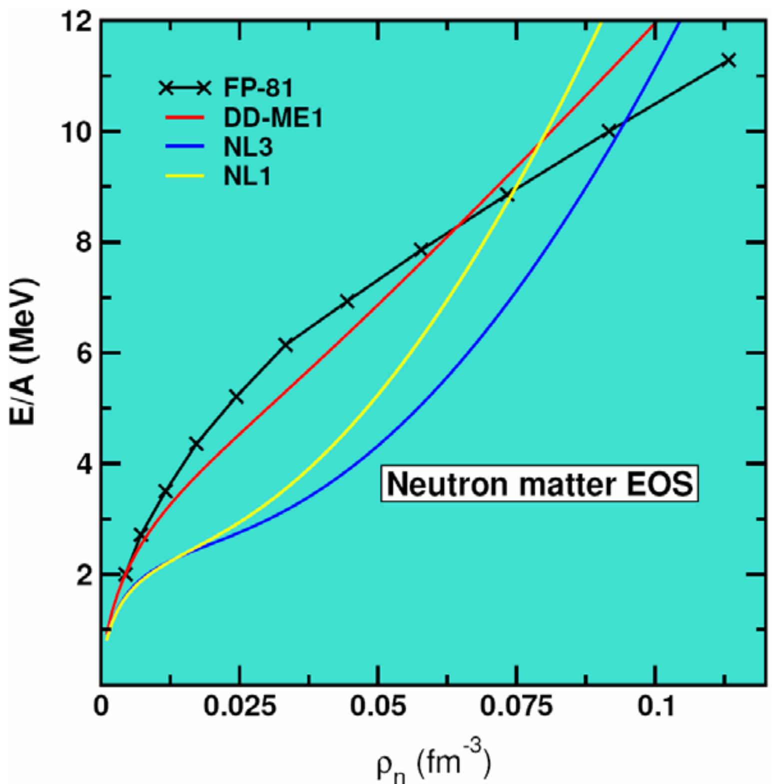
$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + S_4(\rho)\alpha^4 + \cdots$$

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



empirical values:

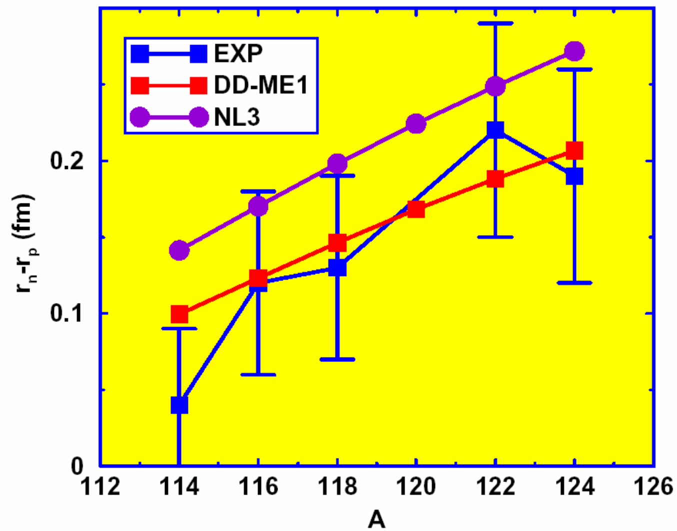
30 MeV ≤ a_4 ≤ 34 MeV
2 MeV/fm³ < p_0 < 4 MeV/fm³
-200 MeV < ΔK_0 < -50 MeV



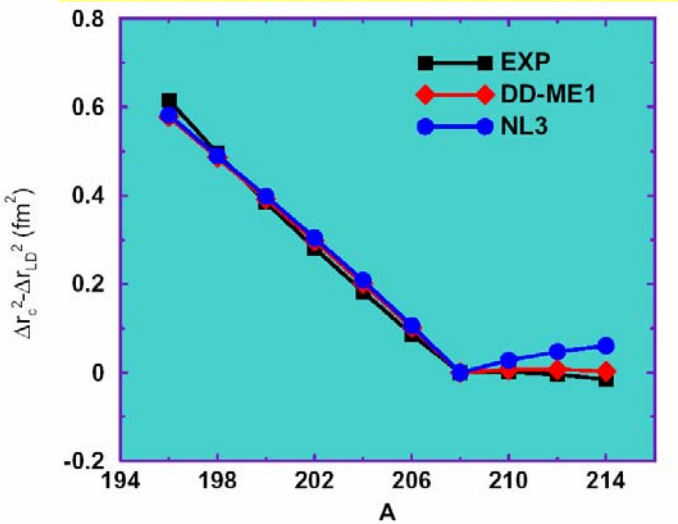
	DD-ME1	NL3	NL1
$a_4(MeV)$	33.1	37.9	43.7
$p_0(MeV/fm^3)$	3.26	5.92	7.0
$\Delta K_0(MeV)$	-128.5	52.1	67.3

DD-ME1

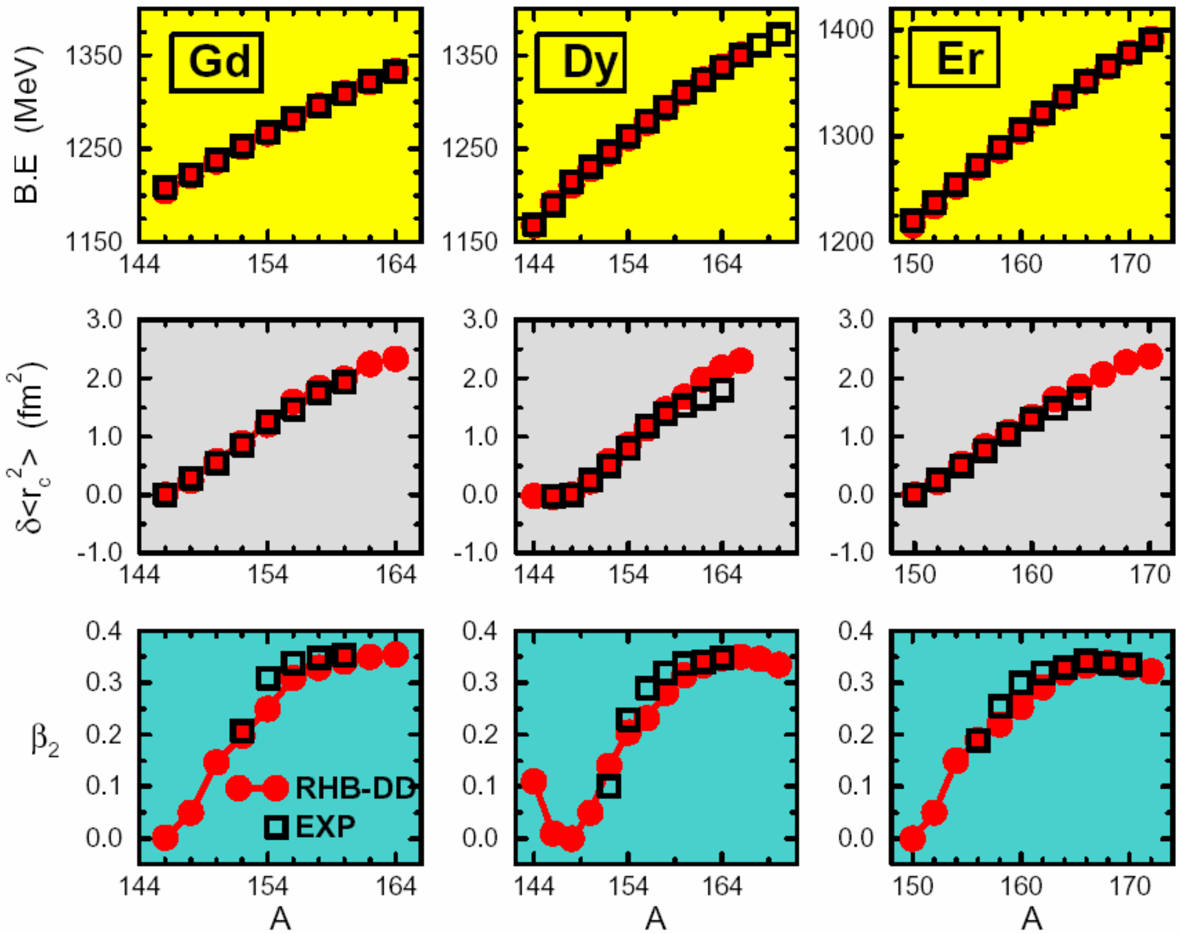
Ground state properties of finite nuclei



