Relativistic description of atomic nuclei

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Content

- I. Covariant density functional theory
- II. Applications

Content I

- **Relativistic density functional theory**

* concept of density functional theory
- Hohenberg-Kohn theorem
- Kohn-Sham theory

* covariant density functionals
- relativistic fields
- non-relativistic limit
- pseudospin symmetry
- effective Lagrangian
- equations of motion
- relativistic saturation mechanism

* relativistic pairing

Hohenberg-Kohn theorem

We consider a realistic manybody system with the kinetic energy T and two-body interaction $V(r_i,r_k)$ in an external field $U(r)$. In this case the expectation value of the exact energy

$$E_{HK}[\rho(\mathbf{r})] = \langle \hat{T} + \hat{V} \rangle$$

is given by a universal functional $E_{HK}[\rho]$, which does only depend on the local density $\rho(r)$, and not on the external potential $U(r)$.

The ground state is determined by minimizing $E_{HK}[\rho]$ with respect to ρ

Kohn-Sham theorem

For the same system the expectation value of the exact energy is also given by a functional

$$E_{KS}[\rho(\mathbf{r}), \tau(\mathbf{r})] = \langle \hat{T} + \hat{V} \rangle$$

is given by a universal functional $E_{KS}\rho]$, which does depend on $\rho(r)$ and on the kinetic energy density

$$\tau(\mathbf{r}) = \nabla_r \nabla_{r'} \langle a^+(\mathbf{r})\, a(\mathbf{r}') \rangle \big|_{\mathbf{r}=\mathbf{r}'}$$

Summary on exact density functionals:

	formally exact	in practice
Kohn-Hohenberg:	E[ρ(r)]	no shell effects
Kohn-Sham:	E[ρ(r),τ(r)]	no l·s,
Skyrme:	E[ρ(r),τ(r),J(r)]	no pairing
Gogny:	E[ρ(r),τ(r),J(r),κ(r)]	no config.mixing

generalized mean field: **no configuration mixing,**
no two-body correlations

local density: $\rho(\mathbf{r}) = \langle \Phi | a^+(\mathbf{r}) a(\mathbf{r}) | \Phi \rangle = \sum_{i=1}^{A} |\varphi_i(\mathbf{r})\rangle\langle\varphi_i(\mathbf{r})|$

kinetic energy density: $\tau(\mathbf{r}) = \sum_{i=1}^{A} |\nabla\varphi_i(\mathbf{r})\rangle \cdot \langle\nabla\varphi_i(\mathbf{r})|$

pairing density: $\kappa(r) = \langle \Phi \,|\, \mathbf{a}(r,s)\,\mathbf{a}(r,-s) \,|\, \Phi \rangle$

two-body density: $\rho_2(\mathbf{r},\mathbf{r}') = \langle \Phi | a^+(\mathbf{r}) a(\mathbf{r}) a^+(\mathbf{r}') a(\mathbf{r}') | \Phi \rangle$

Non-local density functional theory:

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

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

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

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: Pairing correlations, Covariance
Relativistic Hartree Bogoliubov (RHB)

Covariant density functional theory:

Why covariant ?

1) no relativistic kinematic necessary: $\sqrt{p_F^2 + m_N^2} = m_N \sqrt{1 + 0.075}$

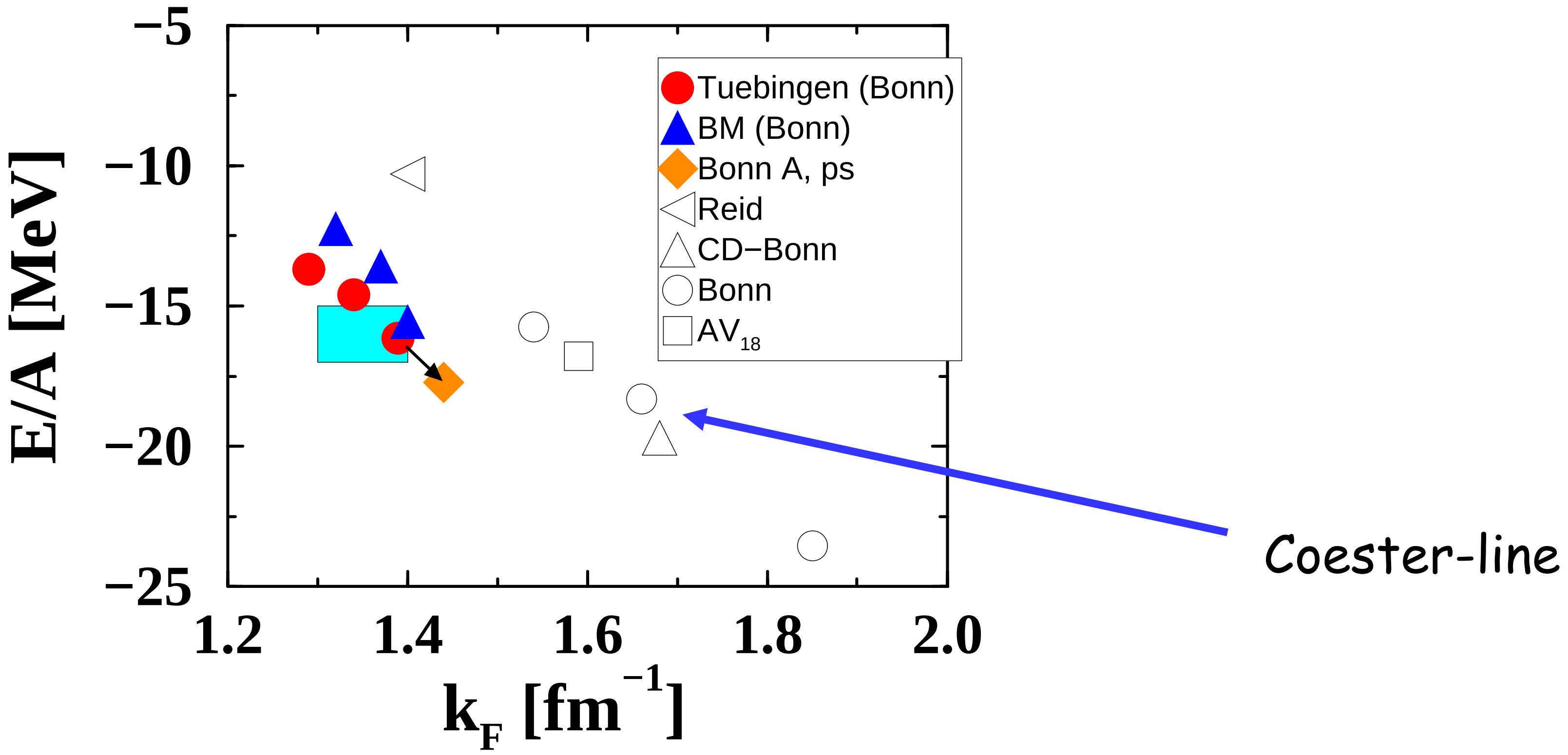
2) non-relativistic DFT works well

3) technical problems:
   no harmonic oscillator
   no exact soluble models
   double dimension
   huge cancellations V-S
   no variational method

4) conceptual problems:
   treatment of Dirac sea
   no well defined many-body theory

Why covariant?

1) Large spin-orbit splitting in nuclei
2) Large fields V≈350 MeV , S≈-400 MeV
3) Success of Relativistic Brueckner
4) Success of intermediate energy proton scatt.
5) relativistic saturation mechanism
6) consistent treatment of time-odd fields
7) Pseudo-spin Symmetry
8) Connection to underlying theories ?
9) As many symmetries as possible



Relativistic densities:

In the **relativistic treatment**, one has to deal with four-component Dirac spinor wave functions. Consequently, there are 16 independent bilinear covariants:

$$\overline{\psi}(\mathbf{r})\Gamma\psi(\mathbf{r})$$

This gives the following local densities:

$\Gamma^s = 1$	scalar density
$\Gamma^v_\mu = \gamma_\mu$	vector density
$\Gamma^t_{\mu\nu} = (i/2)\left(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu\right)$	tensor density
$\Gamma^p = \gamma_5$	pseudoscalar density
$\Gamma^a_\mu = \gamma_\mu\gamma_5$	axial density

(which have isoscalar and isovector components.) In most applications, only three densities are required:

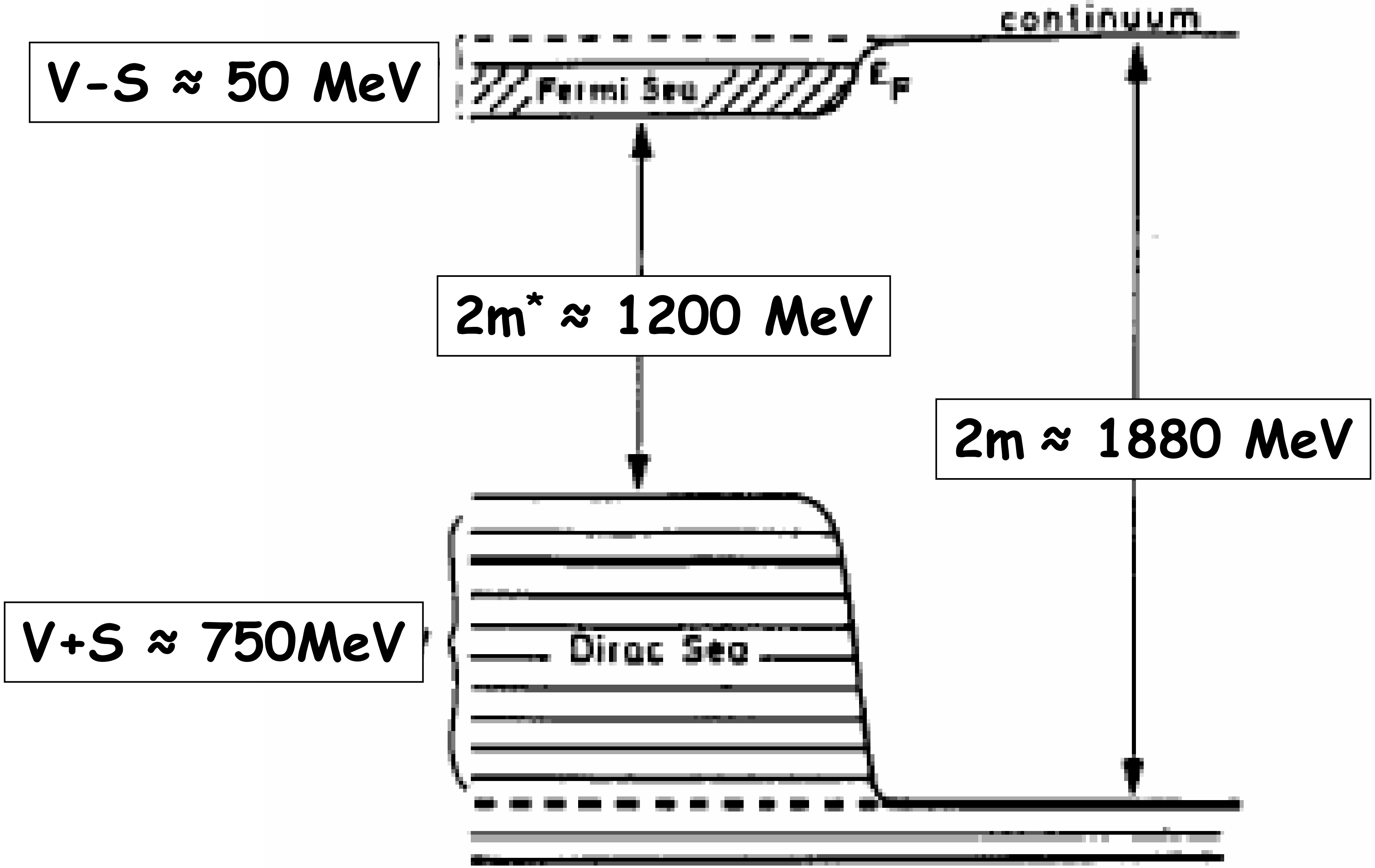
$\overline{\psi}\psi$ **(σ)** $\overline{\psi}\gamma^\mu\psi$ **(ω)** $\overline{\psi}\gamma^\mu\vec{\tau}\psi$ **(ρ)**

Dirac equation:

$$\begin{pmatrix} m + V - S & \vec{\sigma}(\vec{p} - \vec{V}) \\ \vec{\sigma}(\vec{p} - \vec{V}) & -m + V + S \end{pmatrix} \begin{pmatrix} g \\ f \end{pmatrix}_i = \varepsilon_i \begin{pmatrix} g \\ f \end{pmatrix}_i$$

scalar potential	$S(r)$
vector potential (time-like)	$V(r)$
vector potential (space-like)	$\vec{V}(r)$

vector space-like corresponds to magnetic potential (nuclear magnetism)
is time-odd and vanishes in the ground state of even-even systems



continuum
V-S ≈ 50 MeV
Fermi Sea
ϵ_F
2m* ≈ 1200 MeV
2m ≈ 1880 MeV
V+S ≈ 750MeV
Dirac Sea

Elimination of small components:

$(\varepsilon \rightarrow m+\varepsilon)$

$$W_{\pm} = V \pm S$$

$$f_i(\mathrm{r}) = \frac{1}{\varepsilon_i + 2m - W_+} \vec{\sigma}\vec{\mathrm{p}} g_i(\mathrm{r})$$

$$\left\{ \vec{\sigma}\vec{\mathrm{p}} \frac{1}{\varepsilon_i + 2\tilde{m}(\mathrm{r})} \vec{\sigma}\vec{\mathrm{p}} + W_- \right\} g_i(\mathrm{r}) = \varepsilon_i g_i(\mathrm{r})$$

$$\tilde{m}(\mathrm{r}) = m - \frac{1}{2} W_+$$

for $|\varepsilon_i| << 2\tilde{m}$

$$m^*(\mathrm{r}) = m - S$$

$$\left\{ \vec{\mathrm{p}} \frac{1}{2\tilde{m}} \vec{\mathrm{p}} + \frac{1}{4\tilde{m}^2} \frac{1}{r} \frac{\partial W_+}{\partial r} \vec{l}\vec{s} + W_- \right\} g_i(\mathrm{r}) \approx \varepsilon_i g_i(\mathrm{r})$$

Pseudospin:

A.Arima, M.Harvey,K.Shimizu, PLB 30 (1969) 517
K.T.Hecht,A.Alder, NPA 137 (1969) 129
J.N.Ginocchio, PRL 78 (1997) 436

Oscillator-shell N

$l=0$, $j=\frac{1}{2}$	$\tilde{l}=1$, $j=\tilde{l}+\frac{1}{2}$	$\tilde{l}=1$, $j=\tilde{l}-\frac{1}{2}$	$l=2$, $j=\frac{3}{2}$
$l=N-4$, $j=N-\frac{7}{2}$	$\tilde{l}=N-3$, $j=\tilde{l}+\frac{1}{2}$	$\tilde{l}=N-3$, $j=\tilde{l}-\frac{1}{2}$	$l=N-2$, $j=N-\frac{5}{2}$
$l=N-2$, $j=N-\frac{3}{2}$	$\tilde{l}=N-1$, $j=\tilde{l}-\frac{1}{2}$	$\tilde{l}=N-1$, $j=\tilde{l}+\frac{1}{2}$	$l=N$, $j=N-\frac{1}{2}$
$l=N$, $j=N+\frac{1}{2}$		intruder	

Elimination of large components:

($\varepsilon \rightarrow$ m+ε)

$$g_i(\mathrm{r}) = \vec{\sigma}\vec{\mathrm{p}} \frac{1}{\varepsilon_i - W_-} \vec{\sigma}\vec{\mathrm{p}} f_i(\mathrm{r})$$

g(r) has pseudo-spin quantumnumbers

$$\left\{ \vec{\sigma}\vec{\mathrm{p}} \frac{1}{\varepsilon_i - W_-} \vec{\sigma}\vec{\mathrm{p}} + W_+ - 2m \right\} f_i(\mathrm{r}) = \varepsilon_i f_i(\mathrm{r})$$

$$\left\{ \vec{\mathrm{p}} \frac{1}{\varepsilon_i - W_-} \vec{\mathrm{p}} + \frac{1}{(\varepsilon_i - W_-)^2} \frac{1}{r} \frac{\partial W_-}{\partial r} \vec{l}\vec{s} + W_+ - 2m \right\} g_i(\mathrm{r}) = \varepsilon_i g_i(\mathrm{r})$$

For V=S is W_-=0, i.e. pseudo-spin orbit spitting vanishes

J.N.Ginocchio, PRL 78 (1997) 436

QCD-sum rules: V≈S

Furnstahl et al, PRC 46 (1992) 1507

Antinucleons have spin symmetry and no spin-orbit splitting

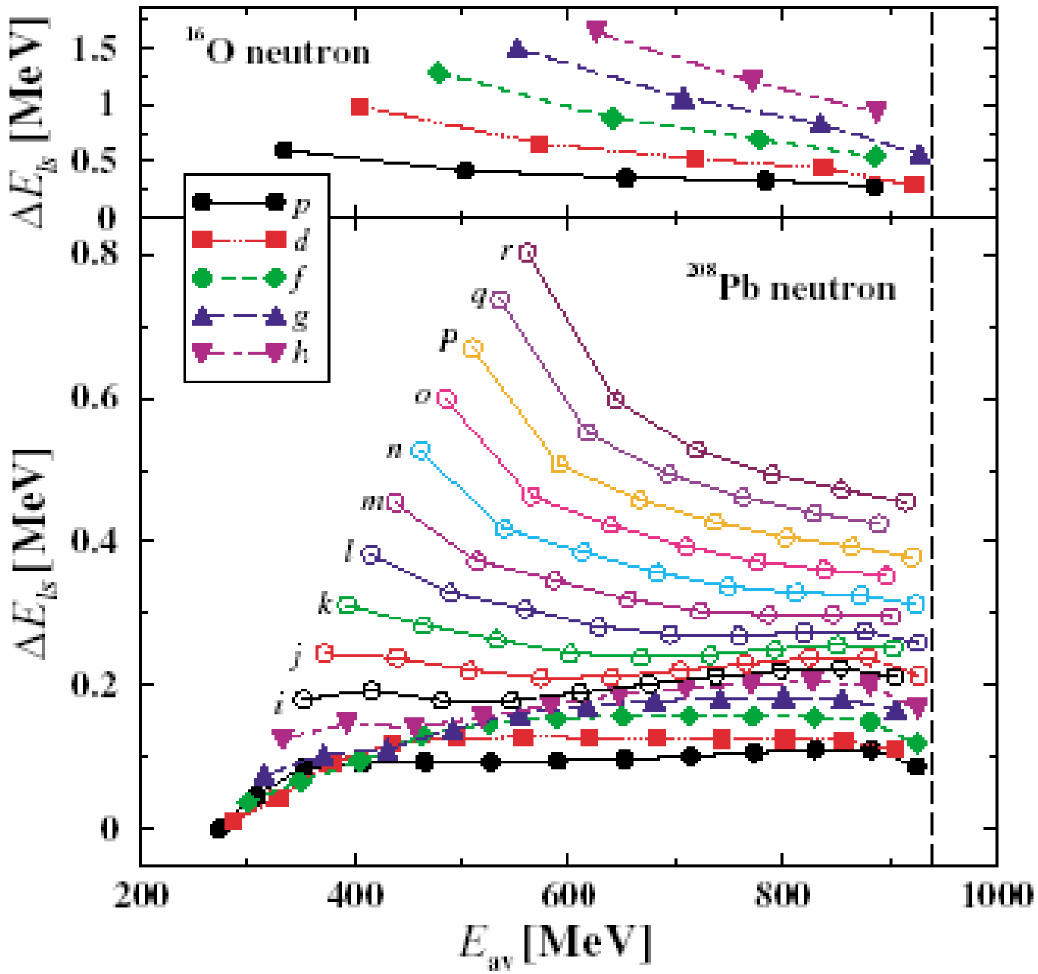
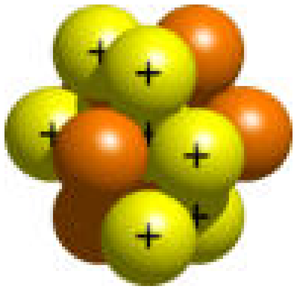


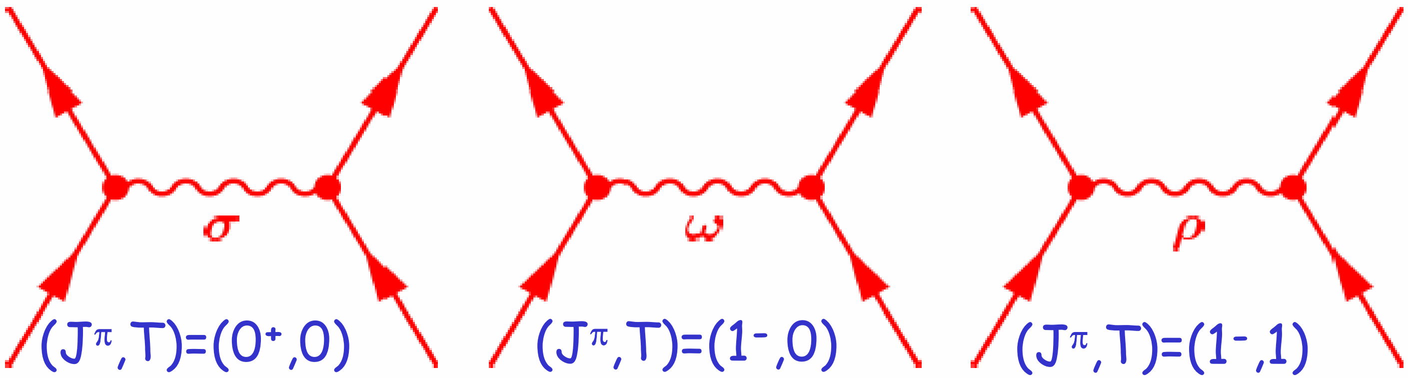
FIG. 2 (color online). Spin-orbit splitting $\epsilon_A(nl_{l-1/2}) - \epsilon_A(nl_{l+1/2})$ in antineutron spectra of ^{16}O and ^{208}Pb versus the average energy of a pair of spin doublets. The vertical dashed line shows the continuum limit.

S.G. Zhou, J. Meng, P.Ring, PRL 91 (2003) 262501

Covariant density functional theory



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

LAGRANGIAN DENSITY

free Dirac particle

free meson fields

free photon field

$$
\begin{aligned}
\mathcal{L} \;=\; & \bar{\psi}\,(i\gamma\cdot\partial - m)\,\psi + \frac{1}{2}(\partial\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 \\
& - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{4}\vec{\mathrm{R}}_{\mu\nu}\vec{\mathrm{R}}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^{\,2} - \frac{1}{4}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} \\
& - g_\sigma\bar{\psi}\sigma\psi - g_\omega\bar{\psi}\gamma\cdot\omega\psi - g_\rho\bar{\psi}\gamma\cdot\vec{\rho}\vec{\tau}\psi - e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi
\end{aligned}
$$

interaction terms

Parameter:

meson masses: m_σ, m_ω, m_ρ

meson couplings: g_σ, g_ω, g_ρ

Equations of motion:

$$\partial_\mu \frac{\partial L}{\partial(\partial_\mu q_k)} - \frac{\partial L}{\partial q_k} = 0.$$

for the nucleons we find the Dirac equation

$$\left(\gamma^\mu\left(i\partial_\mu - V_\mu\right) - m + S\right)\psi_i = 0.$$

No-sea approxim. !

for the mesons we find the Klein-Gordon equation

$$\left(\partial^\nu\partial_\nu + m_\sigma^2\right)\sigma = -g_\sigma\rho_s$$
$$\left(\partial^\nu\partial_\nu + m_\omega^2\right)\omega_\mu = g_\omega j_\mu$$
$$\left(\partial^\mu\partial_\mu + m_\rho^2\right)\vec{\rho}_\mu = g_\rho\vec{j}_\mu$$
$$\partial^\nu\partial_\nu A_\mu = e j_\mu^{(em)}$$

$$\rho_s(x) = \sum_{i=1}^{A} \bar{\psi}_i(x)\psi_i(x)$$
$$j_\mu(x) = \sum_{i=1}^{A} \bar{\psi}_i(x)\gamma_\mu\psi_i(x)$$
$$\vec{j}_\mu(x) = \sum_{i=1}^{A} \bar{\psi}_i(x)\vec{\tau}\gamma_\mu\psi_i(x)$$
$$j_\mu^{(em)}(x) = \sum_{i=1}^{A} \bar{\psi}_i(x)\frac{1}{2}(1-\tau_3)\gamma_\mu\psi_i(x)$$

The static limit (with time reversal invariance)

for the nucleons we find the static Dirac equation

$$\left(\vec{\alpha}\vec{p} + V + \beta(m - S)\right)\psi_i = \varepsilon_i \psi_i .$$

$$S = -g_s \sigma, \quad V = g_\omega \omega_0 + g_\rho \rho_0 + eA_0$$

for the mesons we find the Helmholtz equations

No-sea approxim. !

$$\left(-\Delta + m_\sigma^2\right)\sigma = -g_\sigma \rho_s$$

$$\left(-\Delta + m_\omega^2\right)\omega_0 = g_\omega \rho_B$$

$$\left(-\Delta + m_\rho^2\right)\rho_0^3 = g_\rho \rho^3$$

$$-\Delta A_0 = e\rho^{(em)}$$

$$\rho_s = \sum_{i=1}^{A} \bar{\psi}_i \psi_i$$

$$\rho_B = \sum_{i=1}^{A} \psi_i^+ \psi_i$$

$$\rho^3 = \sum_{i=1}^{A} \psi_i^+ \tau_3 \psi_i$$

$$\rho^{(em)} = \sum_{i=1}^{A} \psi_i^+ \frac{1}{2}\left(1 - \tau_3\right)\psi_i$$

Relativistic saturation mechanism:

We consider only the σ-field, the origin of attraction
its source is the scalar density

$$m_\sigma^2 \sigma = -g_\sigma \sum_{i=1}^{A} \bar{\psi}_i \psi_i = -g_\sigma \sum_{i=1}^{A} \left(g_i^+ g_i - f_i^+ f_i \right)$$

for high densities, when the collapse is close, the Dirac gap ≈2m* decreases, the small components f_i of the wave functions increase and reduce the scalar density, i.e. the source of the σ-field, and therefore also scalar attraction.

$$f_i(\mathrm{r}) = \frac{1}{\varepsilon_i + 2\tilde{m}} \vec{\sigma}\vec{\mathrm{k}} g_i(\mathrm{r})$$

$$m_\sigma^2 \sigma \approx -g_\sigma \rho_B - 2\sum_{i=1}^{A} f_i^+ f_i = -g_\sigma \rho_B + \frac{1}{\tilde{m}} \sum_{i=1}^{A} \nabla g_i^+ \nabla g_i$$

In the non-relativistic case, Hartree with Yukawa forces would lead to collaps

Symmetric nuclear matter:

$$[\alpha \mathbf{k} + \beta(m - S)]\psi = [E - V]\psi$$

with $m^* = m - S$ and $E^* = \sqrt{\mathbf{k}^2 + m^{*2}}$ and $E = E^* + V$

we have plane wave solutions of the Dirac equation:

$$\psi(\mathbf{k}) = \sqrt{\frac{E^* + m^*}{2m^*}} \begin{pmatrix} 1 \\ \dfrac{\sigma \mathbf{k}}{E^* + m^*} \end{pmatrix} \chi$$

the ω-field is given by the density:

$$V = g_\omega \omega_0 = \left(\frac{g_\omega}{m_\omega}\right)^2 \rho_B$$

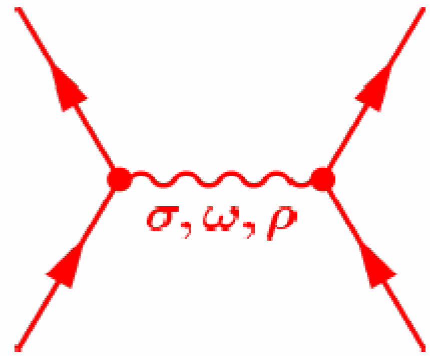
the σ-field has to be determined from a non-linear equation, which gives saturation:

$$S = -g_\sigma \sigma = m - m^* = \frac{g_\sigma^2}{m_\sigma^2} \rho_s = \gamma \frac{g_\sigma^2}{m_\sigma^2} \int \frac{d^3k}{(2\pi)^3} \frac{m^*}{E^*(k)}$$

$$= \frac{\gamma}{4\pi^2} \frac{g_\sigma^2}{m_\sigma^2} m^* \left[k_F E_F^* - m^{*2} \ln\left(\frac{k_F}{m^*} + \frac{E_F^*}{m^*} \right) \right]$$

One needs only 2 constants: $G_\sigma = \left(\frac{g_\sigma}{m_\sigma}\right)^2 = 11{,}75\ \text{fm}^2$ $G_\omega = \left(\frac{g_\omega}{m_\omega}\right)^2 = 8{,}61\ \text{fm}^2$

Relativistic Pairing:



One has to quantize the meson fields:

Fermion fields: $\int d^3r\, \hat{\bar{\psi}}(\alpha\, \mathrm{p} - \beta m)\hat{\psi}$

Boson fields: $\sum_{\mu} \omega^{\mu}\, a^{+}_{\mu} a_{\mu}$

Interaction: $-\sum_{\mu} \hat{\bar{\psi}}\Gamma^{\mu}\hat{\psi}\, \hat{\phi}_{\mu}$

neglect retardation

Eliminate the meson operators: $\hat{\phi}_{\mu}(\mathrm{r}) = \frac{g_{\mu}}{4\pi}\int d^3r' \frac{e^{-m_{\mu}|\mathrm{r}-\mathrm{r}'|}}{|\mathrm{r} - \mathrm{r}'|}\hat{\bar{\psi}}(\mathrm{r}')\Gamma^{\mu}\hat{\psi}(\mathrm{r}')$

Formulation in Green's functions:

Gorkov factorization

$$\langle \psi_1^{+}\psi_2^{+}\psi_3\psi_4 \rangle \approx \langle \psi_1^{+}\psi_4 \rangle\langle \psi_2^{+}\psi_3 \rangle - \langle \psi_1^{+}\psi_3 \rangle\langle \psi_2^{+}\psi_4 \rangle + \langle \psi_1^{+}\psi_2^{+} \rangle\langle \psi_3\psi_4 \rangle$$

direct term   exchange term   pairing term

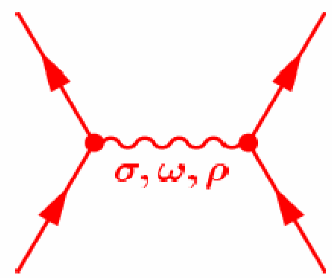
Relativistic HFB equations:

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

$$\hat{h} = \vec{\alpha}\left(\vec{p} - \vec{V}\right) + V + \beta(m - S)$$

$$\hat{\Delta} = \begin{pmatrix} \hat{\Delta}_{++} & \hat{\Delta}_{+-} \\ \hat{\Delta}_{-+} & \hat{\Delta}_{--} \end{pmatrix} = \beta\Delta_s + \Delta_0 + \vec{\alpha}\vec{\Delta}$$

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



Pairing in nuclear matter:

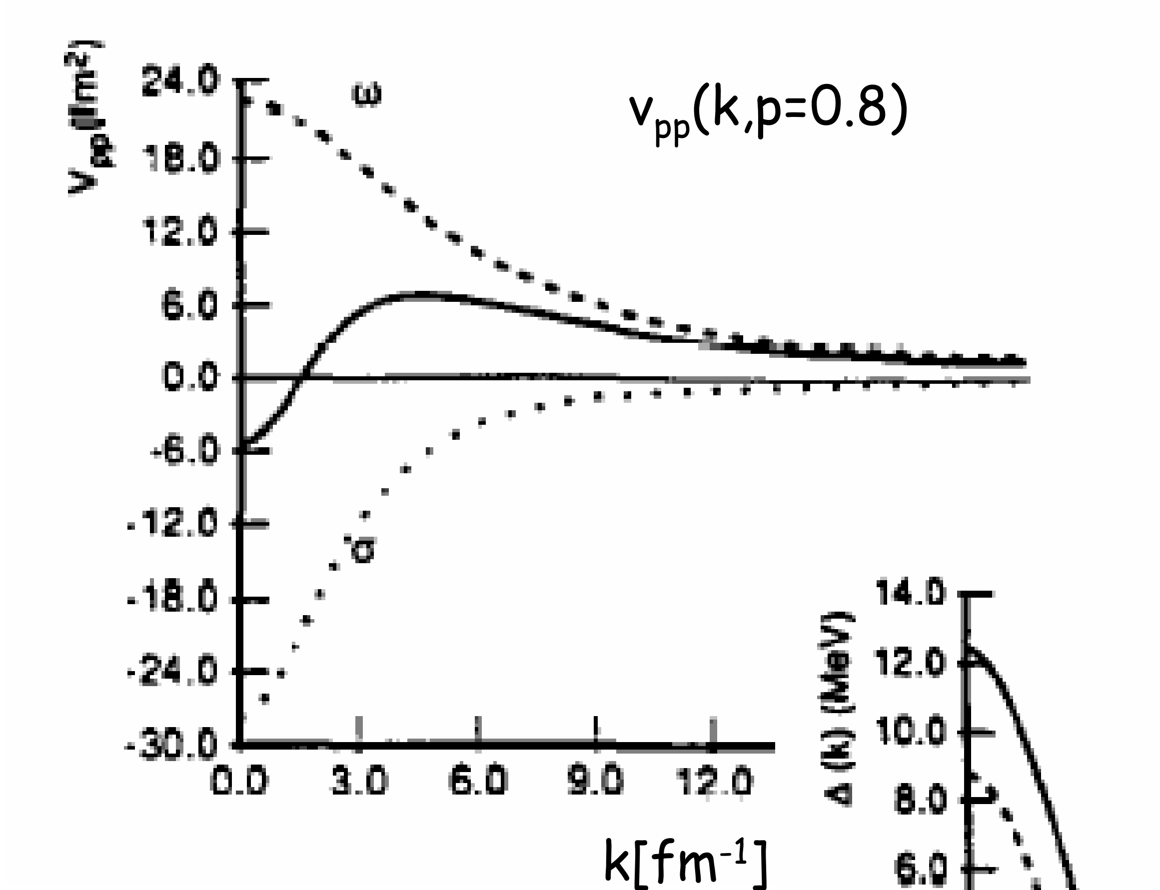
$$^{1}S_{0} - Channel$$

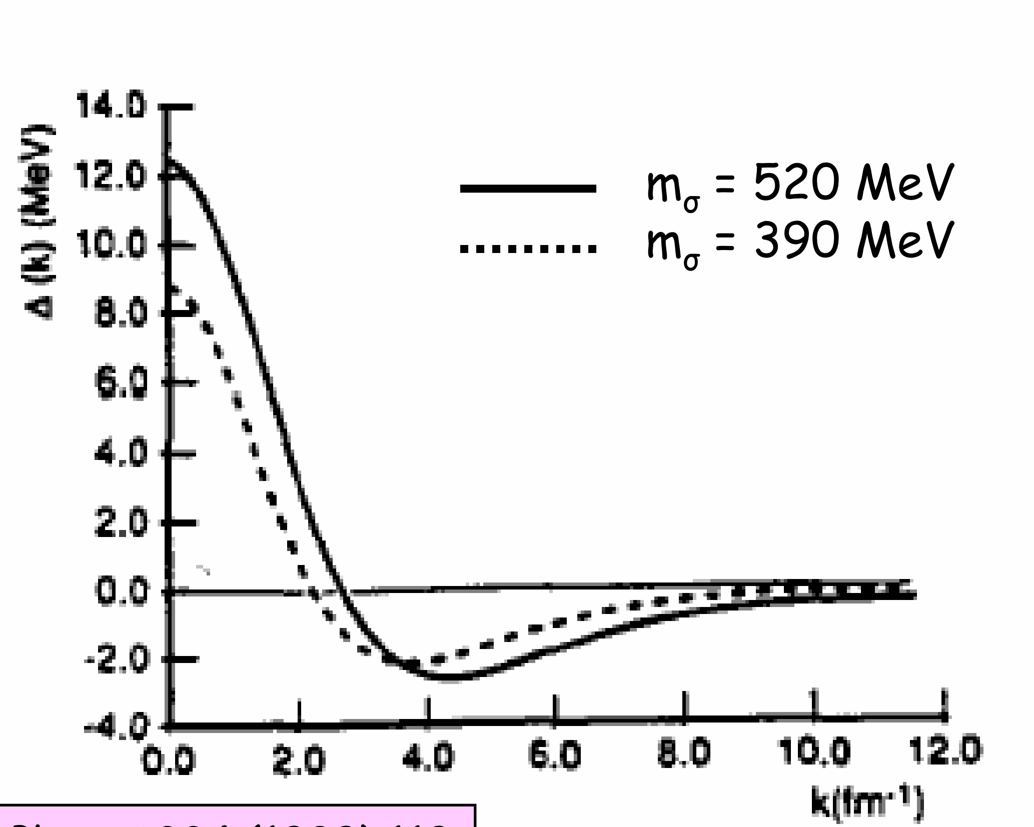
RMF+BCS

Gap equation: Δ = v κ= v uv

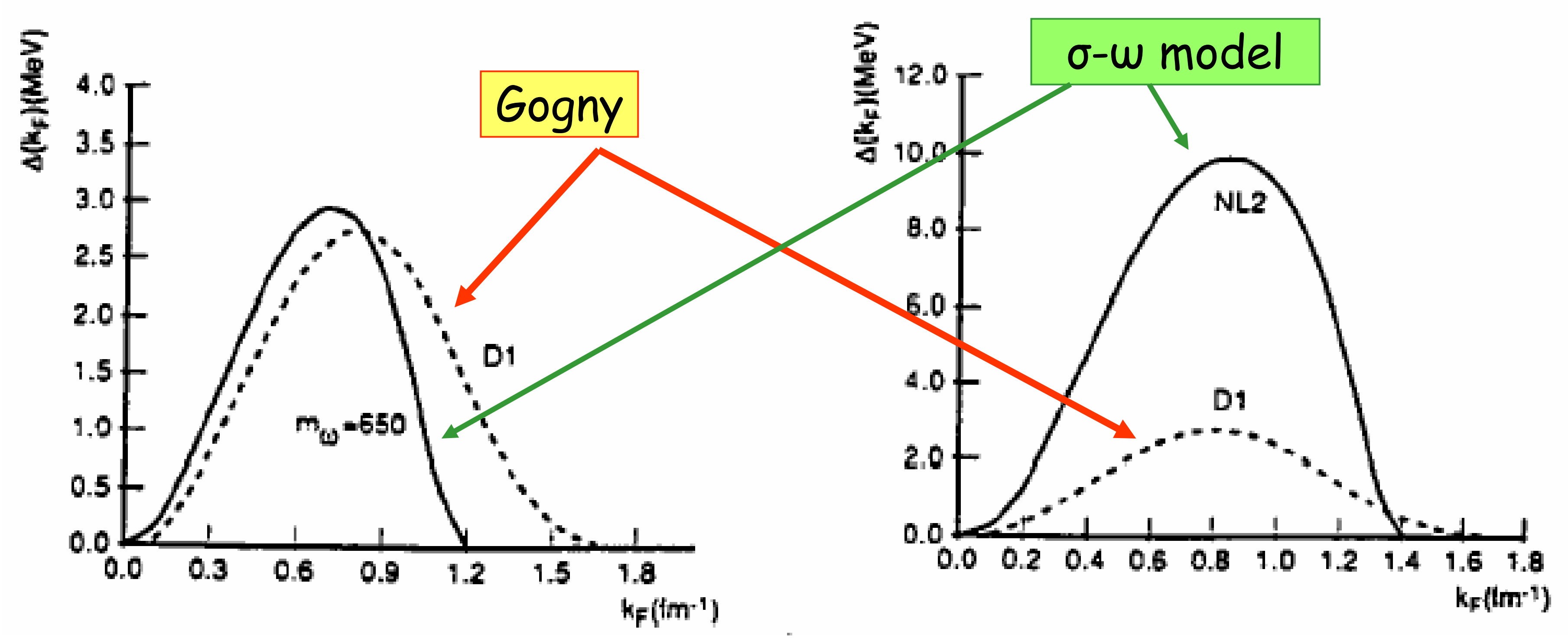
$$\Delta(p) = -\frac{1}{4\pi^2}\int_0^\infty v_{pp}(p,k)\frac{\Delta(k)}{\sqrt{(\varepsilon(k)-\lambda)^2+\Delta^2(k)}}k^2dk$$

$$v_{pp}^{\omega}(p,k) = \frac{g_\omega^2}{2E^*(p)E^*(k)}\frac{m^{*2}+p^2+k^2-(E^*(p)-E^*(k))^2}{pk}\ln\left(\frac{(p+k)^2+m_\omega^2}{(p-k)^2+m_\omega^2}\right)$$