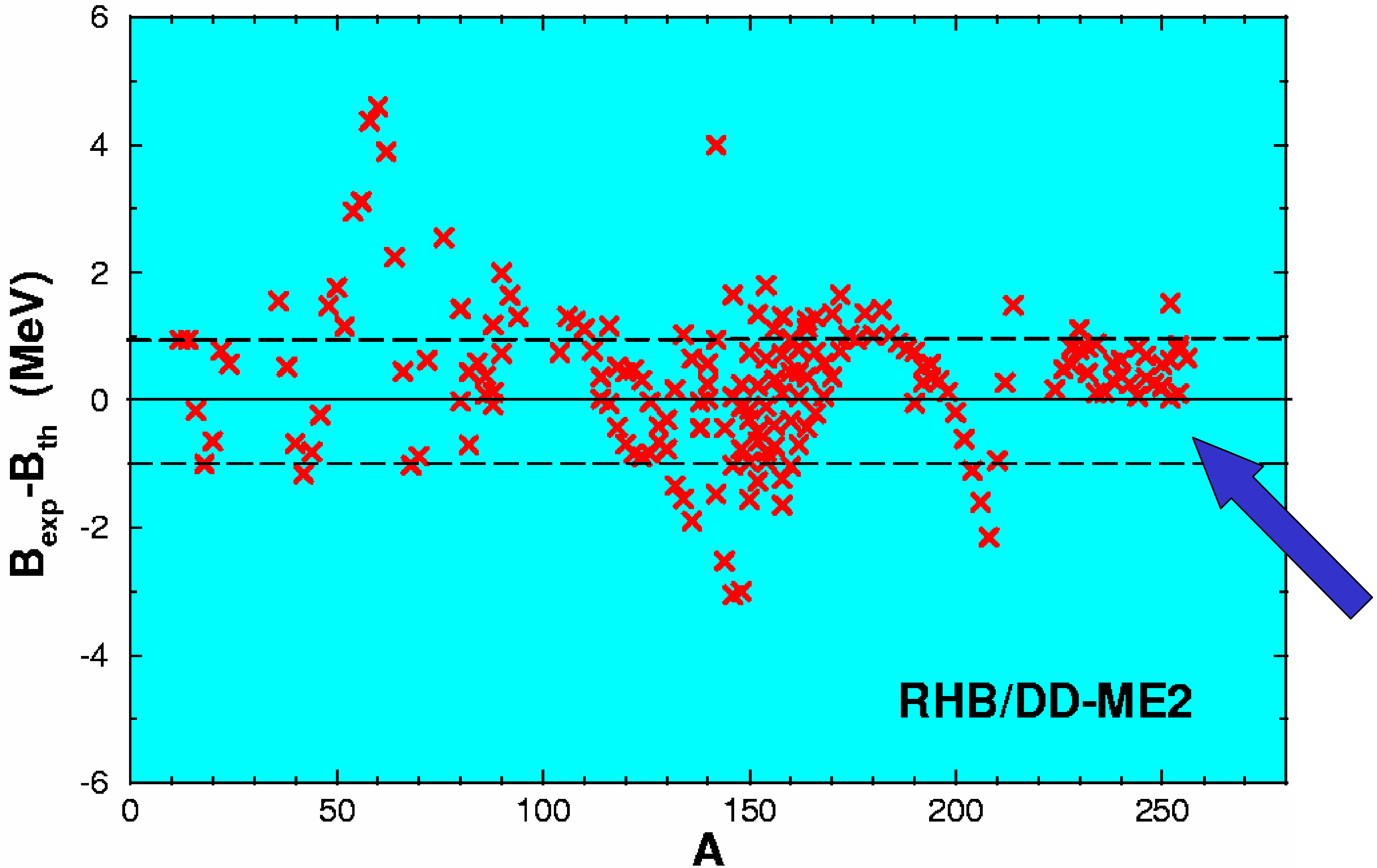
Charge isotope shifts in even-A Pb isotopes.



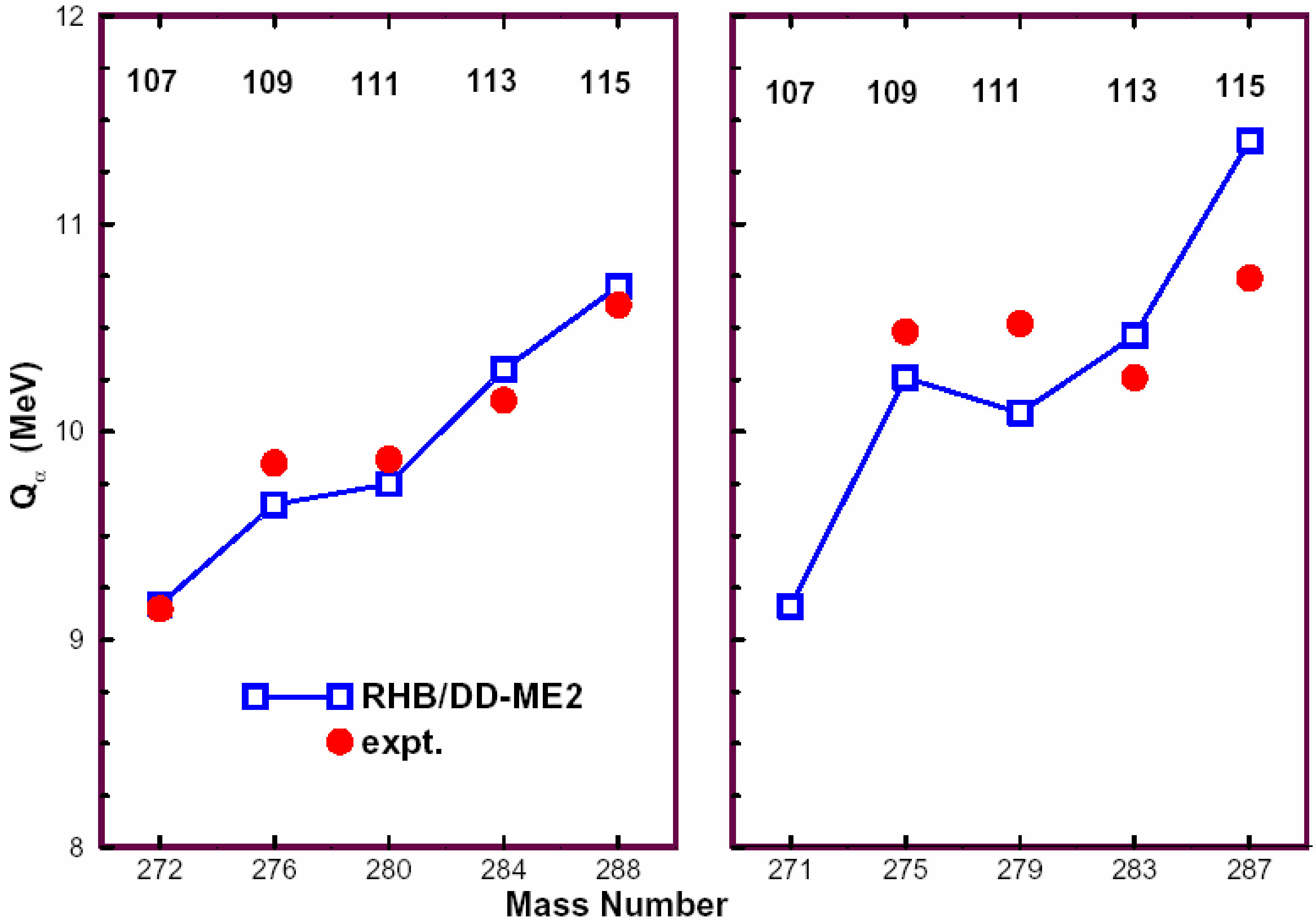
Binding energies, charge isotope shifts, and quadrupole Deformations of Gd, Dy, and Er isotopes.



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

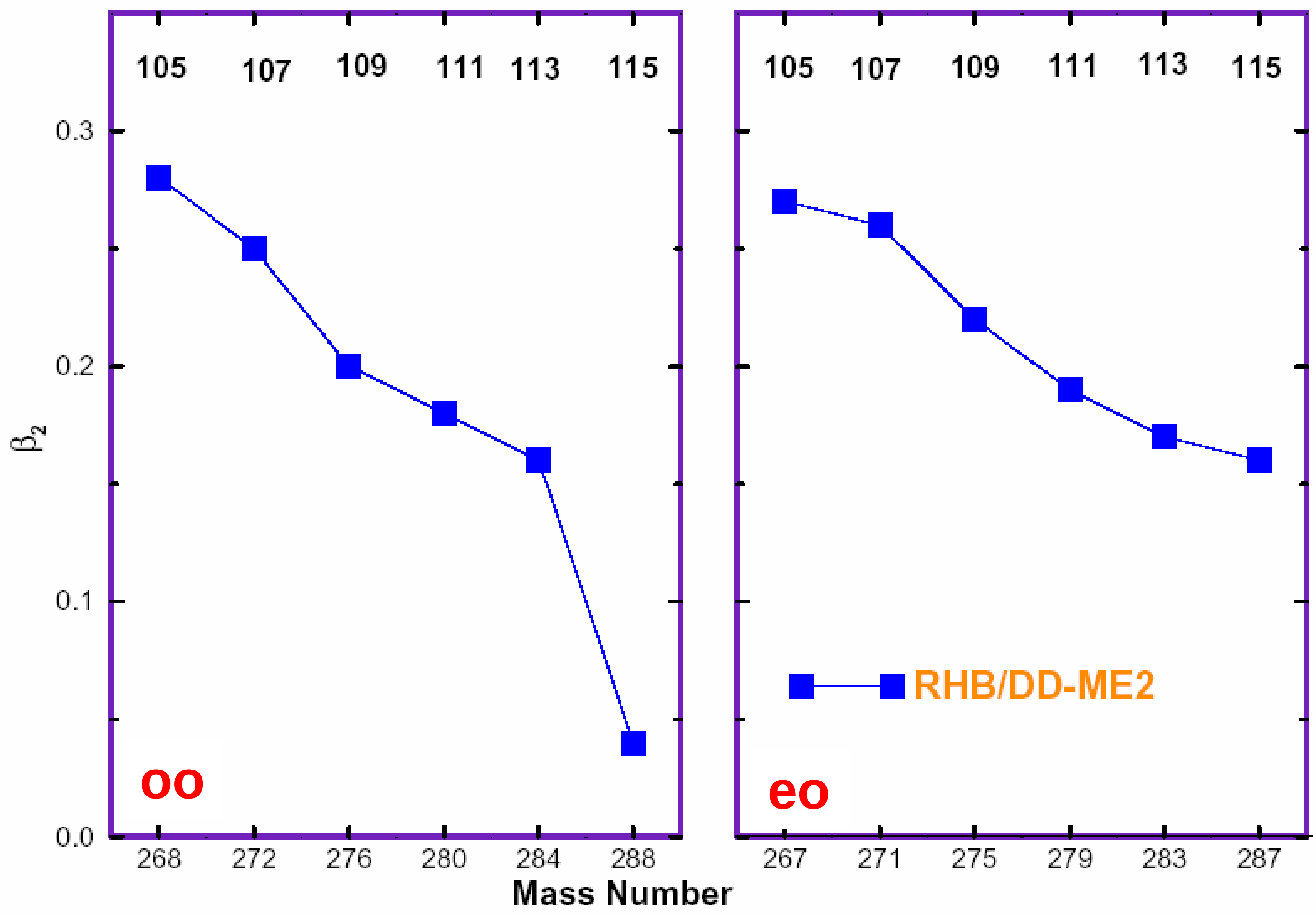


Superheavy Elements: Q_α-values

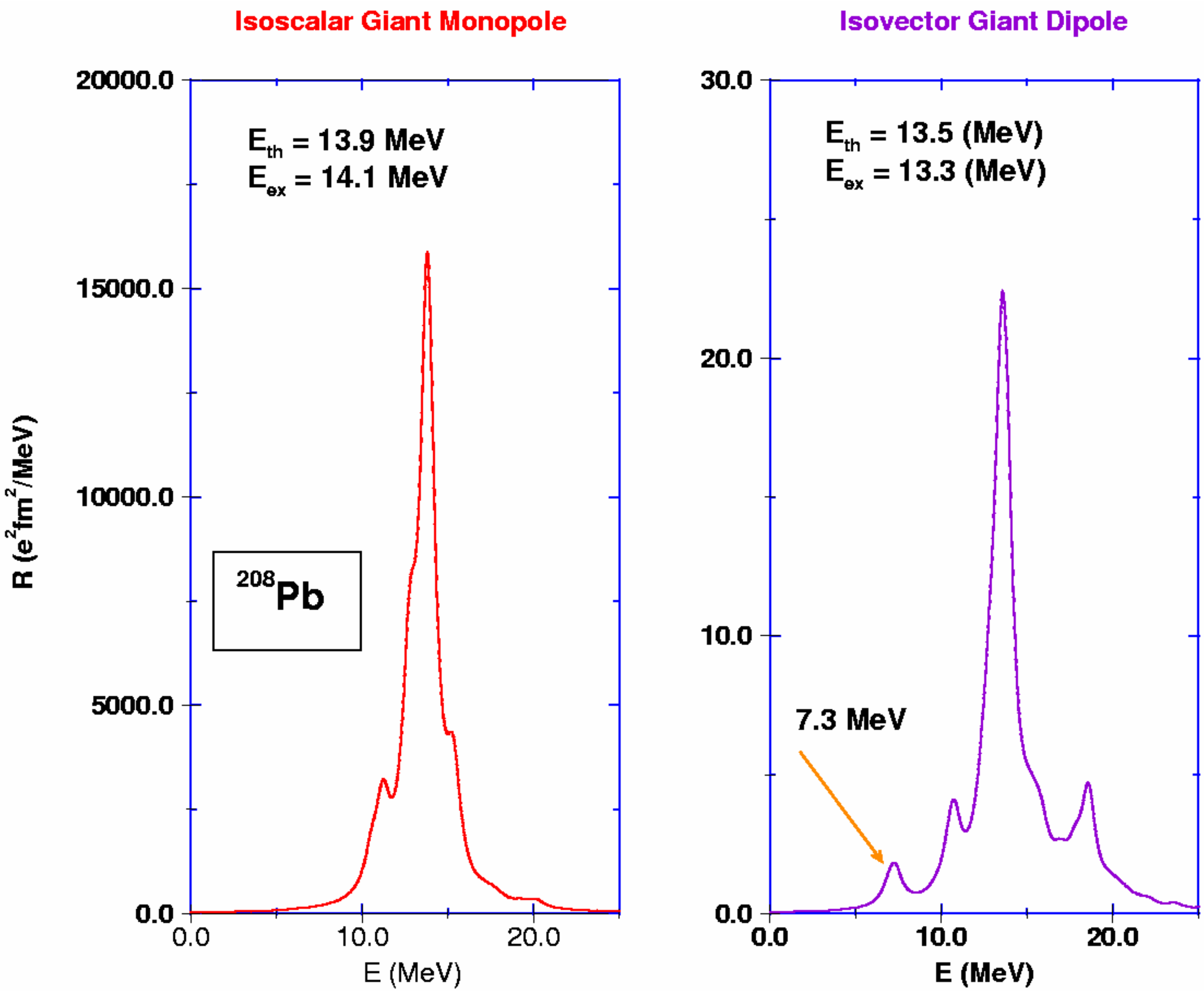


- Exp: Yu.Ts.Oganessian *et al*, PRC 69, 021601(R) (2004)

Superheavy elements: Quadrupole deformations

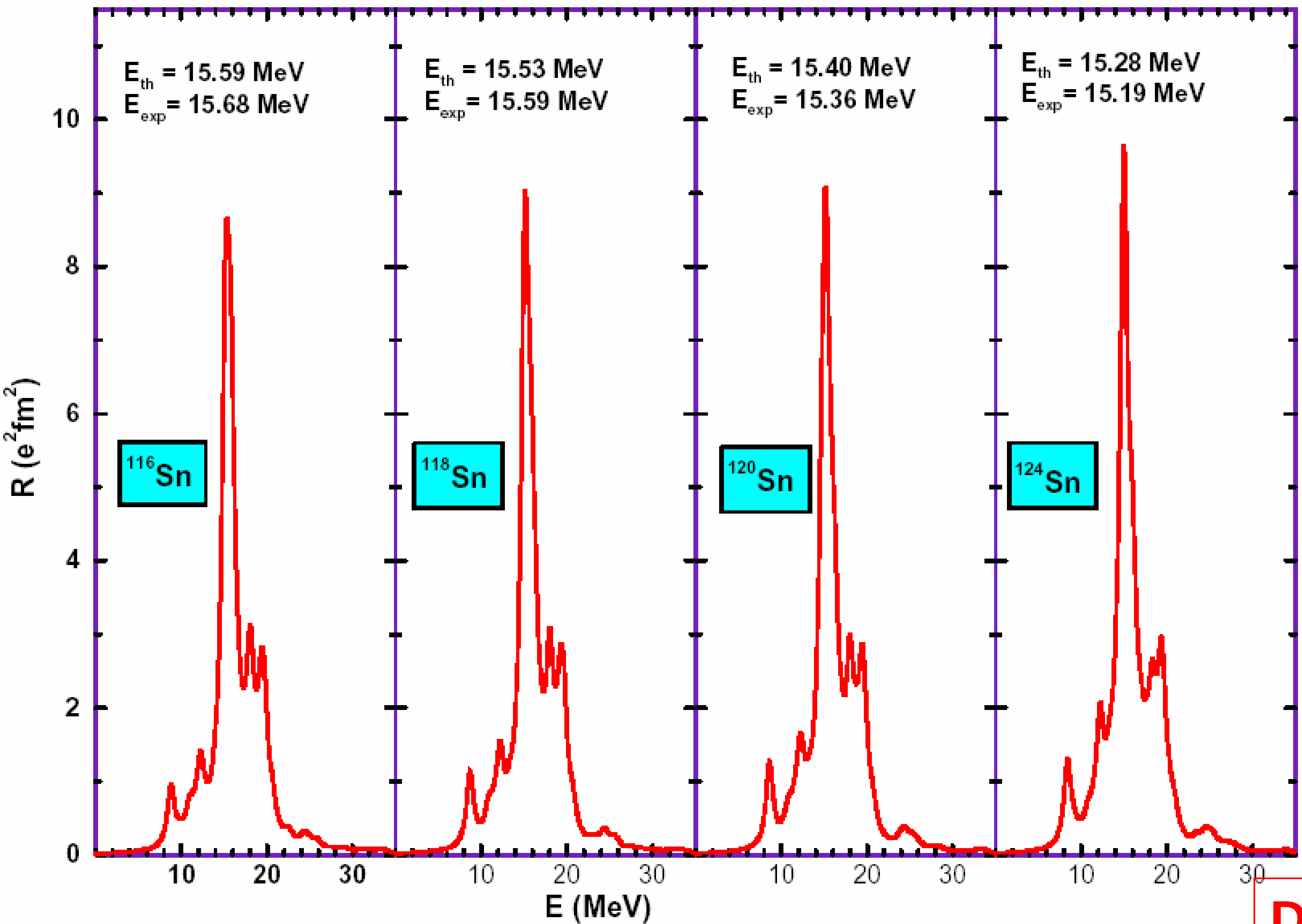


RHB/DD-ME2


Isoscalar Giant Monopole
Isovector Giant Dipole
E_{th} = 13.9 MeV
E_{ex} = 14.1 MeV
^{208}Pb
R (e^2fm^2/MeV)
20000.0
15000.0
10000.0
5000.0
0.0
0.0
10.0
20.0
E (MeV)
E_{th} = 13.5 (MeV)
E_{ex} = 13.3 (MeV)
7.3 MeV
30.0
20.0
10.0
0.0
0.0
10.0
20.0
E (MeV)