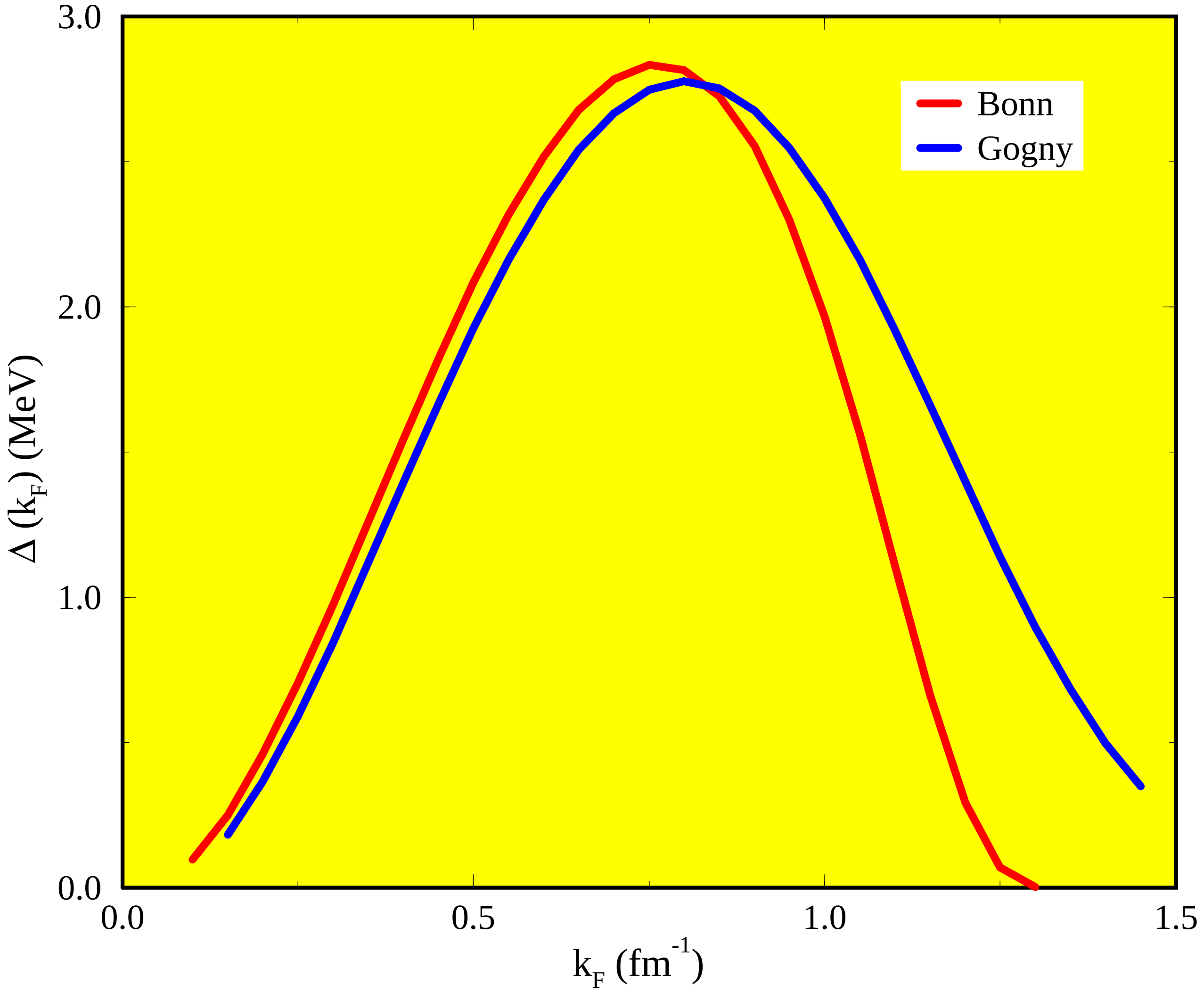


H. Kucharek, P. Ring, and P. Schuck, Z. Phys. A334 (1989) 119



All relativistic forces, e. g. NL1, NL2, … overestimate nuclear pairing by a factor 3, because they do not have a cut off in momentum space

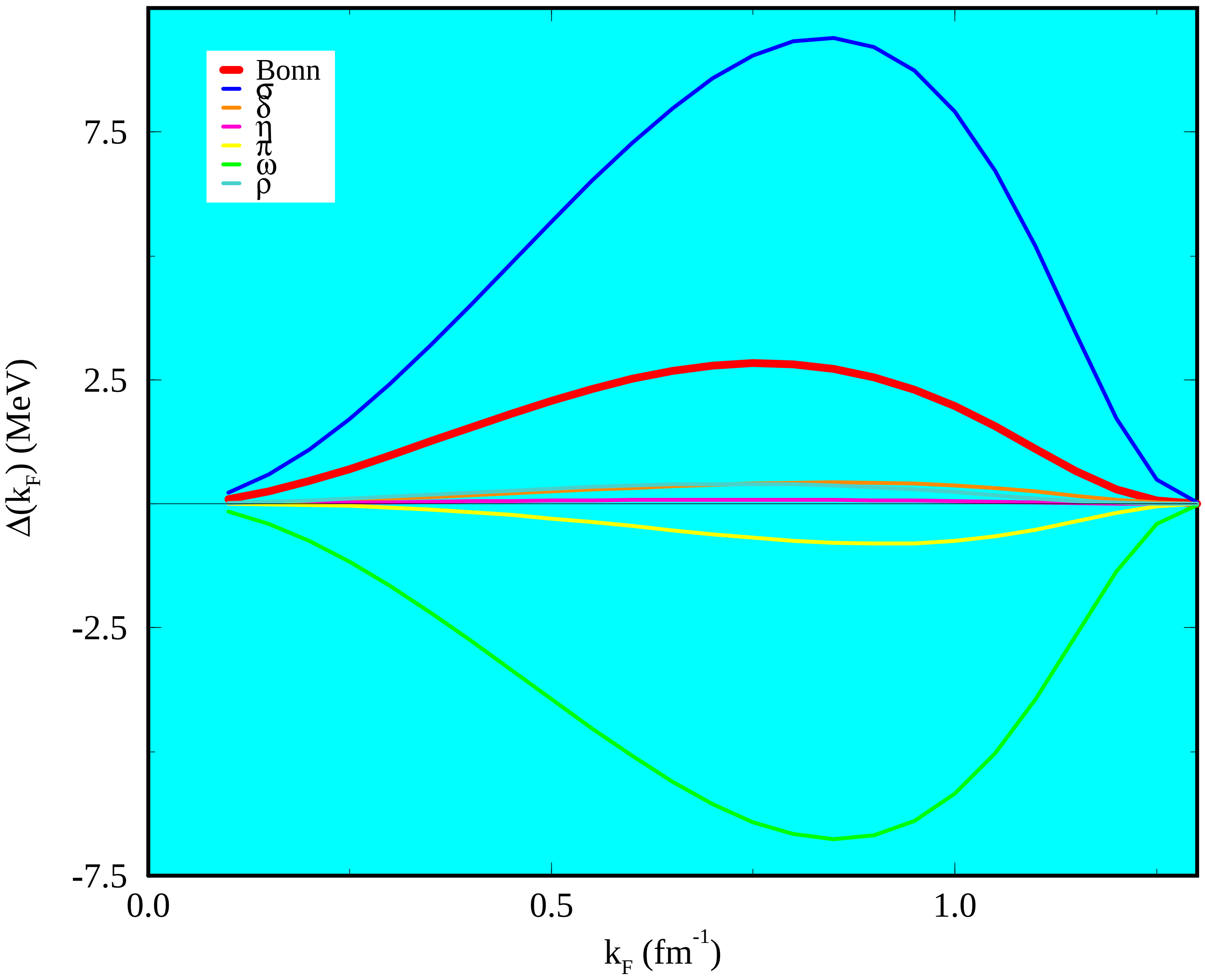
H. Kucharek, P. Ring, and P. Schuck, Z. Phys. A334 (1989) 119



free NN-forces, which reproduce the phase shift in the 1S0 channel, give pairing similar to the Gogny force

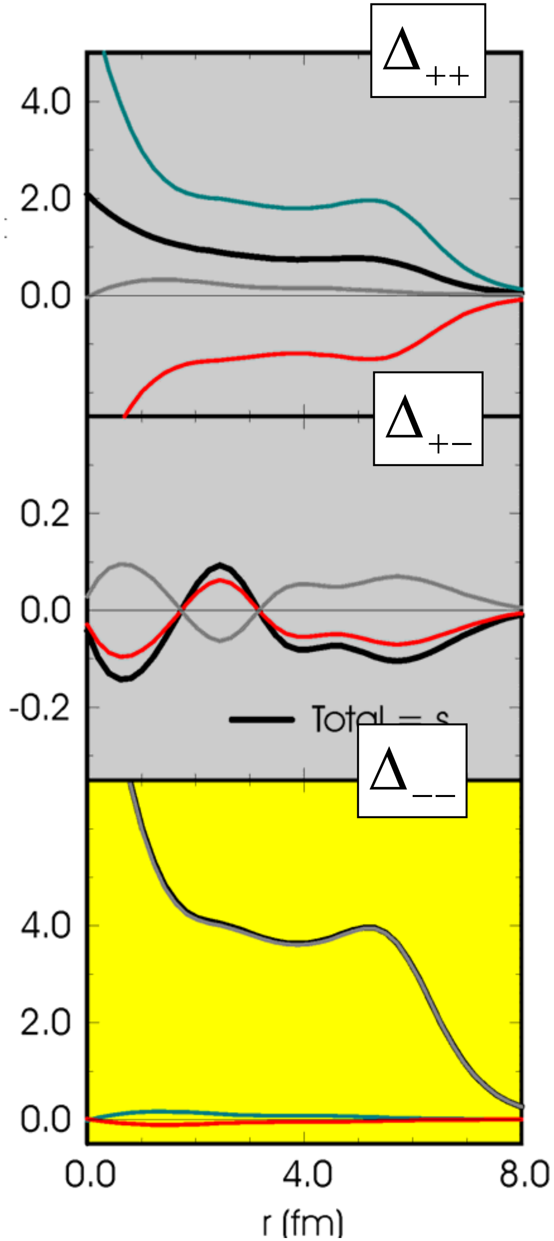
M. Serra, A. Rummel, P. Ring, PRC 65 (2002) 014304

M. Serra, A. Rummel, P. Ring, PRC 65 (2002) 014304



contributions of the various meson fields in the B-potential to pairing

Relativistic structure of pairing



$$\mathbf{H} = \begin{pmatrix} m+V-S & \boldsymbol{\sigma}\mathbf{p} & \Delta_{++} & \Delta_{+-} \\ \boldsymbol{\sigma}\mathbf{p} & -m-V-S & \Delta_{-+} & \Delta_{--} \\ \Delta_{++} & \Delta_{+-} & -m-V+S & -\boldsymbol{\sigma}\mathbf{p} \\ \Delta_{-+} & \Delta_{--} & -\boldsymbol{\sigma}\mathbf{p} & m+V+S \end{pmatrix}$$

$$\Delta_{+-} = \Delta_{-+} \ll \Delta_{++} \ll \boldsymbol{\sigma}\mathbf{p}$$

therefore we neglect Δ_{+-}

- total
- scalar
- vector time-like
- vector spacelike

M. Serra, P. Ring, PRC 65 (2002) 064324

Relativistic Hartree Bogoliubov (RHB):

A	E/A			E_{pair}	
	expt.	RHB	Gogny	RHB	Gogny
112	-8.513	-8.558	-8.419	-22.84	-19.04
116	-8.523	-8.563	-8.437	-22.75	-19.39
120	-8.505	-8.538	-8.417	-21.89	-17.92
124	-8.467	-8.487	-8.378	-19.68	-14.94
128	-8.418	-8.414	-8.326	-13.97	-9.45
132	-8.355	-8.319	-8.283	0.00	0.00

$$\hat{h} = \frac{\delta E'_{\mathrm{RMF}}}{\delta \hat{\rho}}$$

$$\hat{\Delta} = \frac{\delta E_{\mathrm{GOG}}}{\delta \hat{\kappa}}$$

$$E[\rho,\kappa] = E_{\mathrm{RMF}}[\rho] + E_{\mathrm{Gogny}}[\kappa]$$

T. Gonzales-Llarena, J.L. Egido, G.A. Lalazissis, P. Ring PLB 379 (1996) 13

Conclusions part I:

1) density functional theory is in principle exact
2) microscopic derivation of E(ρ) very difficult
3) Lorentz symmetry gives essential constraints
   - large spin orbit splitting
   - relativistic saturation
   - unified theory of time-odd fields
4) pairing effects are non-relativisitic

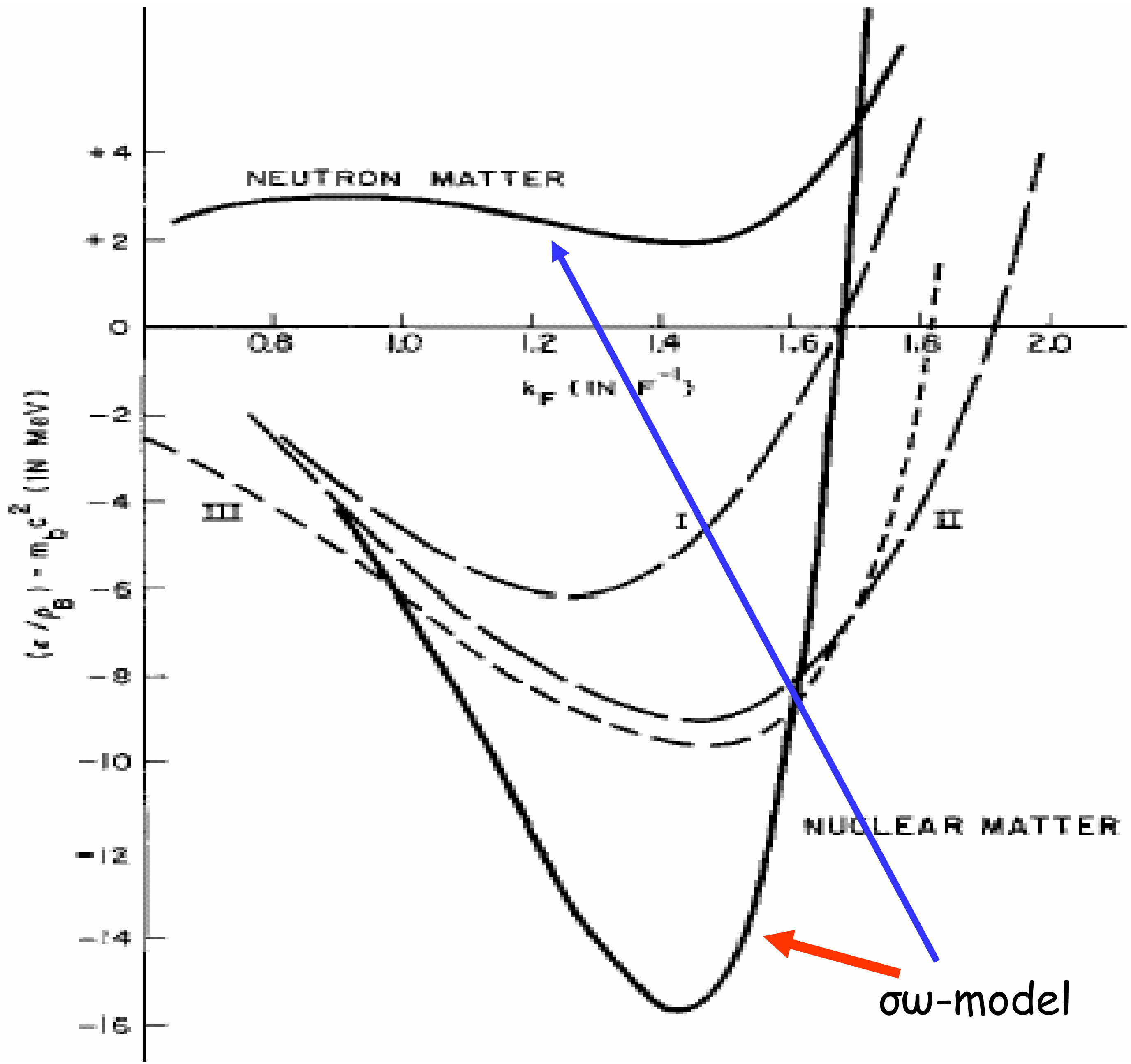
Content II

- **Ground state properties**

* nuclear matter
* masses, radii, deformations
* shell quenching
* neutron skins and halo phenomena
* proton emitters
* superheavy elements

- **Vibrational excitations**

* breathing modes (incompressibility)
* giant dipole modes (symmetry energy)
* pygmy resonances
* isobaric analog resonances
* Gamov-Teller resonances



J.D. Walecka, Ann.Phys. (NY) 83, (1974) 491

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)

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

new

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

DD-ME1,DD-ME2

Parameterization of denstiy dependence

MICROSCOPIC: Dirac-Brueckner calculations

PHENOMENOLOGICAL:

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

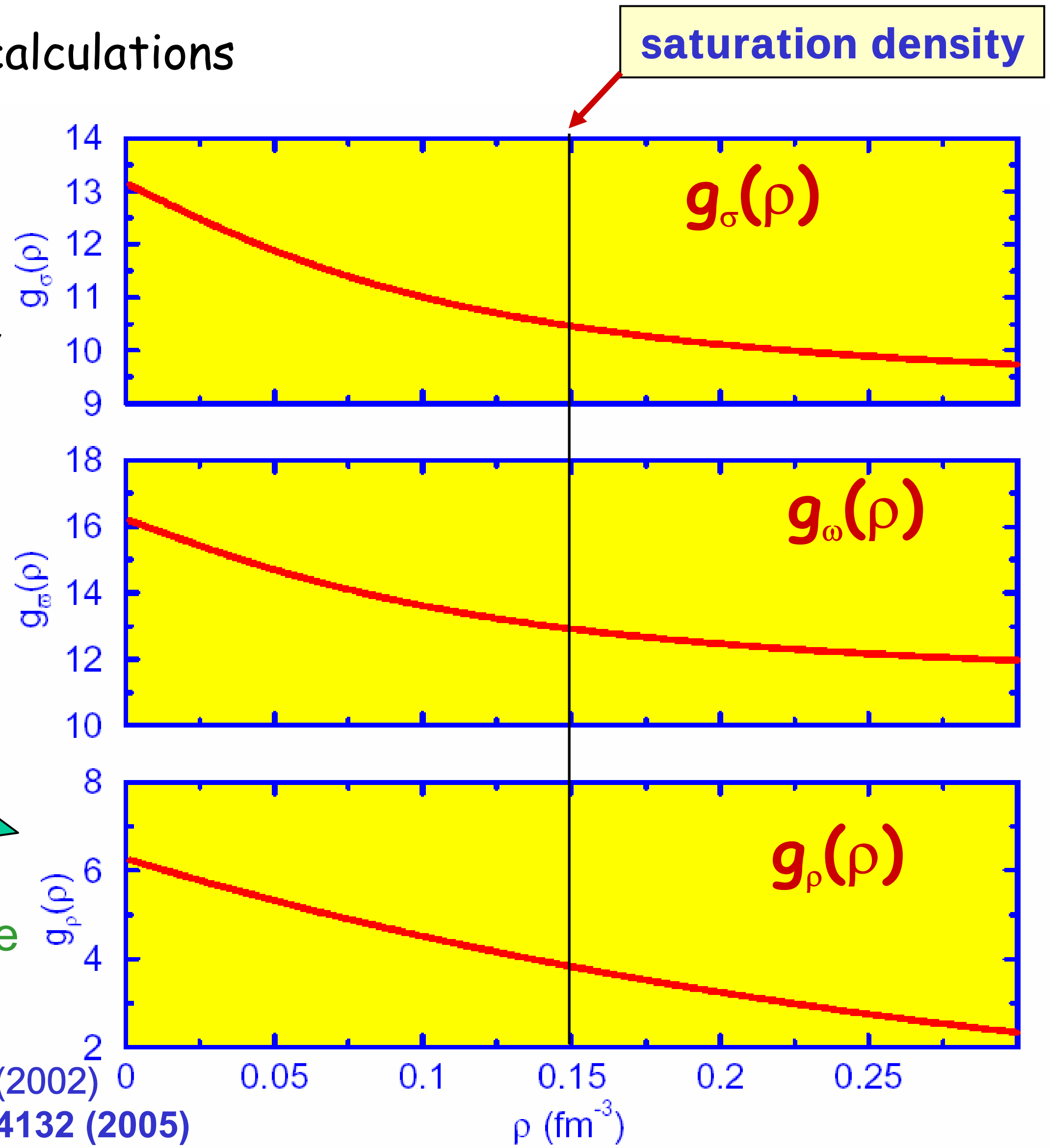
$$f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}$$

$$i = \sigma, \omega$$

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

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

4 parameters for density dependence



Typel and Wolter, NPA 656, 331 (1999)
Niksic, Vretenar, Finelli, Ring, PRC 66, 024306 (2002)
Lalazissis, Niksic, Vretenar, Ring, PRC 71 024132 (2005)

How many parameters ?

7 parameters

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

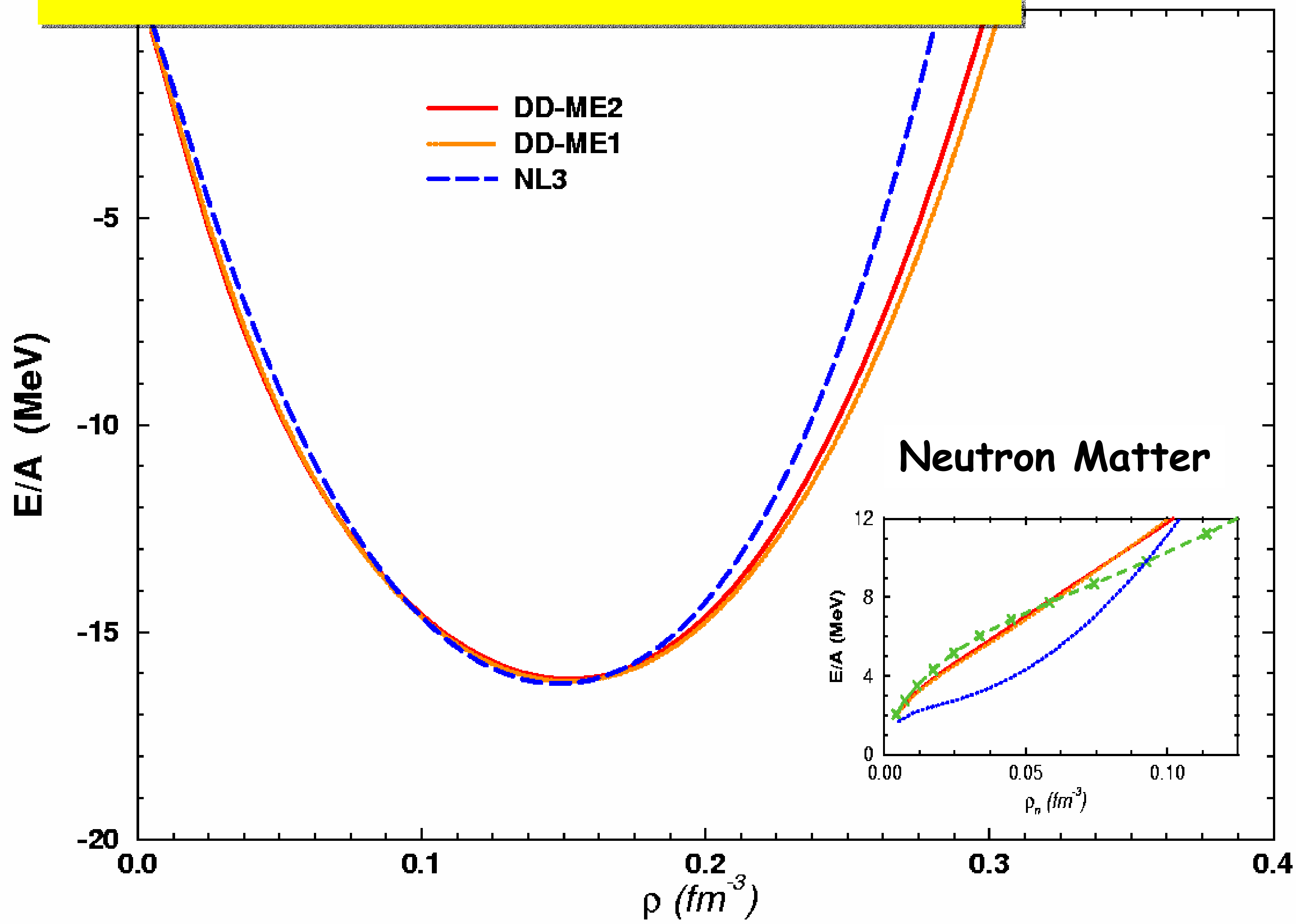
finite nuclei (N=Z): E/A, radii
spinorbit for free → m_σ

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

density dependence: T=0 K_∞ → g_2 g_2

T=1 r_n - r_p → a_ρ

Nuclear matter equation of state



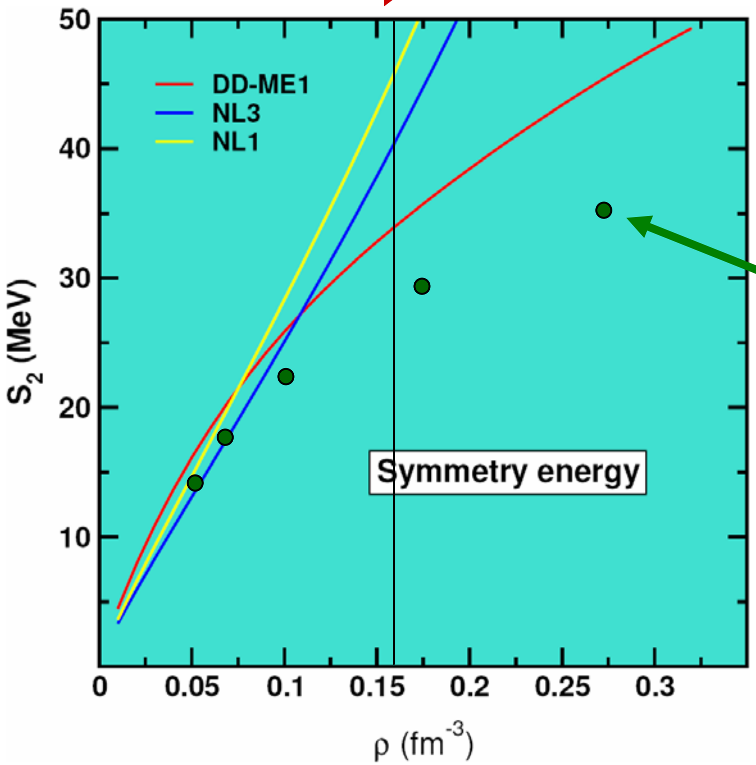
Symmetry energy

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

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

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

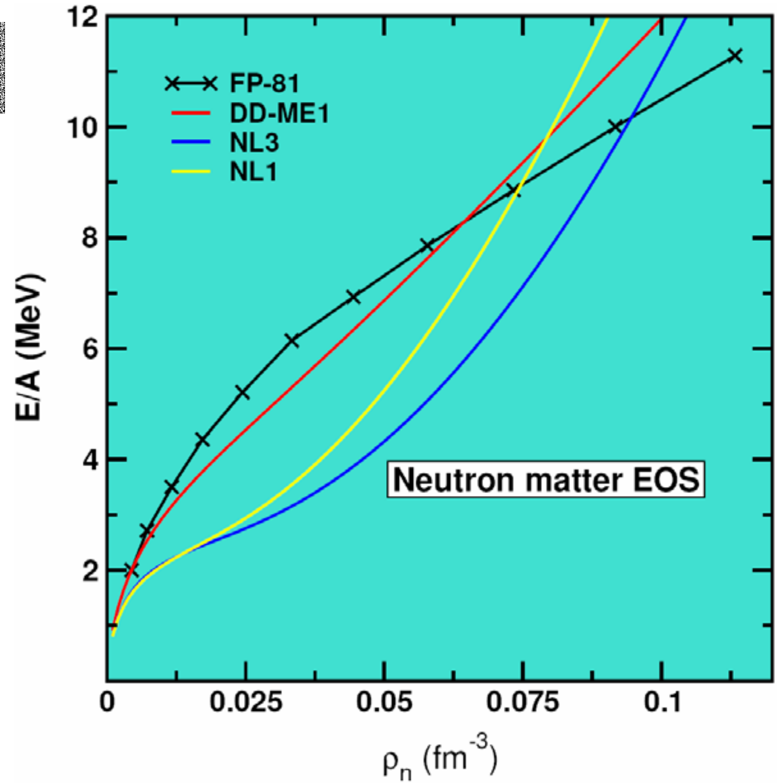
saturation density



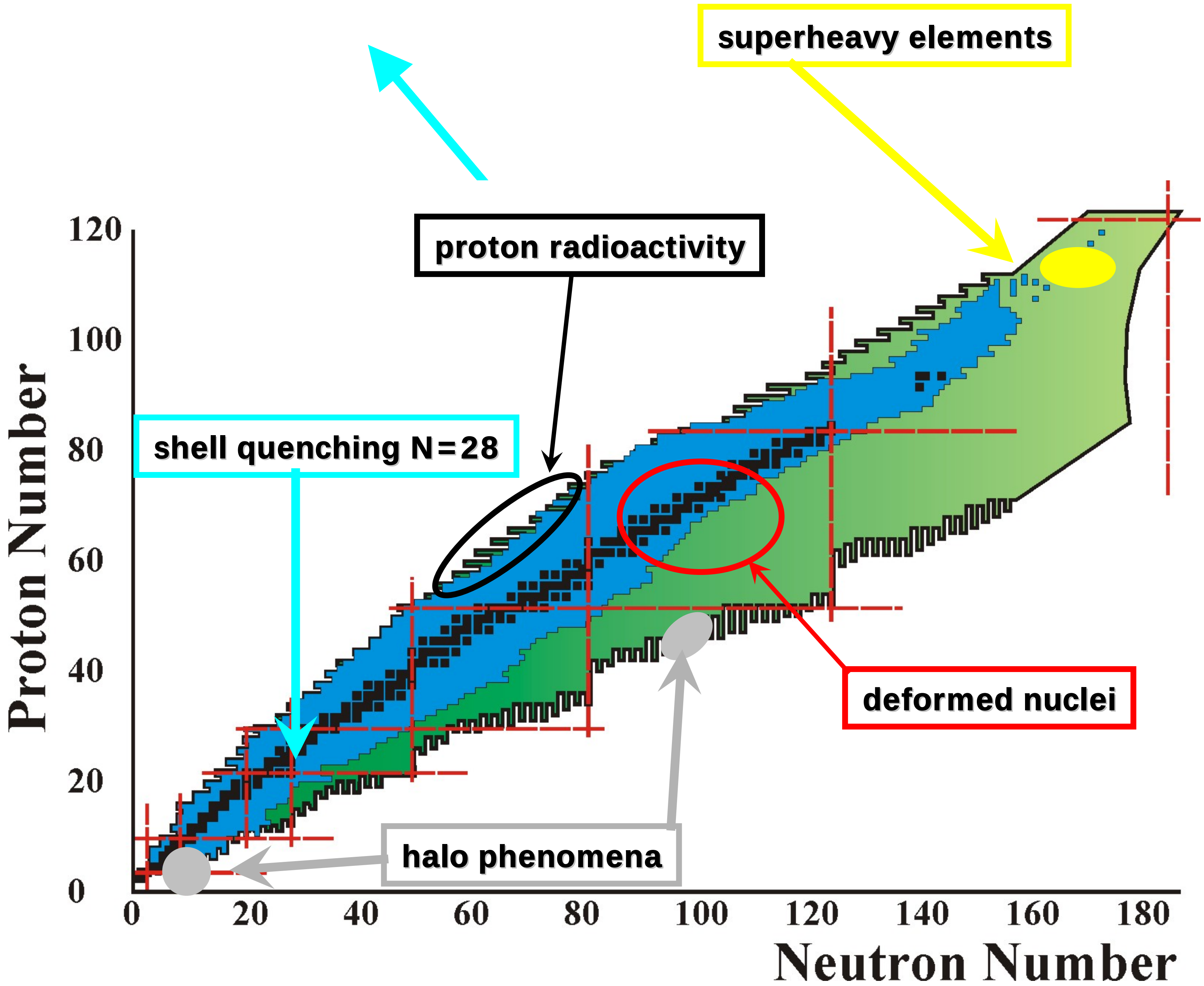
Lombardo

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



superheavy elements
proton radioactivity
shell quenching N=28
deformed nuclei
halo phenomena
120
100
80
60
40
20
0
Proton Number
0
20
40
60
80
100
120
140
160
180
Neutron Number

Relativistic Hartree Bogoliubov theory (RHB)

Ground-state properties of weakly bound nuclei far from stability

→ Unified description of mean-field and pairing correlations

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

Dirac hamiltonian

chemical potential

quasiparticle energy

pairing field

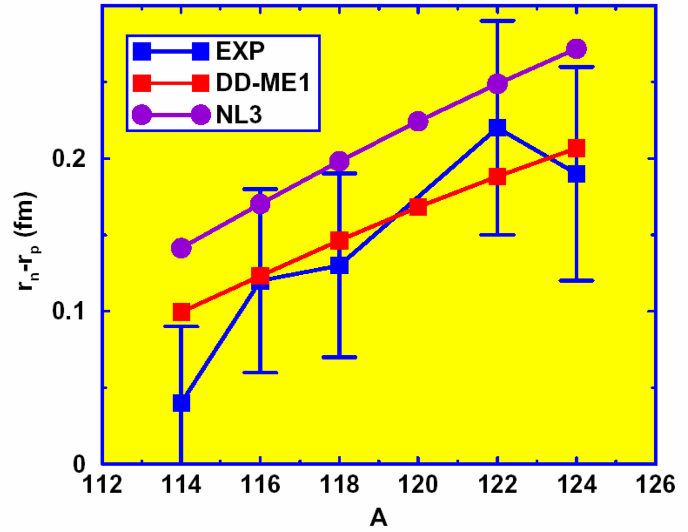
nucleon mass

quasiparticle wave function

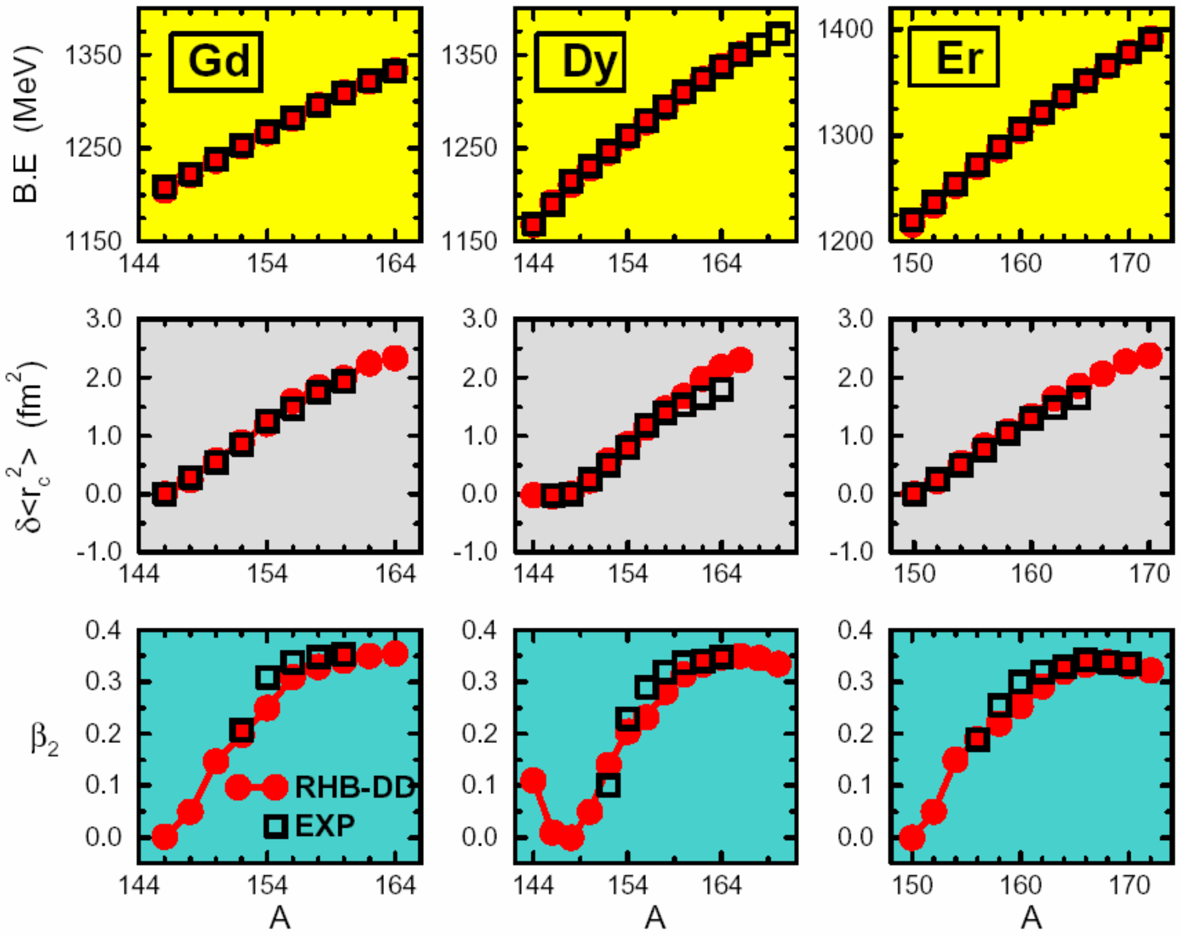
$$\Delta_{ab}(\vec{r}, \vec{r}') = \frac{1}{2} \sum_{c,d} V^{pp}_{abcd}(\vec{r}, \vec{r}') \kappa_{cd}(\vec{r}, \vec{r}')$$