DD-ME2

IV-GDR in Sn-isotopes



DD-ME2

Spin-Isospin Resonances: IAR - GTR

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

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

spin flip σ

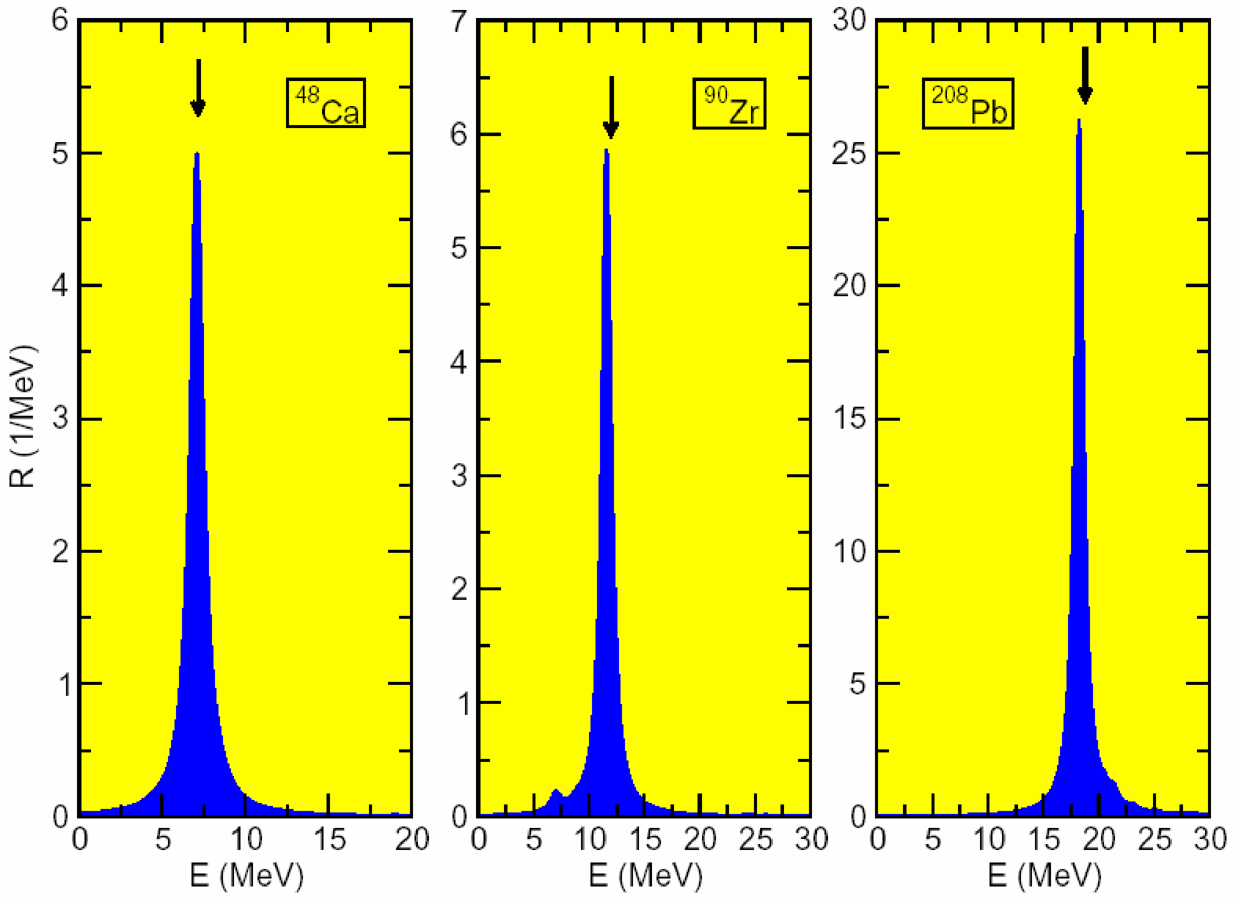
$$|Z,N\rangle \rightarrow |IAR\rangle = T_{+}|Z,N\rangle$$

isospin flip τ

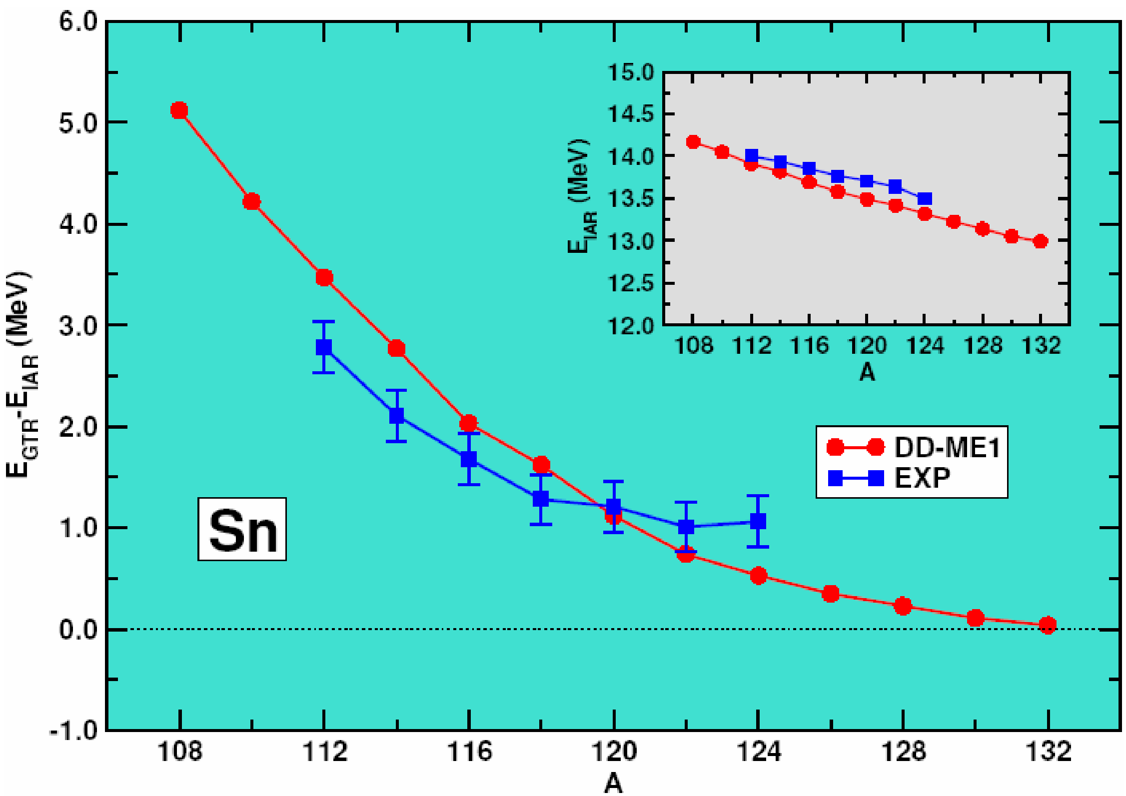
$$E_{GTR} - E_{IAR} \sim \Delta(l \cdot s) \sim \frac{dV}{dr} \sim \text{neutron skin}$$

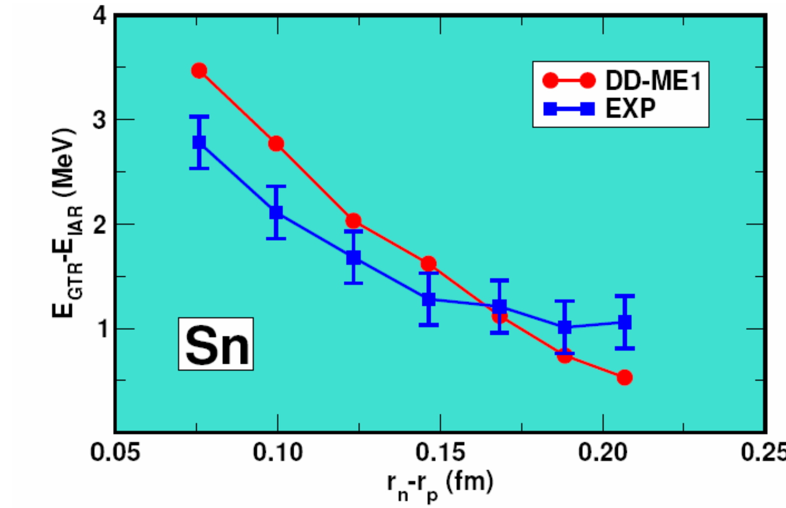
Isobaric Analog Resonance: IAR

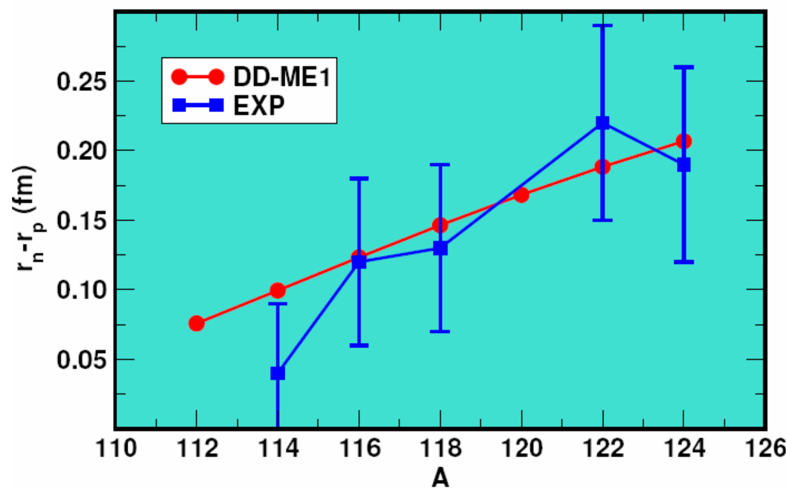
N. Paar, T. Niksic, D. Vretenar, P.Ring, PRC. (2004) in print



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

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
Institut für Kernphysik, Johann Wolfgang Goethe-Universität, D-60486 Frankfurt, Germany
Gesellschaft für Schwerionenforschung (GSI), D-64291 Darmstadt, Germany
Institut für Kernchemie, Johannes Gutenberg-Universität, D-55099 Mainz, Germany
Institut für Kernphysik, Technische Universität, D-64289 Darmstadt, Germany
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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 a
clear or electromagneticeld is
the properties of the nuclear n
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 unc
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 depender
nucleon-nucleon interaction [7
Systematic experimental inf
response of exotic nuclei, how
For some light halo nuclei, lov
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].

gmy resonance, may arise
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
mostly sensitive to electric
nall 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
titatively from a measure-
magnetic dissociation cross
ee parameters by applying
24]. The high secondary
eV nucleon allows for the

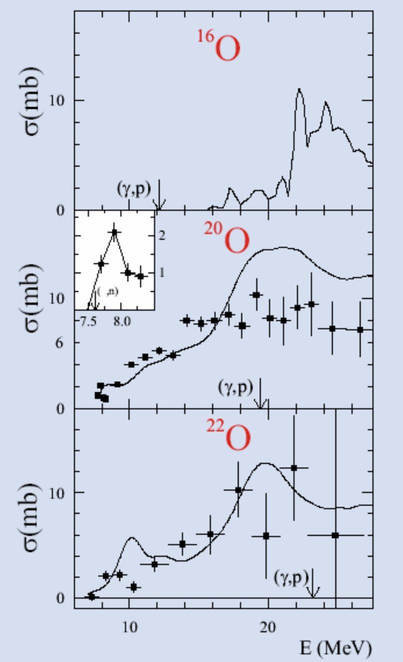
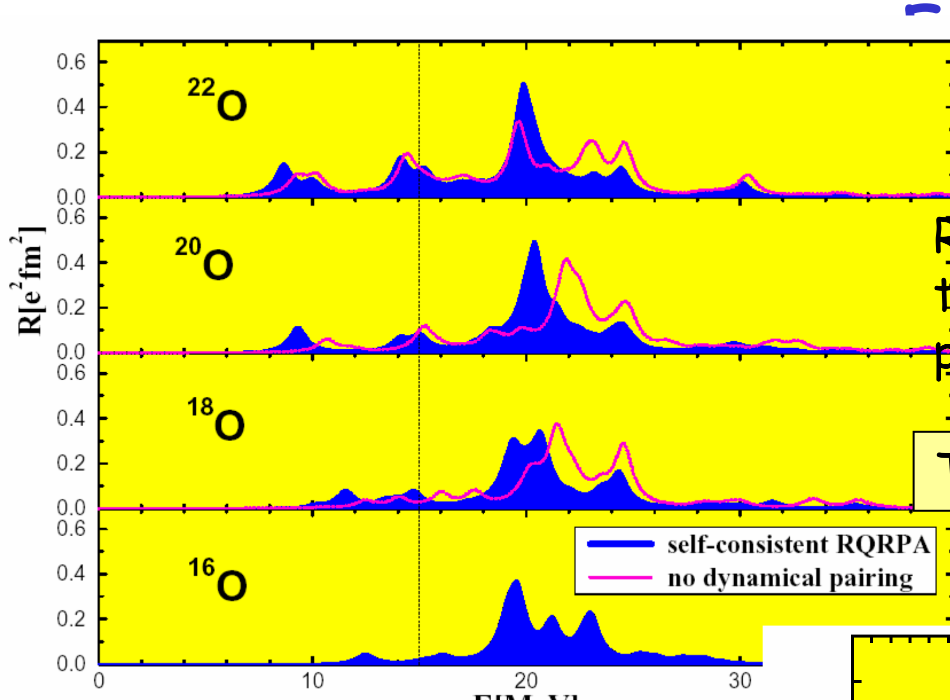


FIG. 2. Photoneutron cross sections for O16 (upper panel) and for the unstable isotopes ^{20,22}O (lower panels) as extracted from the measured electromagnetic excitation cross section (symbols). The inset displays the cross section for near the neutron threshold on an expanded energy scale. The thresholds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

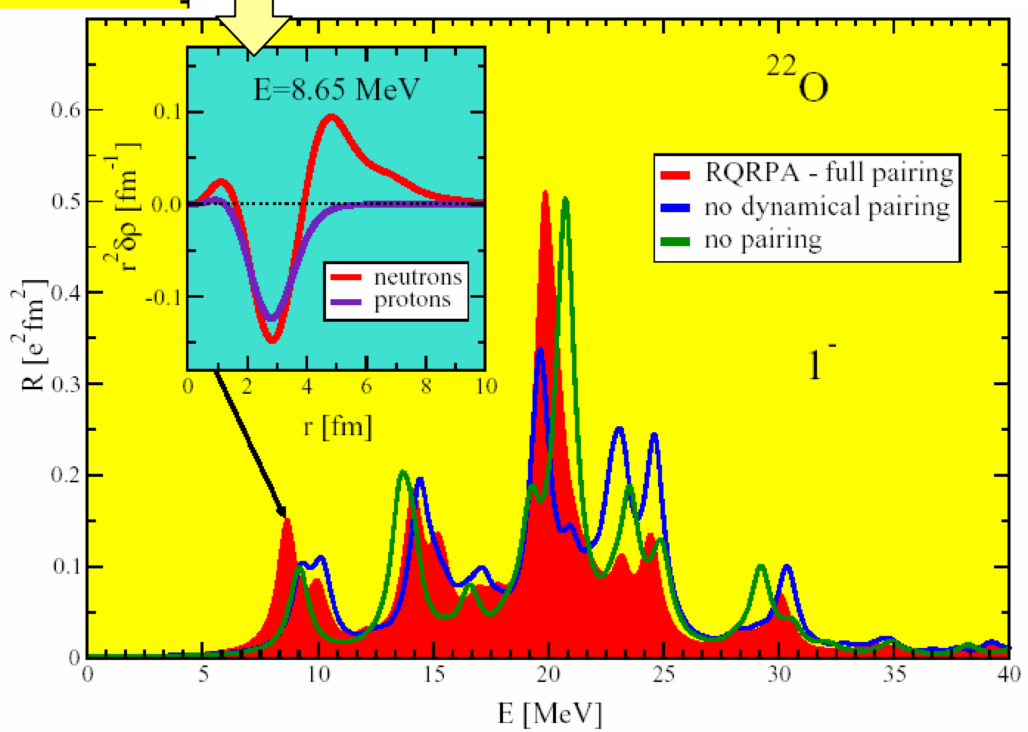
Evolution of IV dipole strength in Oxygen isotopes