DD-ME1

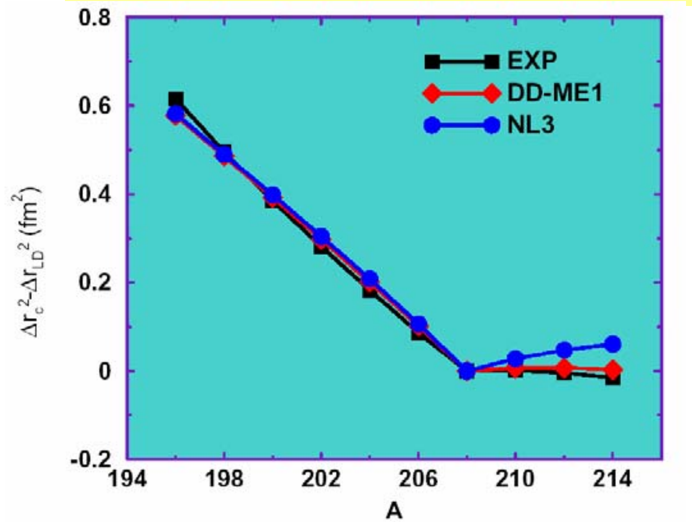
Ground state properties of finite nuclei



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

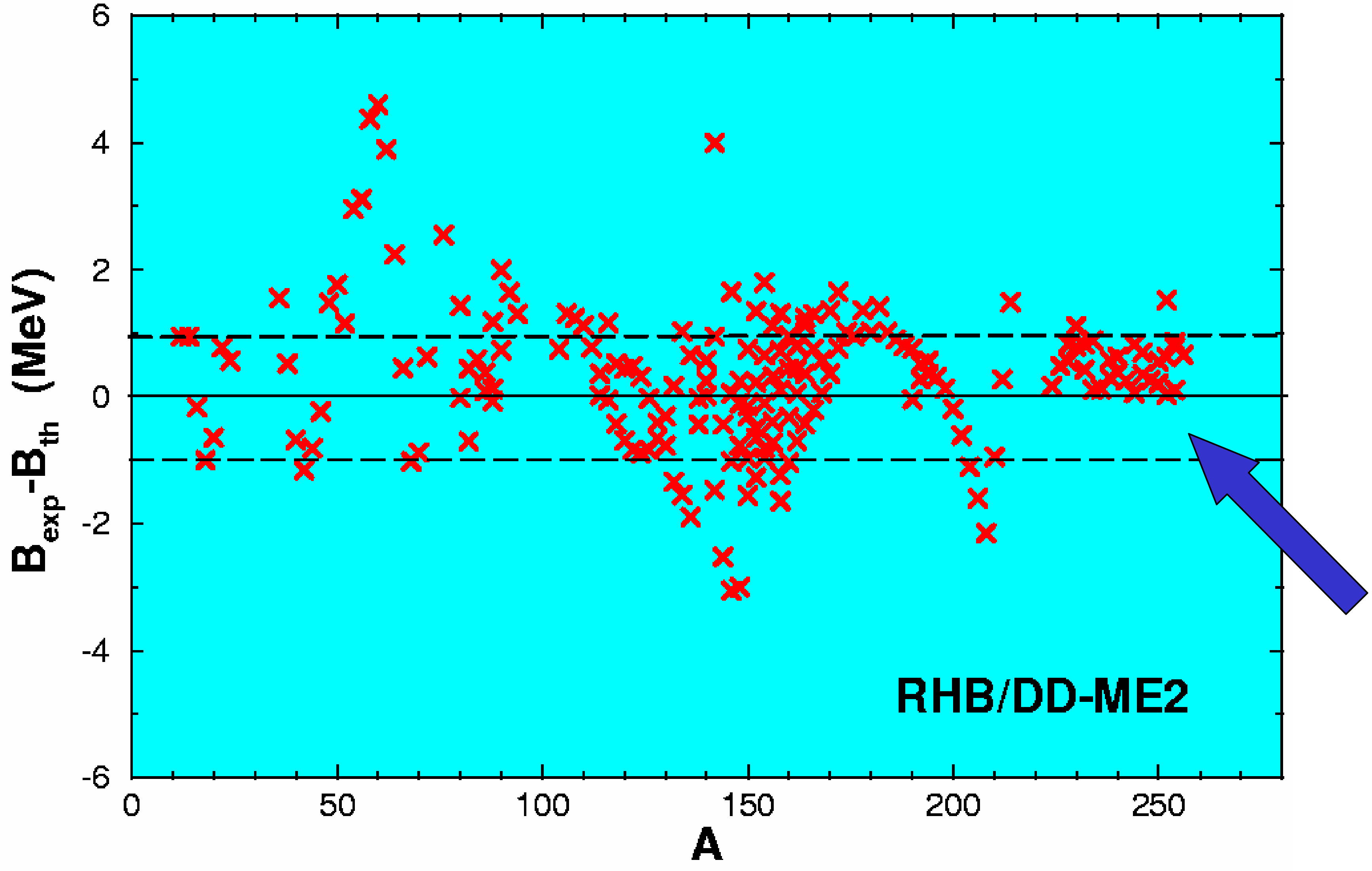


Charge isotope shifts in even-A Pb isotopes.



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

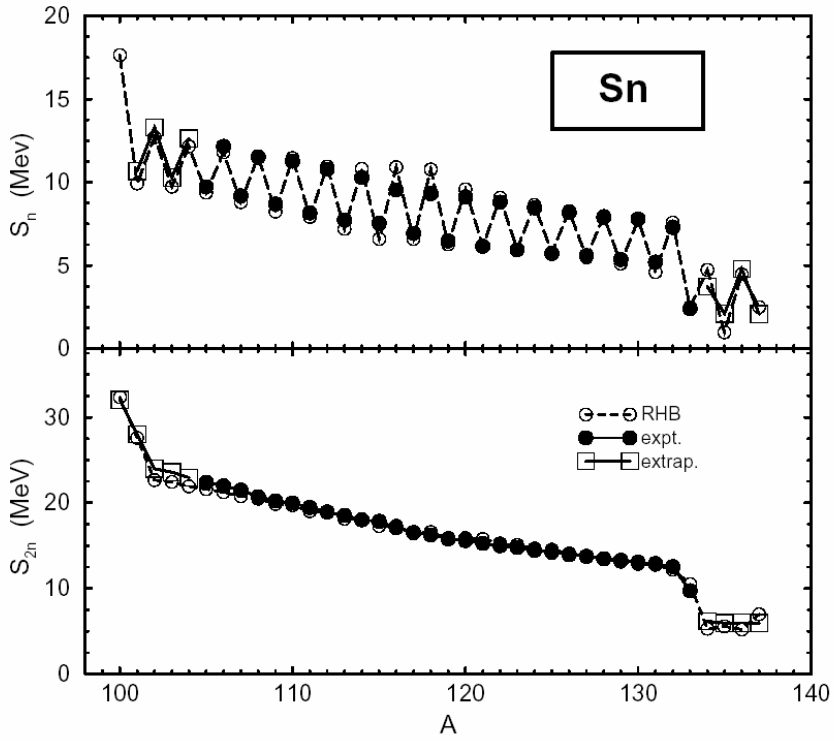
Lalazissis, Niksic, Vretenar, Ring, PRC submitted



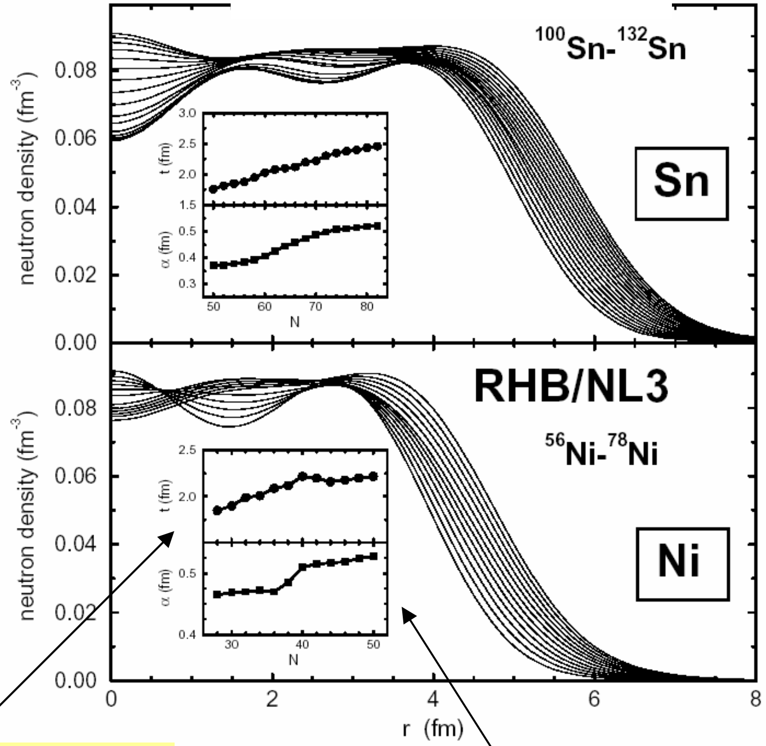
ground state properties of Ni and Sn isotopes

Lalazissis, Vretenar, Ring, Phys. Rev. C57, 2294 (1998)

combination of the NL3 effective interaction for the RMF Lagrangian, and the Gogny interaction with the parameter set D1S in the pairing channel.



Neutron densities



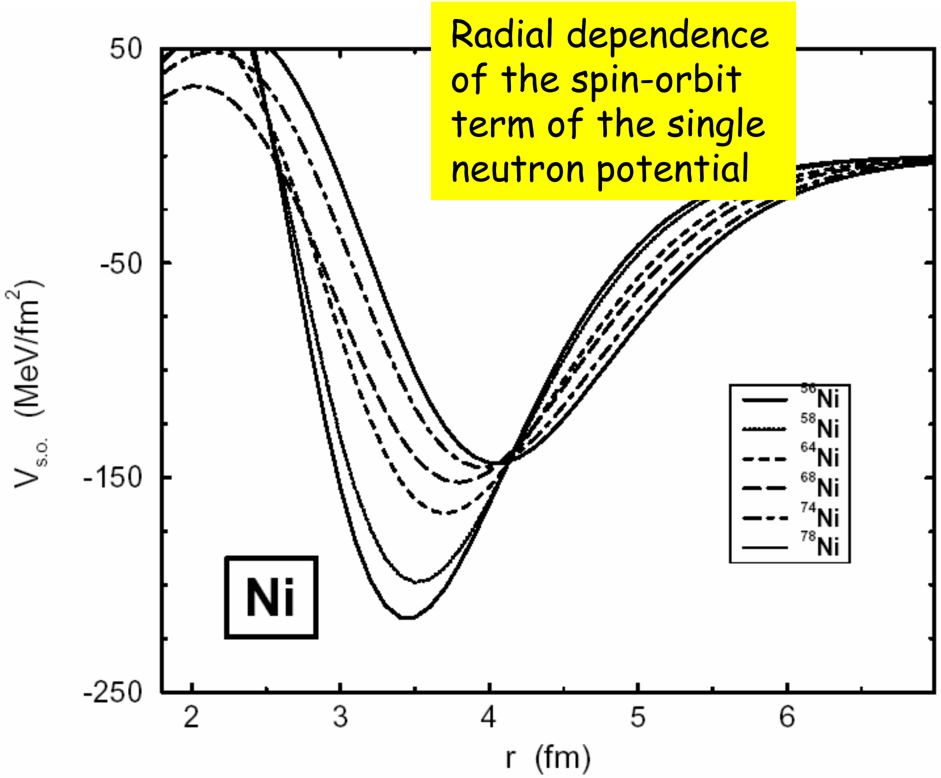
One- and two-neutron separation energies

surface thickness

surface diffuseness α

$$\rho(r) = \rho_0 \left(1 + exp(\frac{r - R_0}{\alpha})\right)^{-1}$$

reduction of the spin-orbit potential



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).

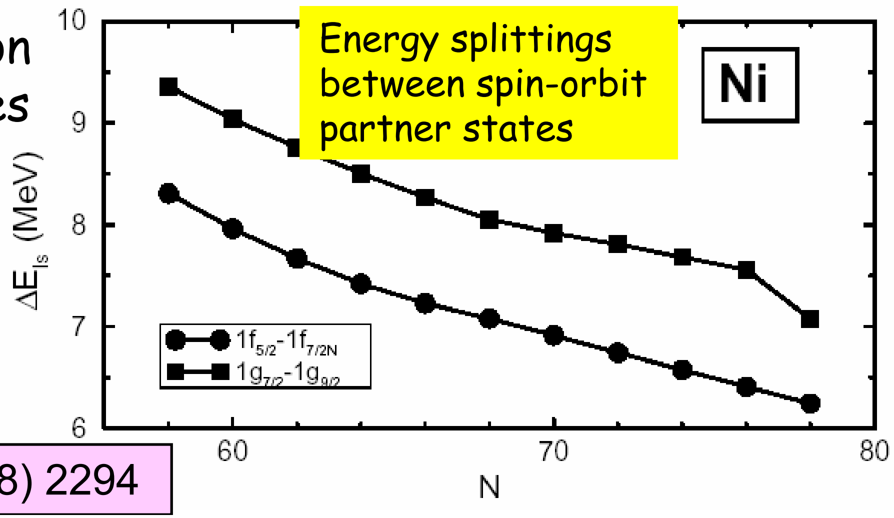
$$V_{s.o.} \approx \frac{1}{r}\frac{\partial}{\partial r} V_{ls}(r)$$

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

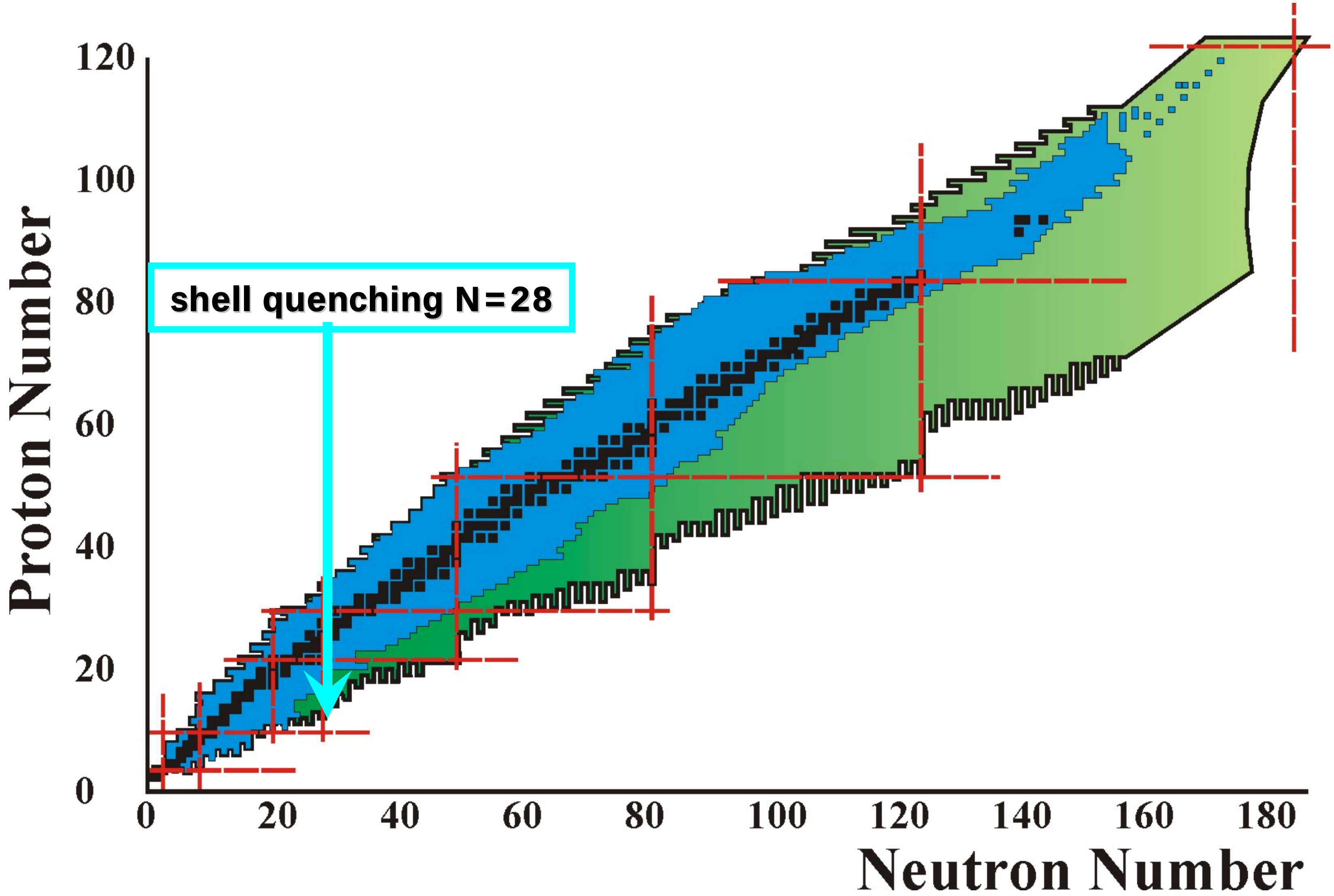
weakening of the effective single-neutron spin-orbit potential in neutron-rich isotopes

⇒ reduced energy spacings between spin-orbit partners

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



G. A. Lalazissis, D. Vretenar, P. Ring, NPA **57** (1998) 2294



shell quenching N=28
120
100
80
60
40
20
0
Proton Number
0
20
40
60
80
100
120
140
160
180
Neutron Number