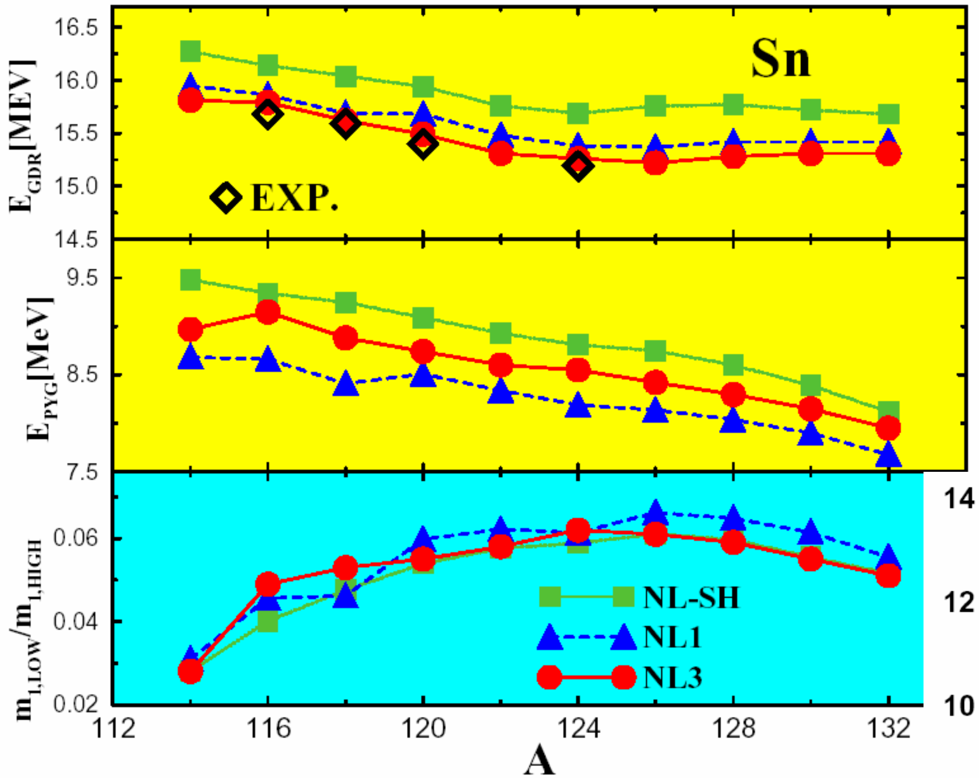
RHB + RQRPA calculations with the NL3 relativistic mean-field plus D1S Gogny pairing interaction.

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

Transition densities



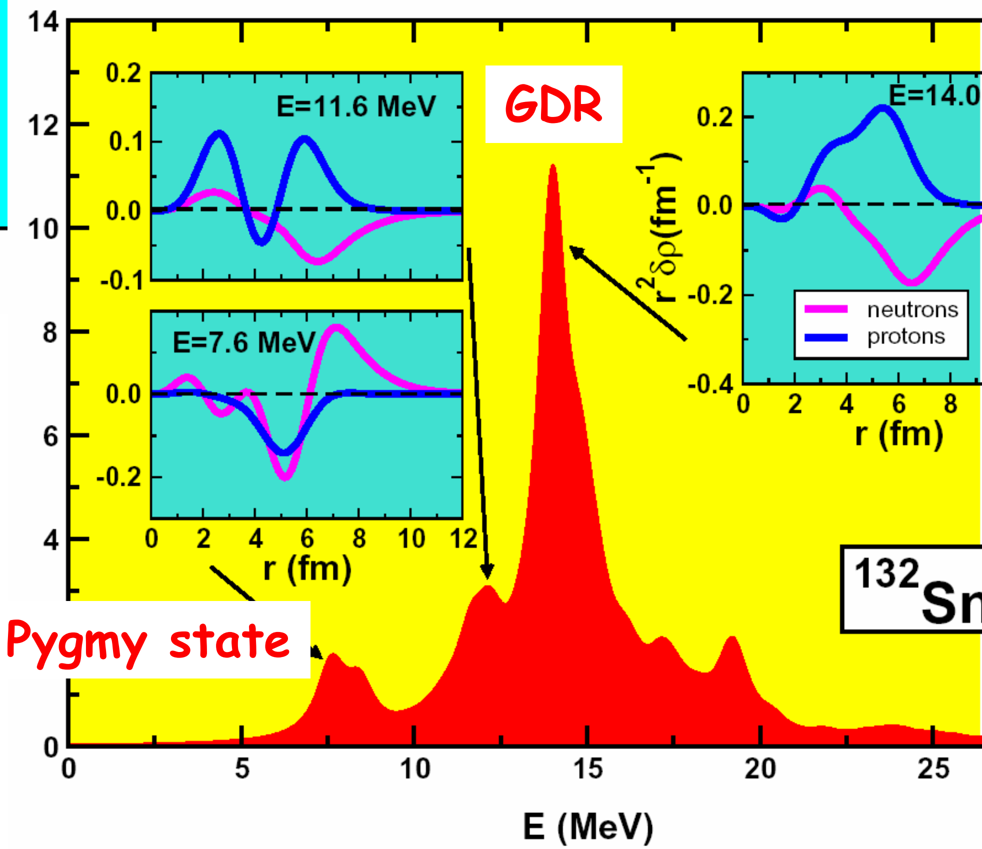
Effect of pairing correlations on the dipole strength distribution



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)

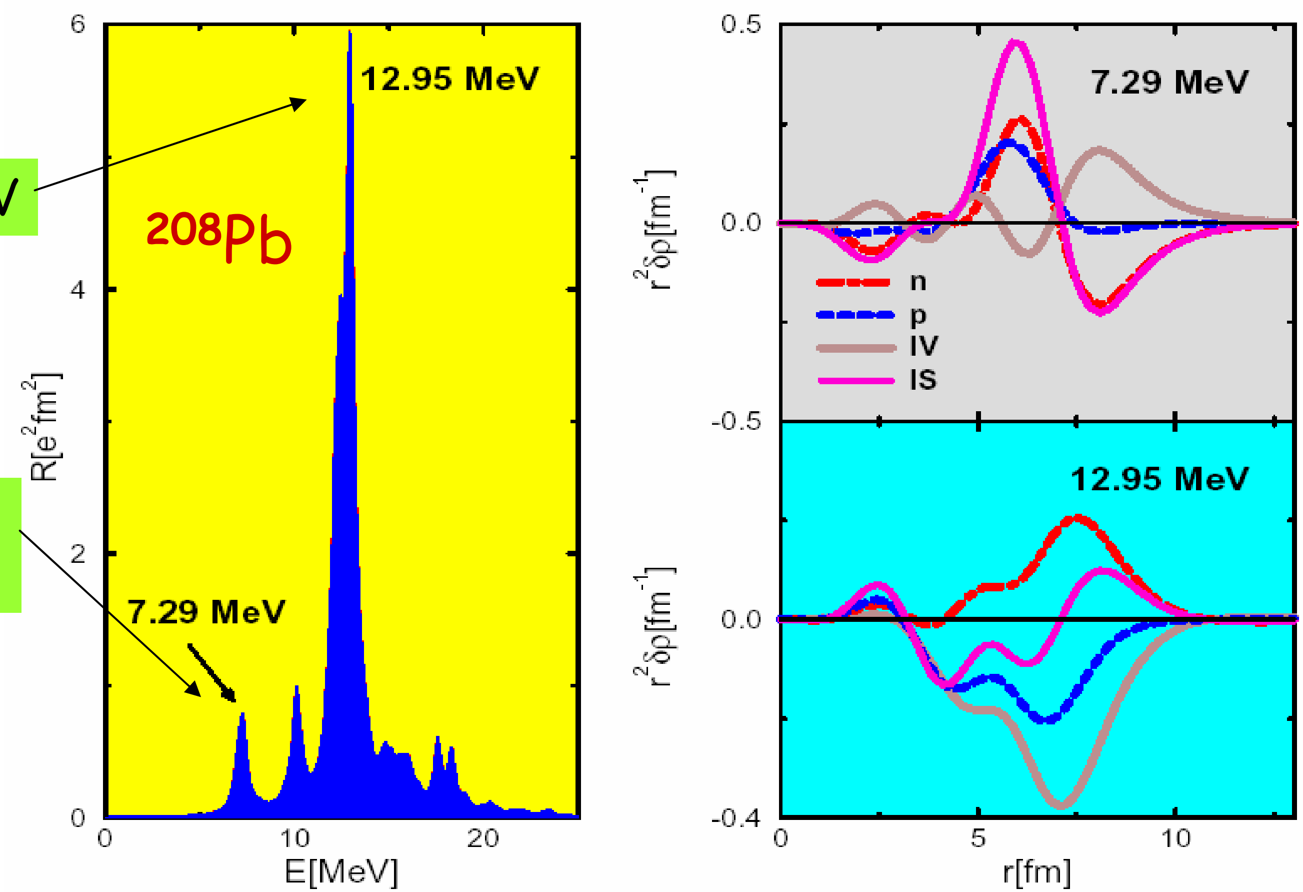
^{132}Sn at 7.6 MeV	
28.2%	$2d_{3/2} \rightarrow 2f_{5/2}$
21.9%	$2d_{5/2} \rightarrow 2f_{7/2}$
19.7%	$2d_{3/2} \rightarrow 3p_{1/2}$
10.5%	$1h_{11/2} \rightarrow 1i_{13/2}$
3.5%	$2d_{5/2} \rightarrow 3p_{3/2}$
1.9%	$1g_{7/2} \rightarrow 2f_{5/2}$
1.5%	$1g_{7/2} \rightarrow 1h_{9/2}$
0.6%	$1g_{7/2}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

IV Dipole Strength for ^{208}Pb and transition densities for the peaks at 7.29 MeV and 12.95 MeV

Phys. Rev. C63, 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.

Among several single-particle transitions, a single collective dipole state is found below 10 MeV and its amplitude represents a coherent superposition of many neutron particle-hole configurations.

Nature of Low-Energy Dipole Strength in Nuclei: The Case of a Resonance at Particle Threshold in ^{208}Pb

N. Ryezayeva,[1] T. Hartmann,[1] Y. Kalmykov,[1] H. Lenske,[2] P. von Neumann-Cosel,[1,*] V. Yu. Ponomarev,[1,†] A. Richter,[1] A. Shevchenko,[1] S. Volz,[1] and J. Wambach[1]

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(Received 31 August 2002; published 18 December 2002)

A high-resolution (γ, γ') study of the electric dipole response in ^{208}Pb at the S-DALINAC reveals a resonance structure centered around the neutron emission threshold. Microscopic quasiparticle phonon model calculations in realistic model spaces including the coupling to complex configurations are able to describe the data in great detail. The resonance is shown to result from surface density oscillations of the neutron skin relative to an approximately isospin-saturated core. It also forms an integral part of a toroidal $E1$ mode representing an example of vortex collective motion in nuclei.

DOI: 10.1103/PhysRevLett.89.272502 PACS numbers: 25.20.Dc, 21.60.Jz, 24.30.Cz, 27.80.+w

Although low-energy electric dipole resonances in stable nuclei have been known for a long time [1], their nature and systematic features remain under discussion. Experimentally, these modes are typically found in the vicinity of the particle emission threshold, but with varying widths and centroid energies. They are commonly termed pygmy dipole resonances (PDR) since their cross sections are small compared to the main portion of $E1$ response

resonance (

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[17,18]) and

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The presen

Indeed, the resonance fluorescence (NRF) experiment

the example of ^{208}Pb [15]: *"In order to test the predictions of the present analysis, it would be important to obtain experimental data also in the energy region between 6 and 8 MeV."* We here report on the observation of a PDR in this excitation energy window with a centroid energy right at the neutron emission threshold (E_{th} = 7.37 MeV). Evidence for $E1$ transitions in this energy region has been presented in previous work including NRF

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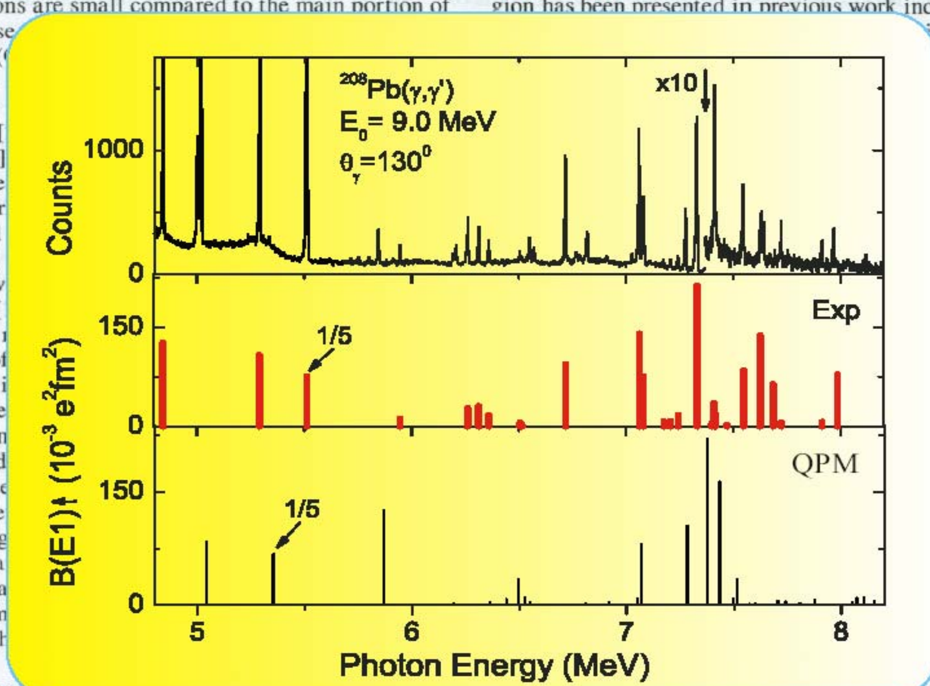
limator to a 1.2 g enriched ^{208}Pb target (99% purity). The



Exp: 7.37 MeV
Theory: 7.29 MeV

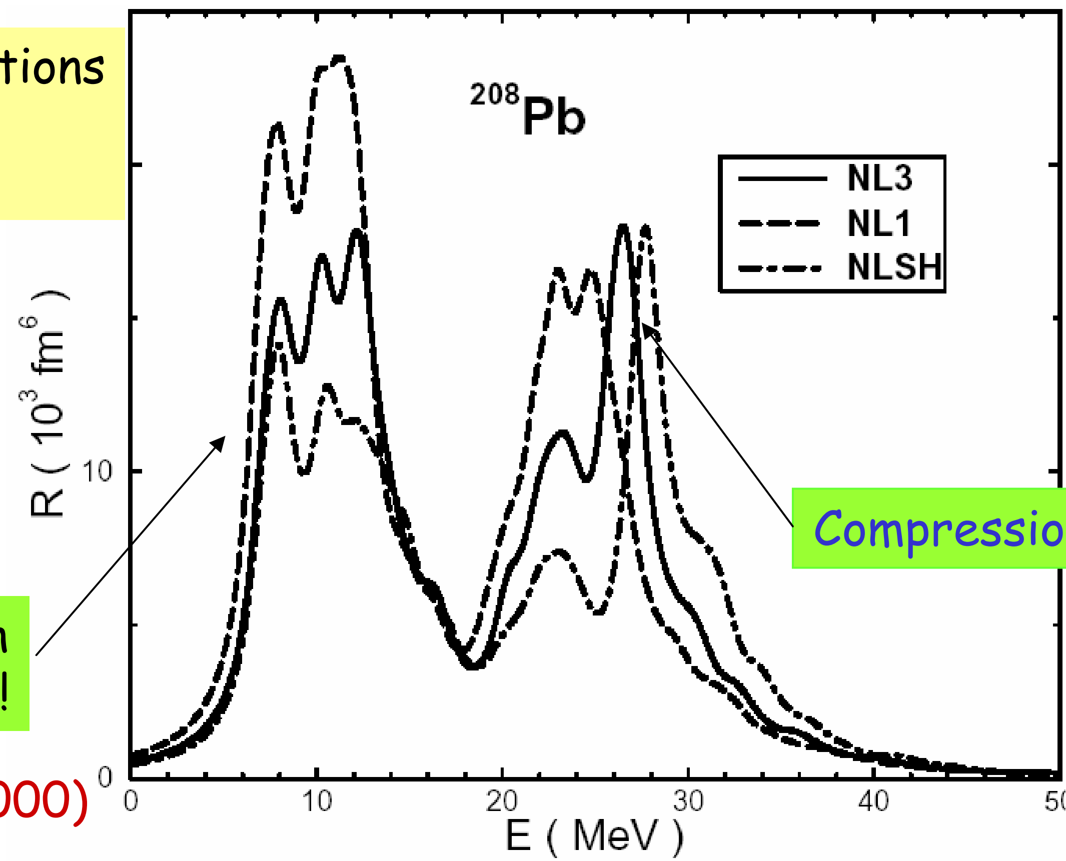
Isoscalar dipole compression -- toroidal modes

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

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

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

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

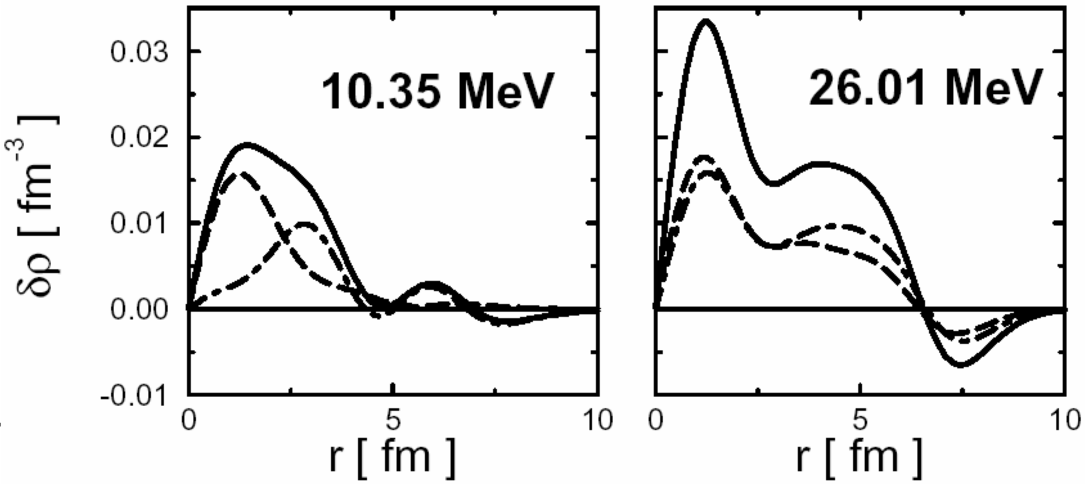


Compression mode

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

Phys. Lett. B487, 334 (2000)