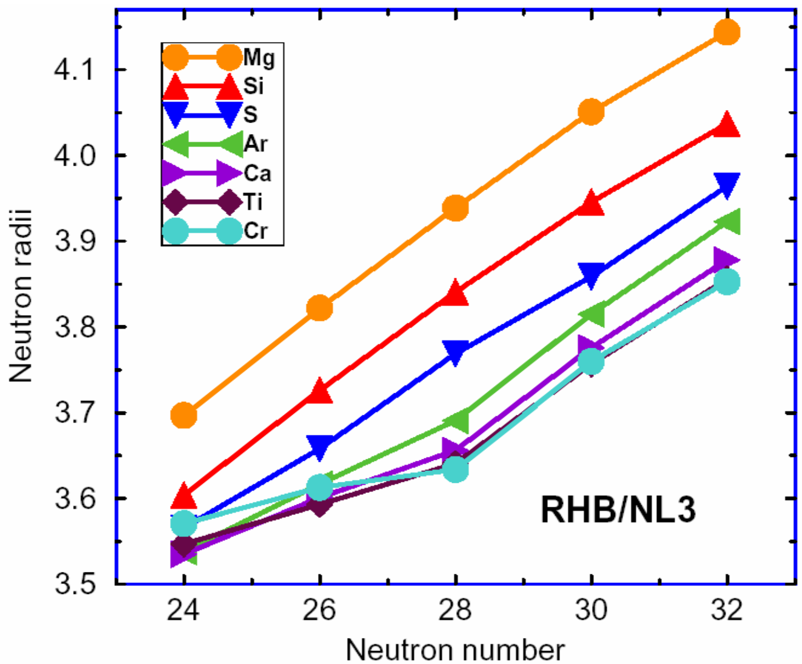
Shape coexistence in the deformed N=28 region

Lalazissis, Vretenar, Ring, Stoitsov, Robledo, Phys. Rev. C60, 014310 (1999)

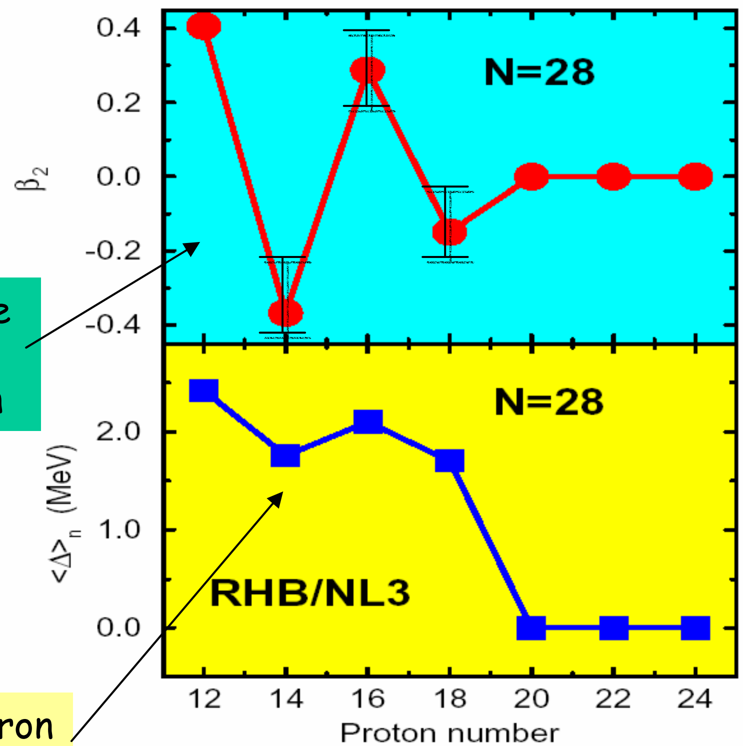
RHB description of neutron rich N=28 nuclei. NL3+D1S effective interaction.

Strong suppression of the spherical N=28 shell gap.

1f7/2 -> fp core breaking → Shape coexistence

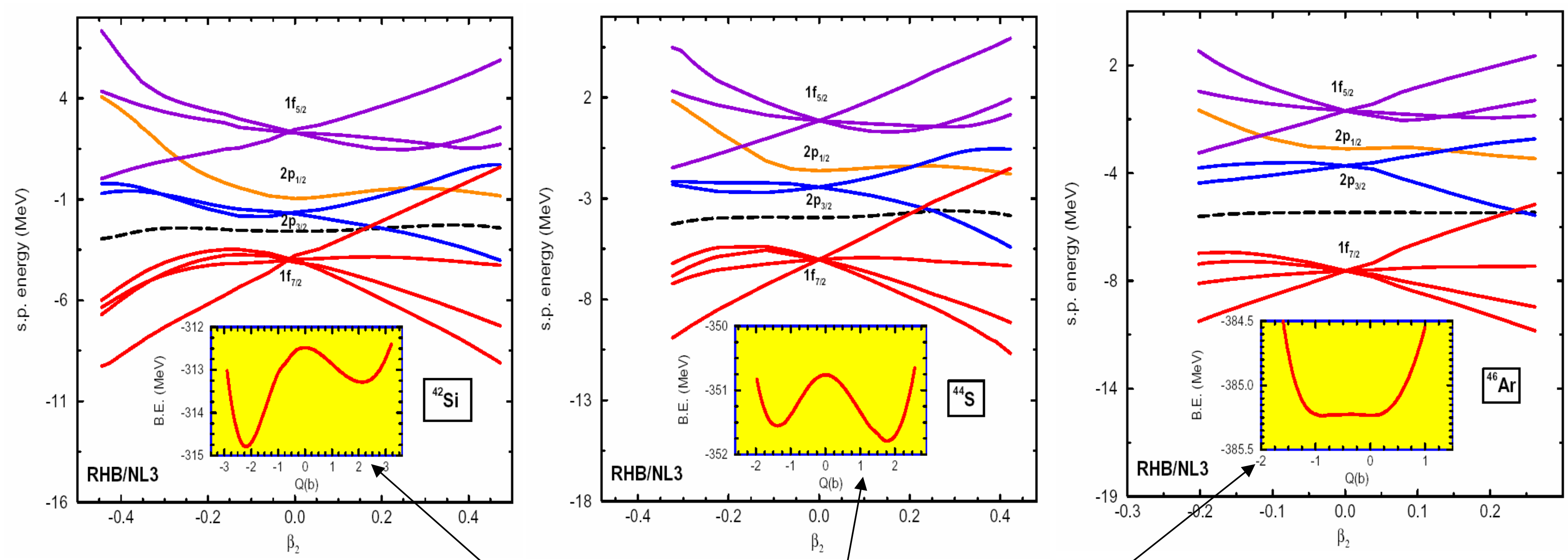


Ground-state quadrupole deformation



Average neutron pairing gaps

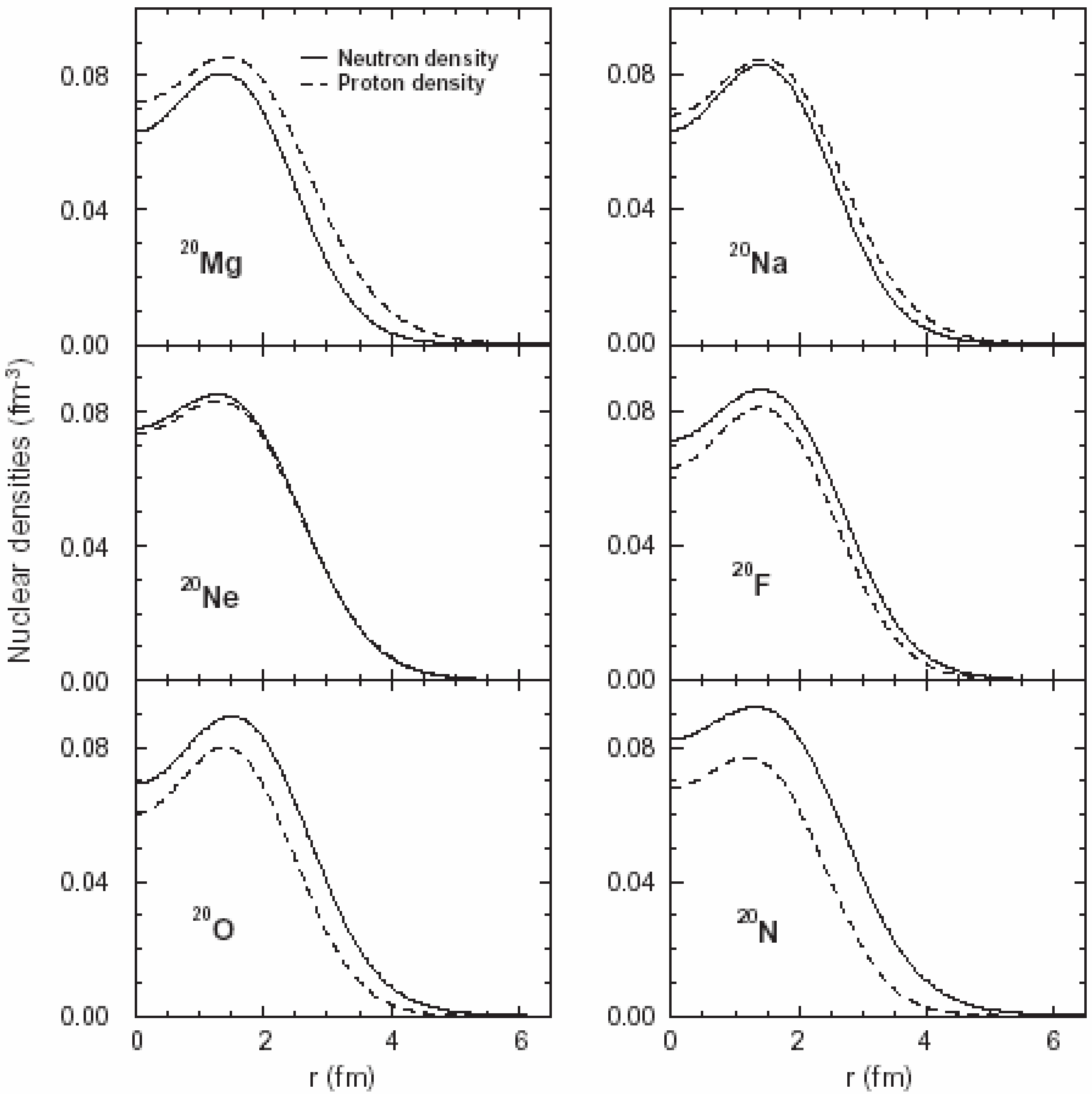
Neutron single-particle levels for ^{42}Si, ^{44}S, and ^{46}Ar as functions of the quadrupole deformation. The energies in the canonical basis correspond to ground-state RHB solutions with constrained quadrupole deformation.



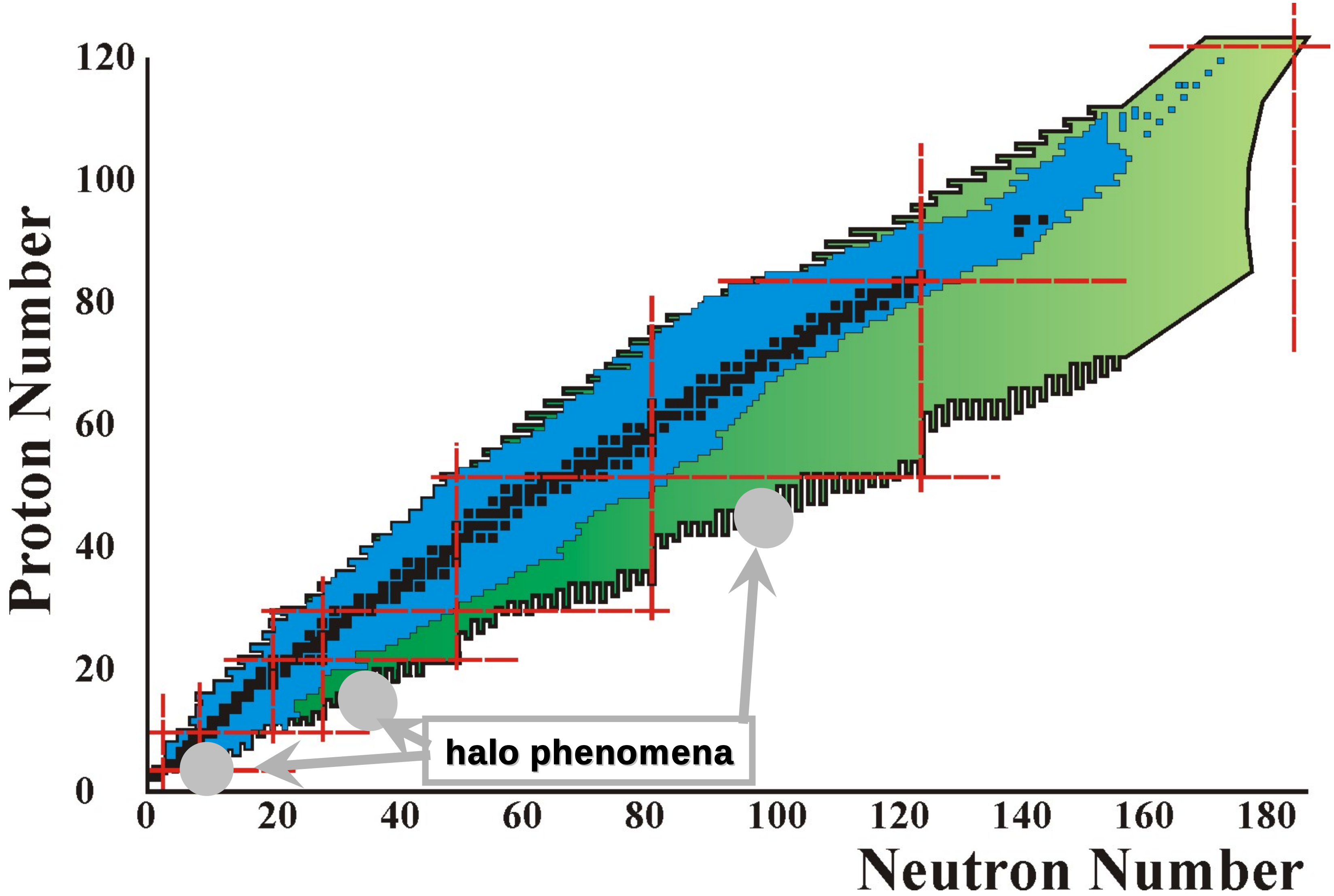
Total binding energy curves

SHAPE COEXISTENCE

Evolution of the shell structure, shell gaps and magicity with neutron number!

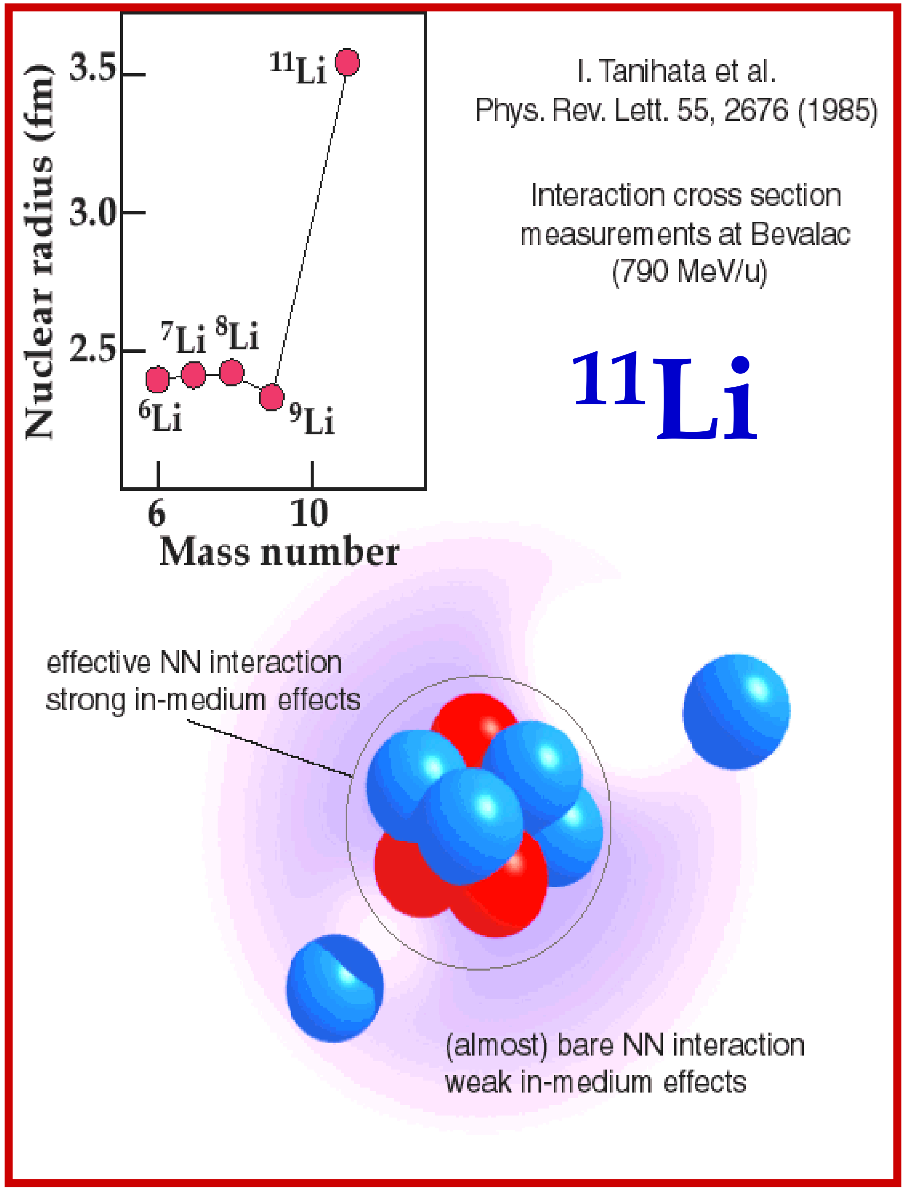


proton- and
neutron skins



halo phenomena
Proton Number
Neutron Number
0
20
40
60
80
100
120
140
160
180

Neutron halo's



Mean field theory of halo's: (RHB in the continuum)

advantages:

* residual interaction by pairing
* self-consistent description
* universal parameters
* polarization of the core
* treatment of the continuum

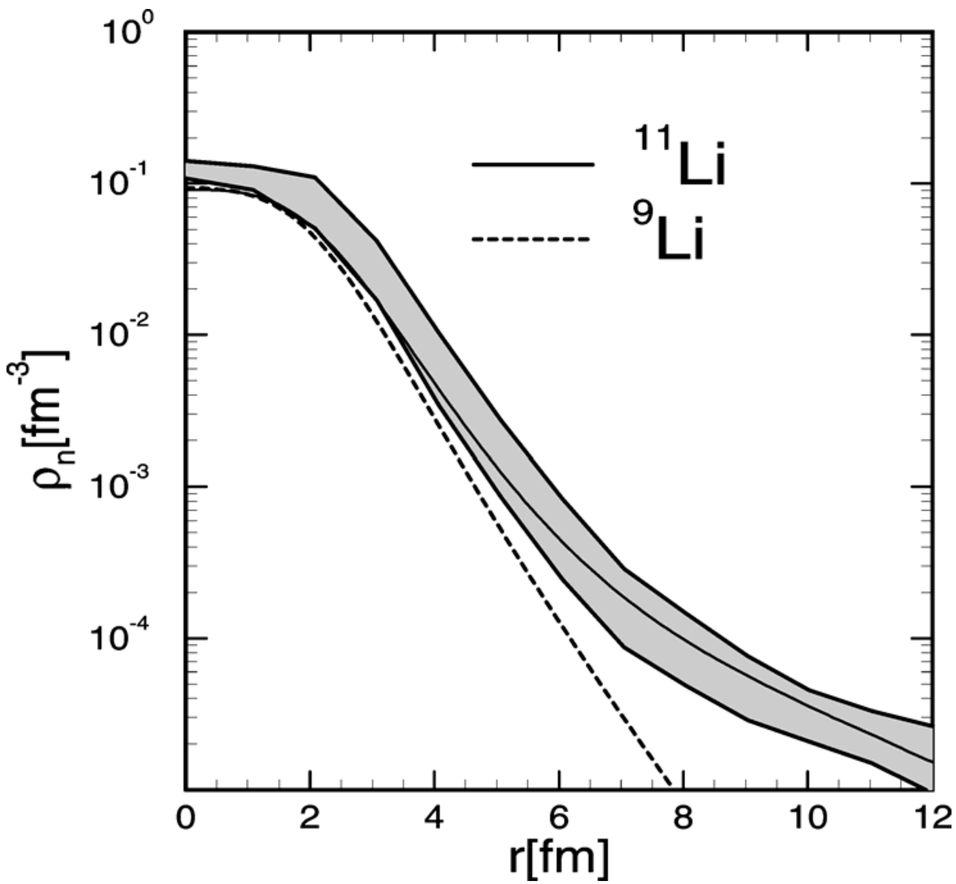
problems:

*center of mass motion

*boudary conditions at infinity

Densities in Li-isotopes

J. Meng and P. Ring , PRL 77, 3963 (1996)
J. Meng and P. Ring , PRL 80, 460 (1998)



rel. Hartree-Bogoliubov

in the continuum

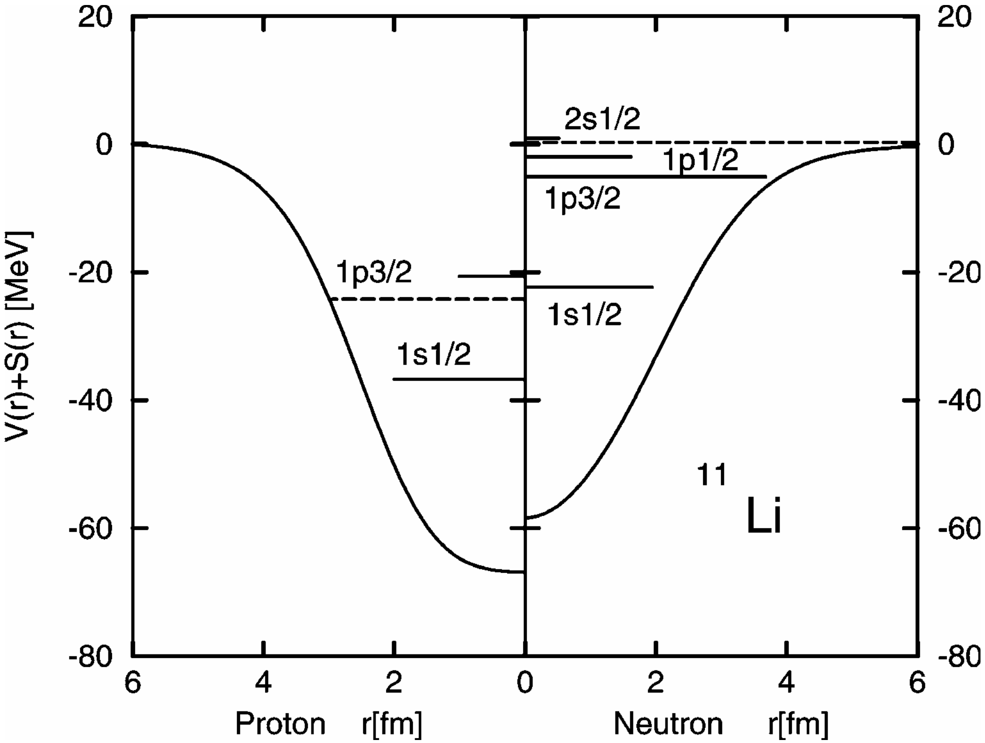
density dependent δ–pairing

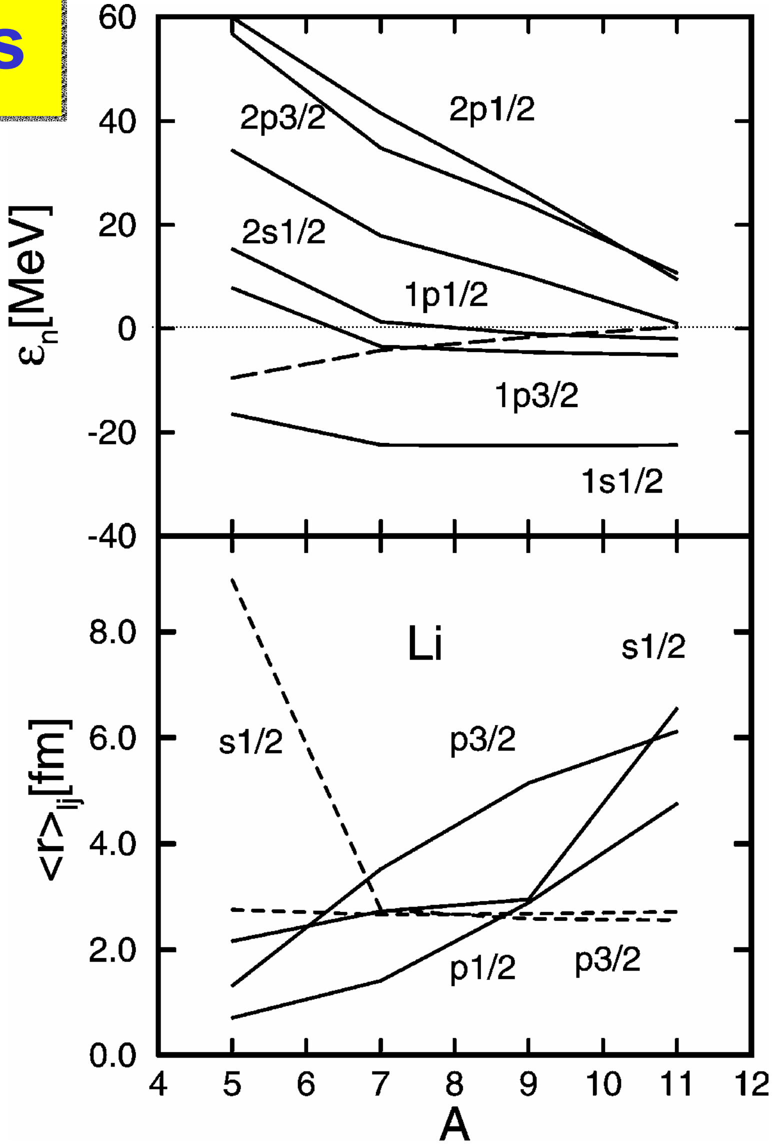
canonical basis in Li-isotopes

* eigenstates of the density matrix
* wavefunction has BCS-type

$$|\Phi\rangle = \prod_n (u_n + v_n a_n^+ a_{\bar{n}}^+)|-\rangle$$

$$\varepsilon_n = \langle n|h|n\rangle, \quad \Delta_n = \langle n|\Delta|n\rangle$$

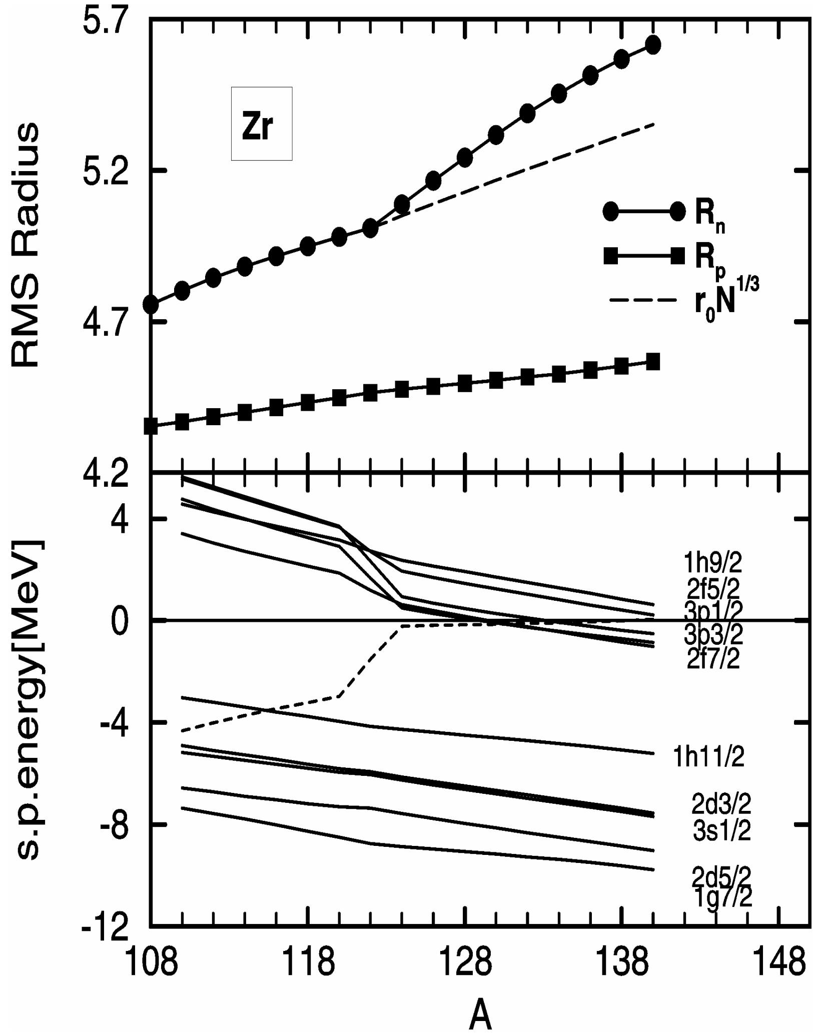


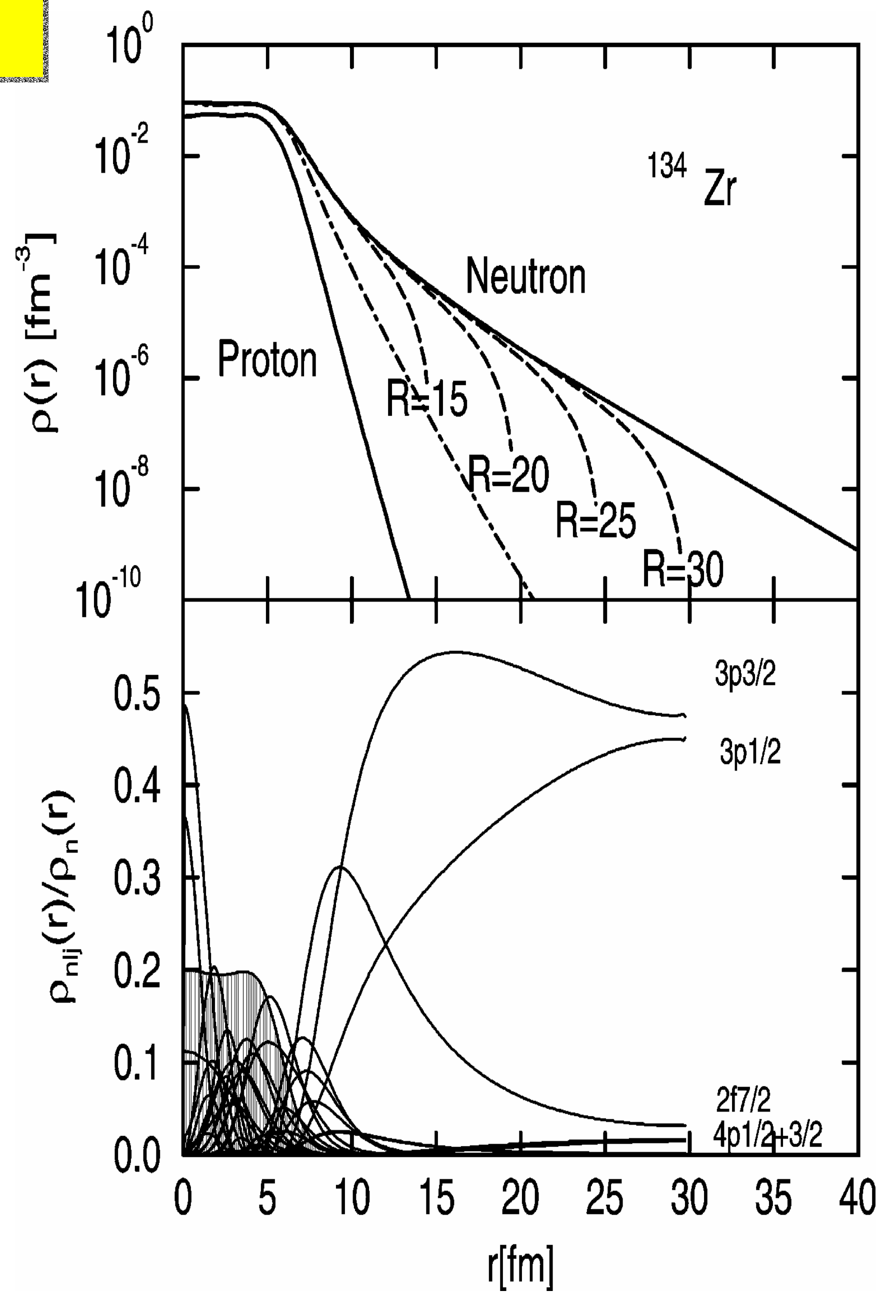


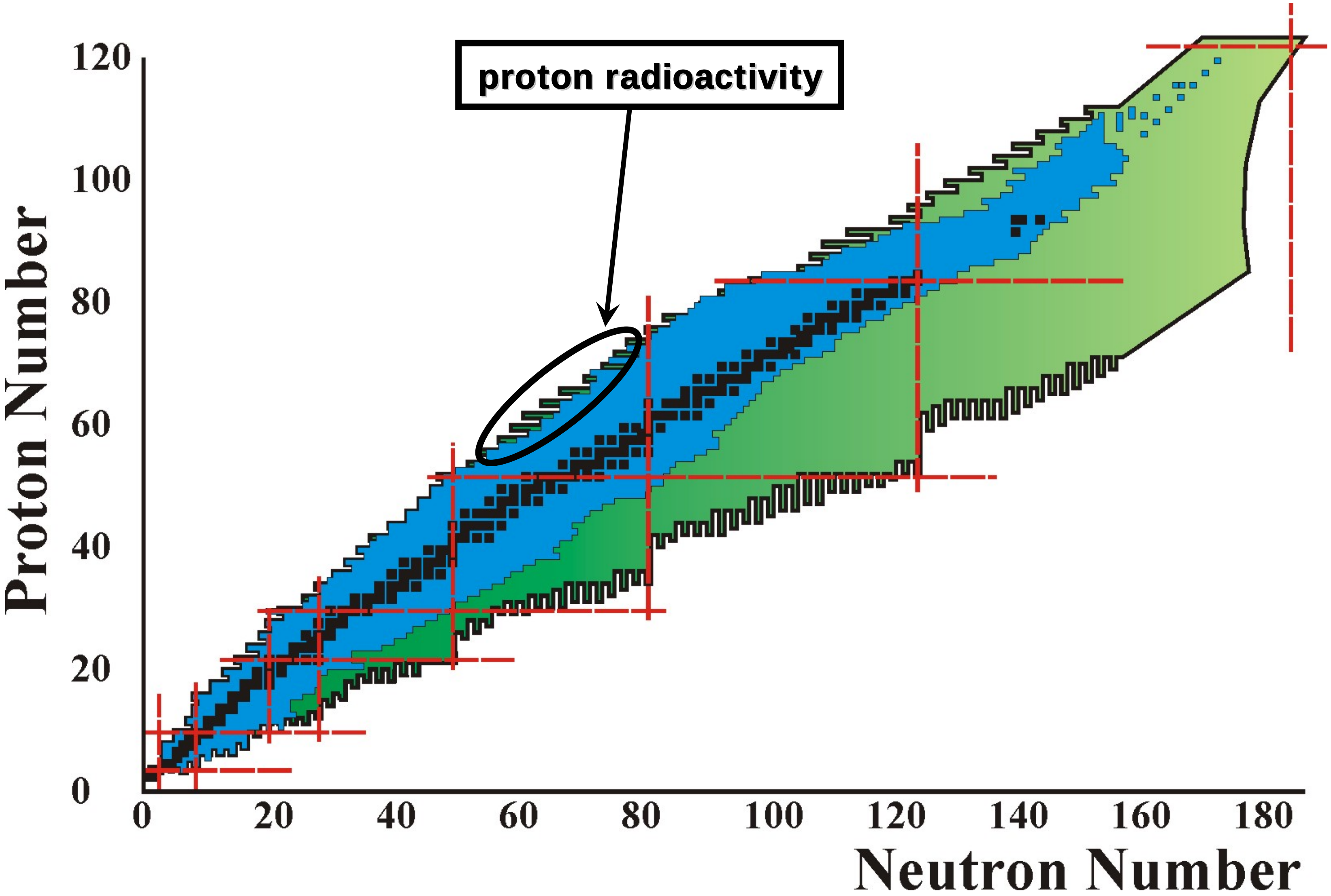
J. Meng and P. Ring , PRL 77, 3963 (1996)

Giant halo in the Zr region:

J. Meng and P. Ring , PRL 80, 460 (1998)





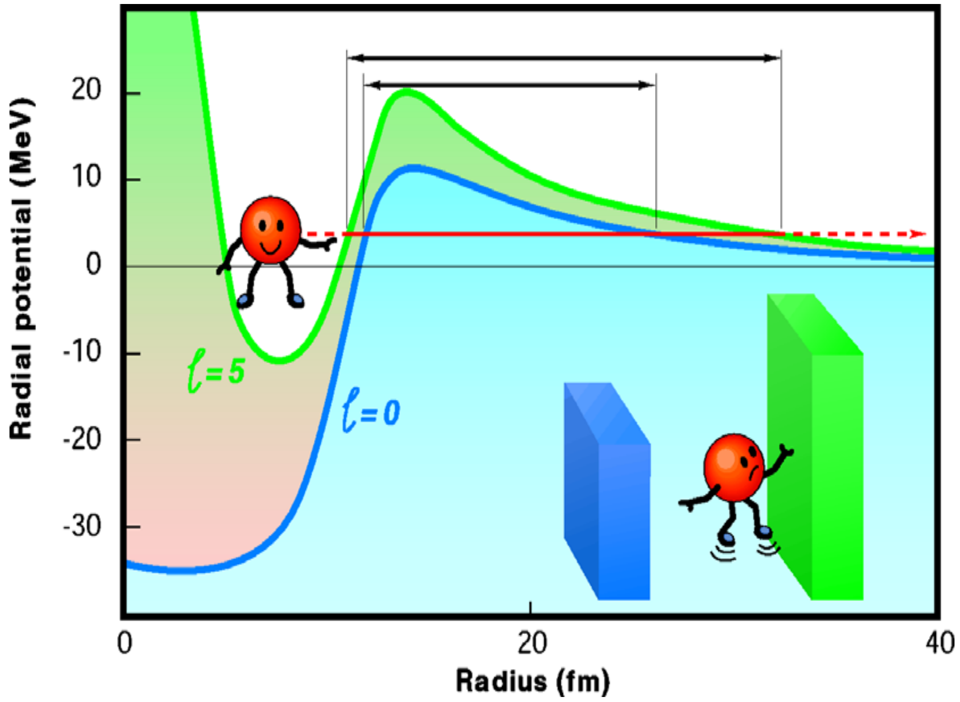


proton radioactivity
Proton Number
Neutron Number
0
20
40
60
80
100
120
140
160
180

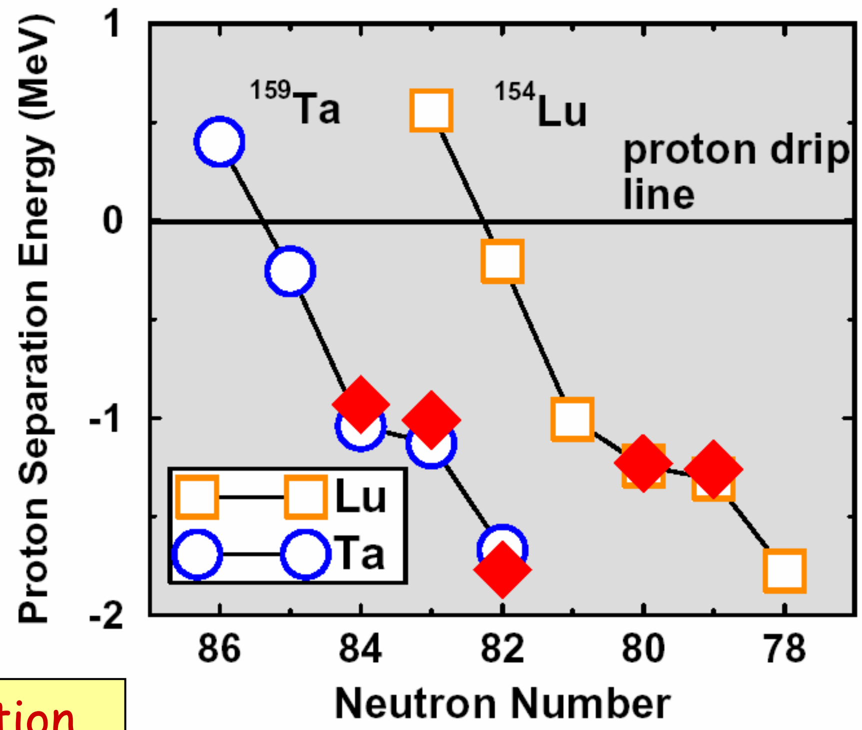
Nuclei at the proton drip line:

Vretenar, Lalazissis, Ring, Phys.Rev.Lett. 82, 4595 (1999)

characterized by exotic ground-state decay modes such as the direct emission of charged particles and β -decays with large Q-values.