Toroidal motion

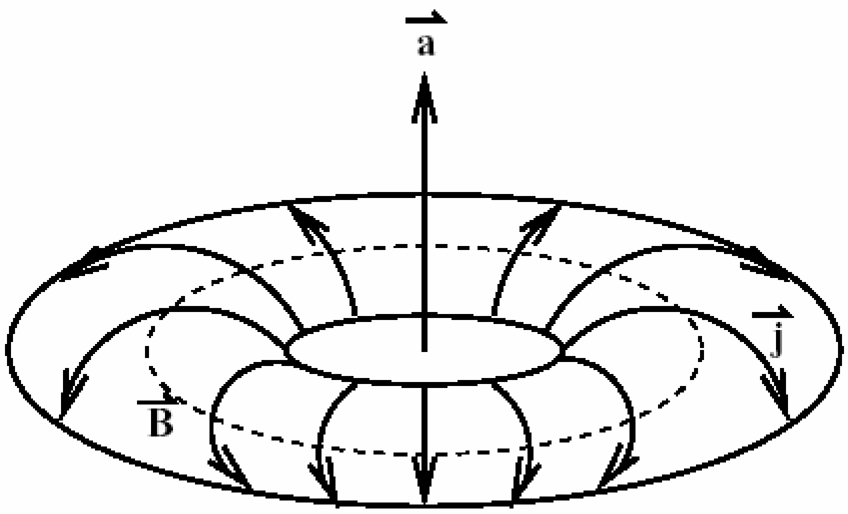


ISGDR transition densities for ^{208}Pb (NL3 interaction)

multipole expansion of a four-

charge moments
magnetic moments
electric transverse moments -> toroidal moments

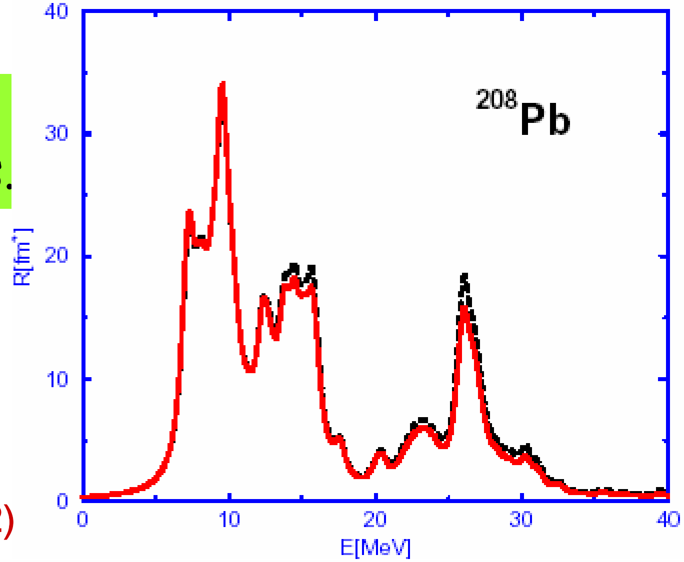
toroidal dipole moment: poloidal currents on a torus

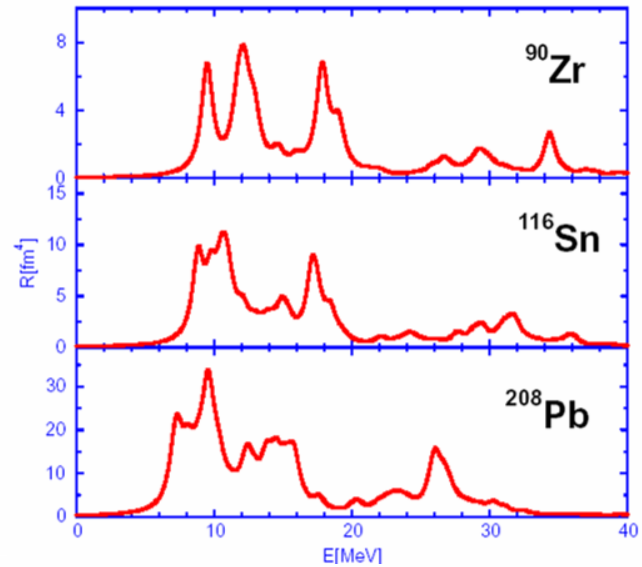


isoscalar toroidal dipole operator:

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

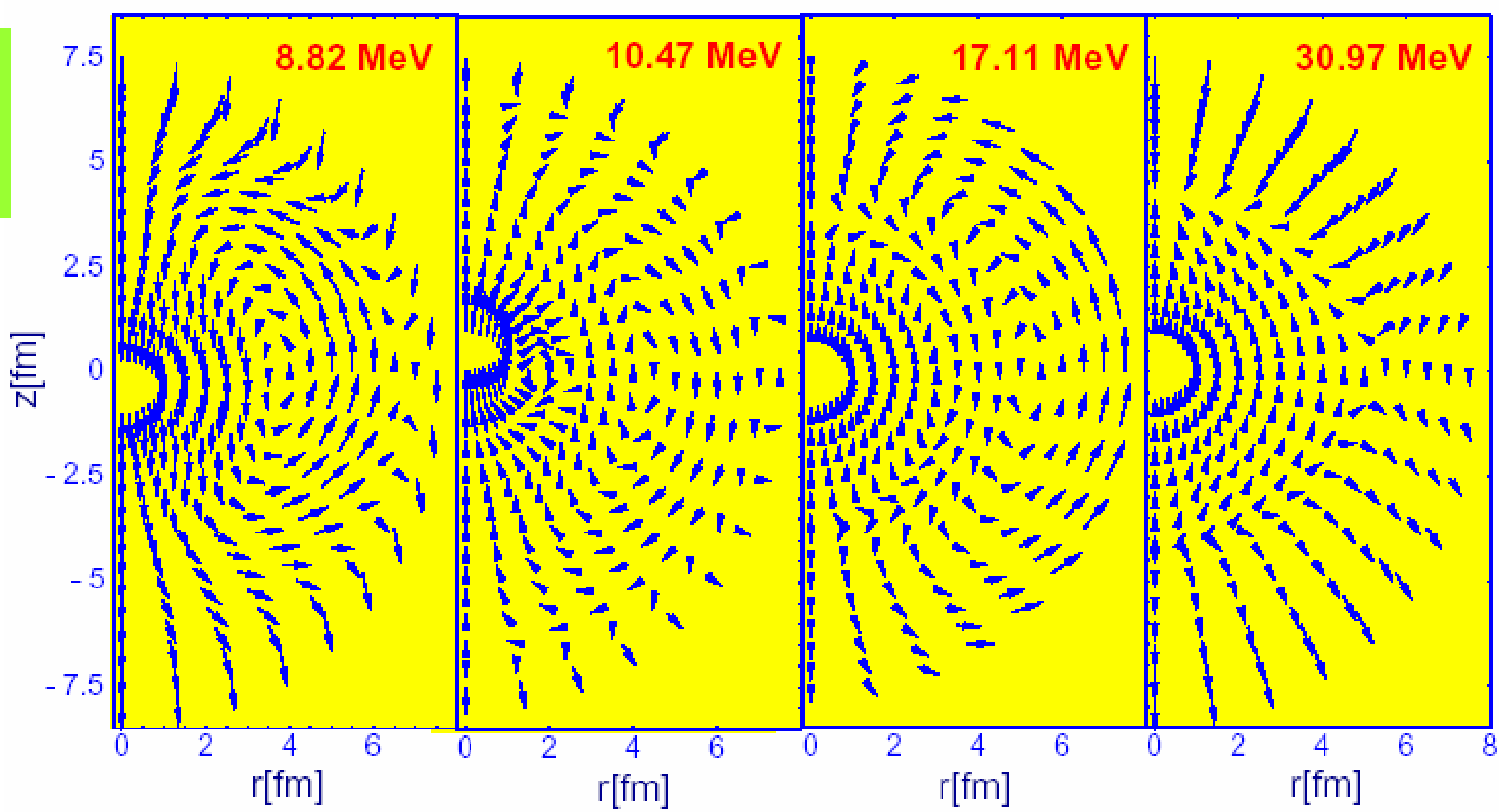
Toroidal dipole strength distributions.





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

Velocity distributions in ^{116}Sn



Conclusions:

Density dependence in the ρ channel

- most of results as NL3
- better equation of state
- better symmetry energy
- on the way to a mass-formula
- superheavy elements

- GMR: $250 < K < 270$
- GDR: $32 < J < 34$
- spin-isospin modes: -> neutron skin
- new exotic modes:
  * pygmy resonances
  * toroidal resonances

RMF models with density-dependent meson-nucleon couplings

Outlook:

covariant density functionals with density dependent meson couplings are an intermediate step on the way to a

Optimal density functional:

- As a basis for correlations
- As a basis for connections to QCD