Ground-state proton emitters

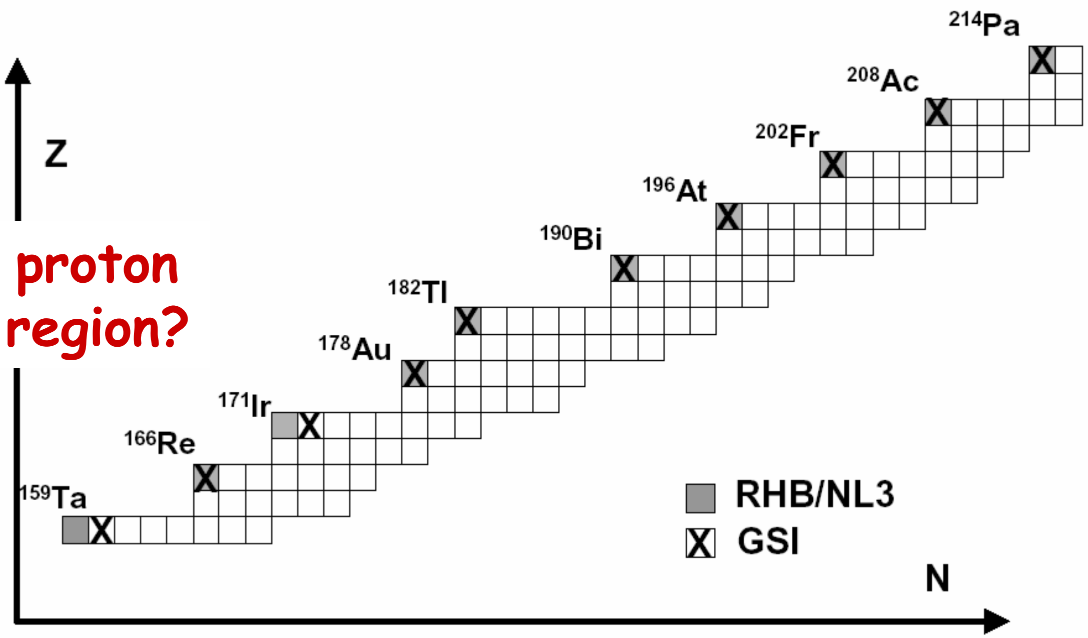


Self-consistent RHB calculations -> separation energies, quadrupole deformations, odd-proton orbitals, spectroscopic factors

Lalazissis, Vretenar, Ring
Phys.Rev. C60, 051302 (1999)

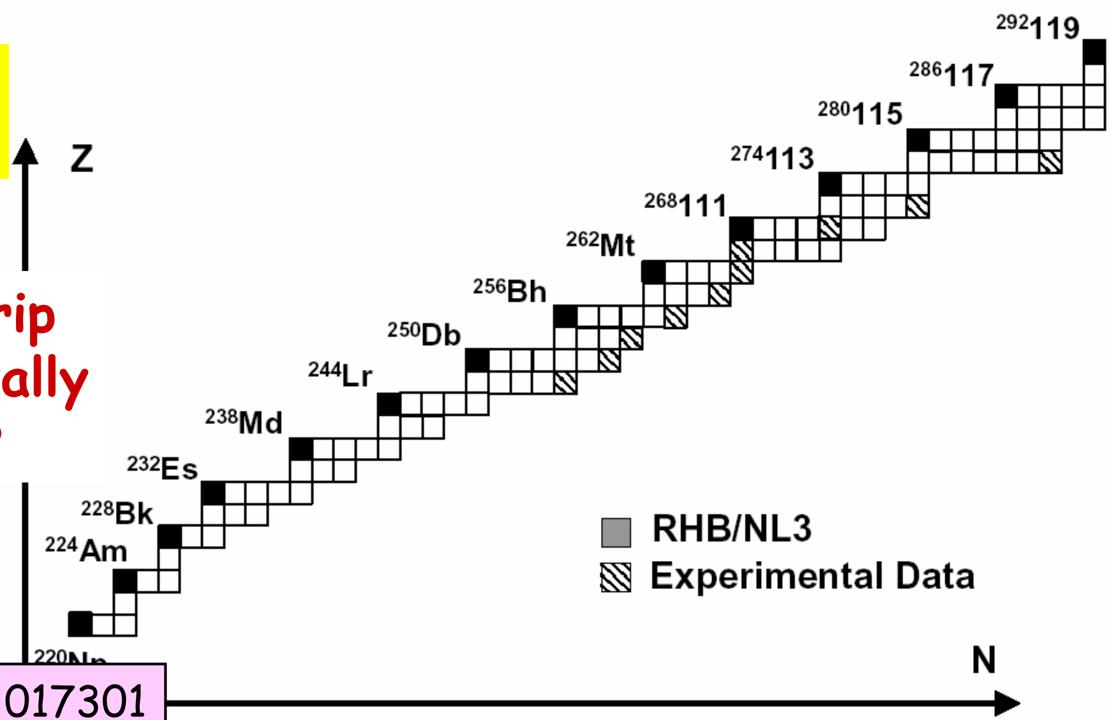
The proton drip-line in the sub-Uranium region.

Possible ground-state proton emitters in this mass region?

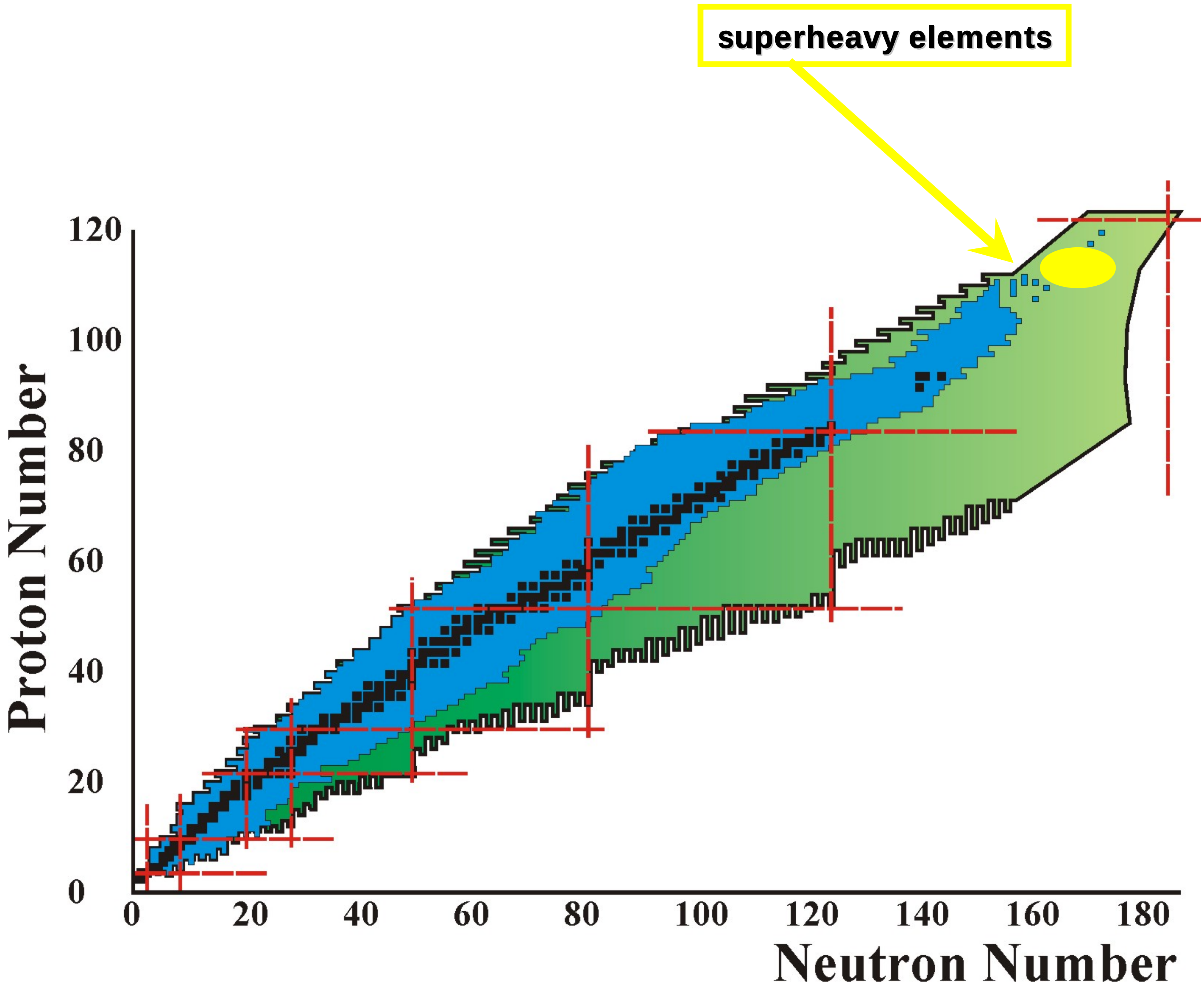


The proton drip-line in the region of superheavy elements.

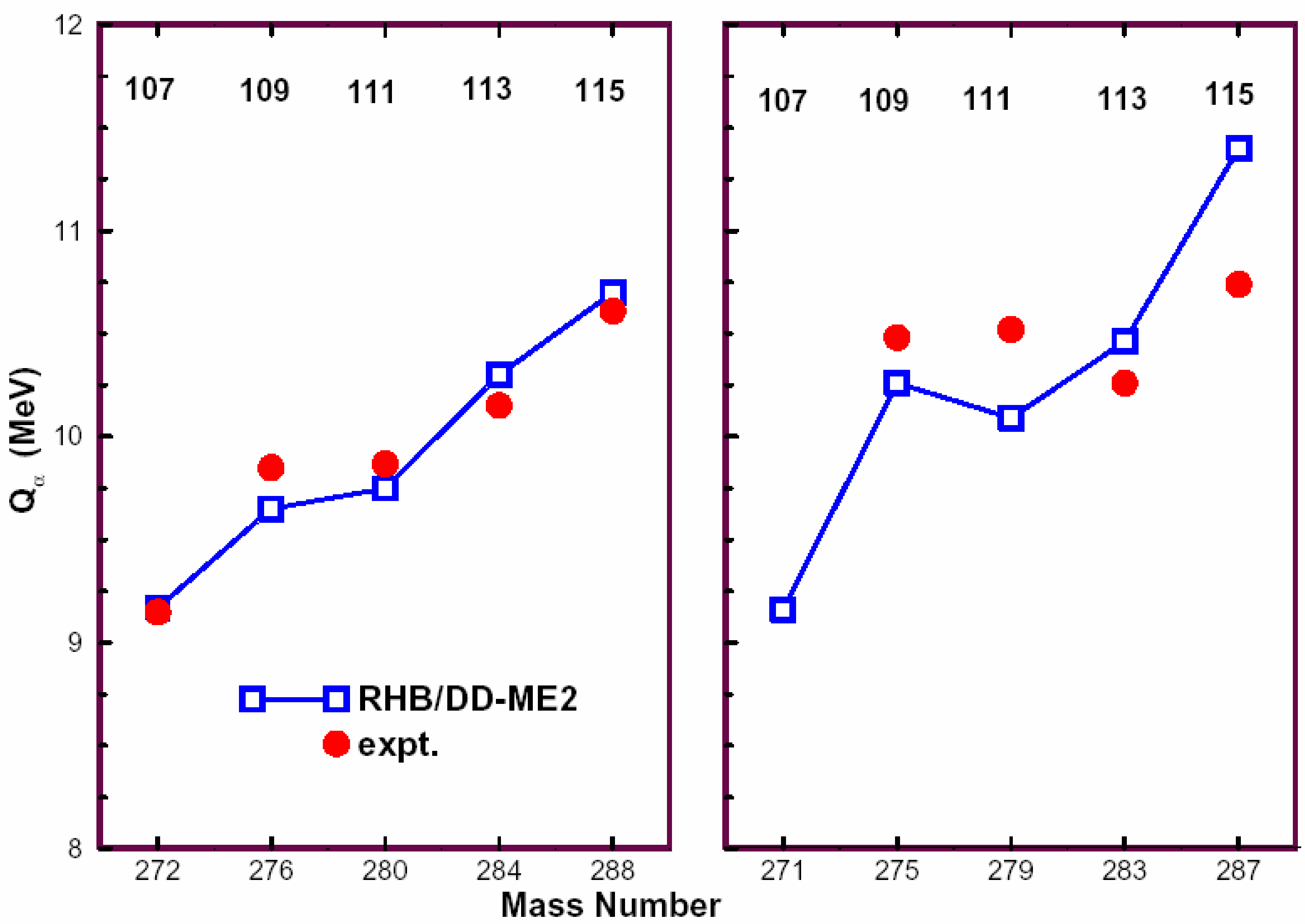
How far is the proton-drip line from the experimentally known superheavy nuclei?



G. A. Lalazissis et al., PRC **59** (2004) 017301

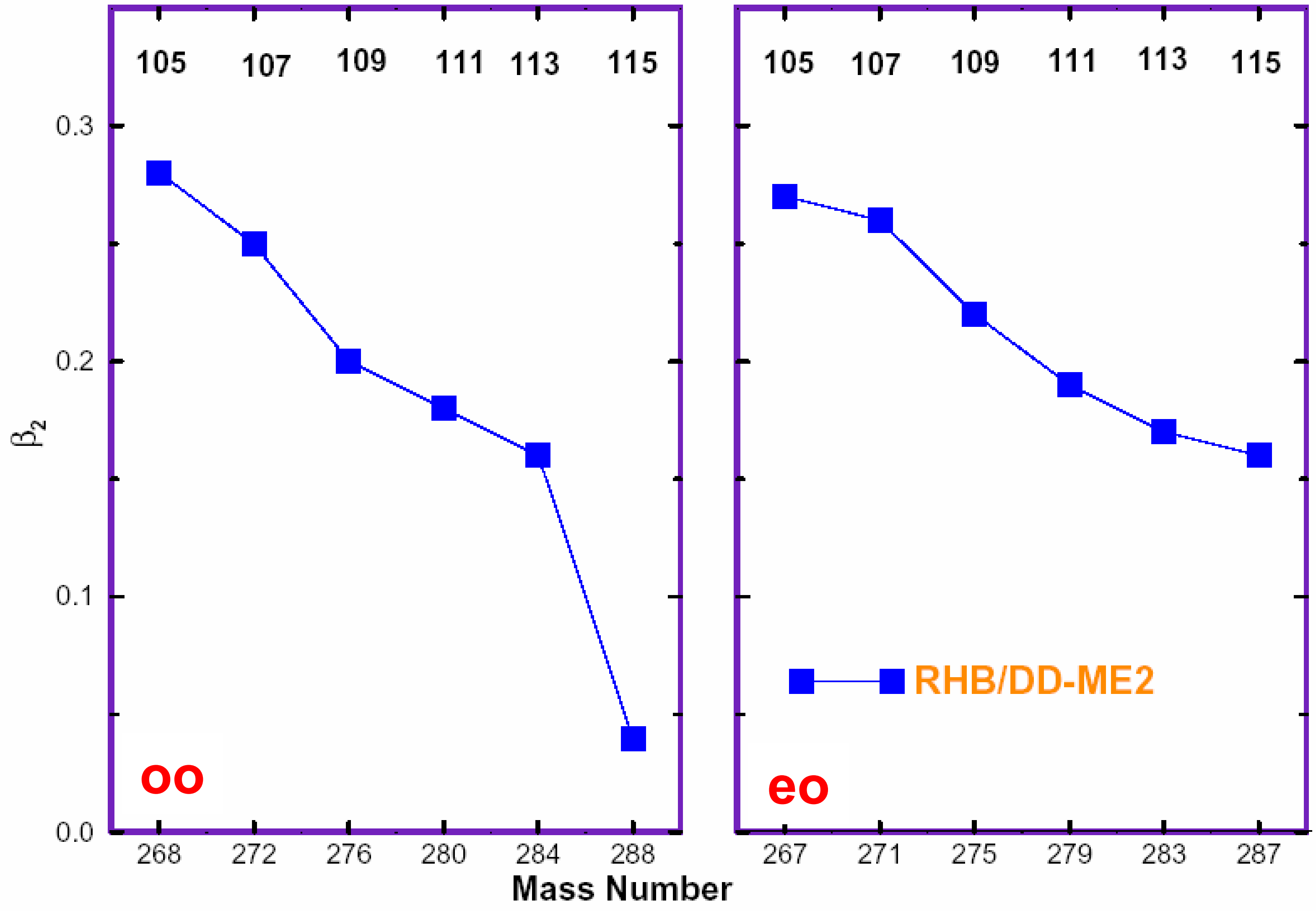

superheavy elements
Proton Number
Neutron Number
0
20
40
60
80
100
120
140
160
180

Superheavy Elements: Q_α-values



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

Superheavy elements: Quadrupole deformations



RHB/DD-ME2

Time dependent mean field theory:

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

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

$$i\partial_t \psi_i(t) = \left(\vec{\alpha}\left(\frac{1}{i}\vec{\nabla} - \vec{V} \right) + V + \beta(m - S) \right) \psi_i(t)$$

No-sea approxim. !

$$\left[-\Delta + m_\sigma^2 \right] \sigma(t) = -g_\sigma \rho_s(t) \qquad \rho_s = \sum_{i=1}^{A} \bar{\psi}_i \psi_i$$

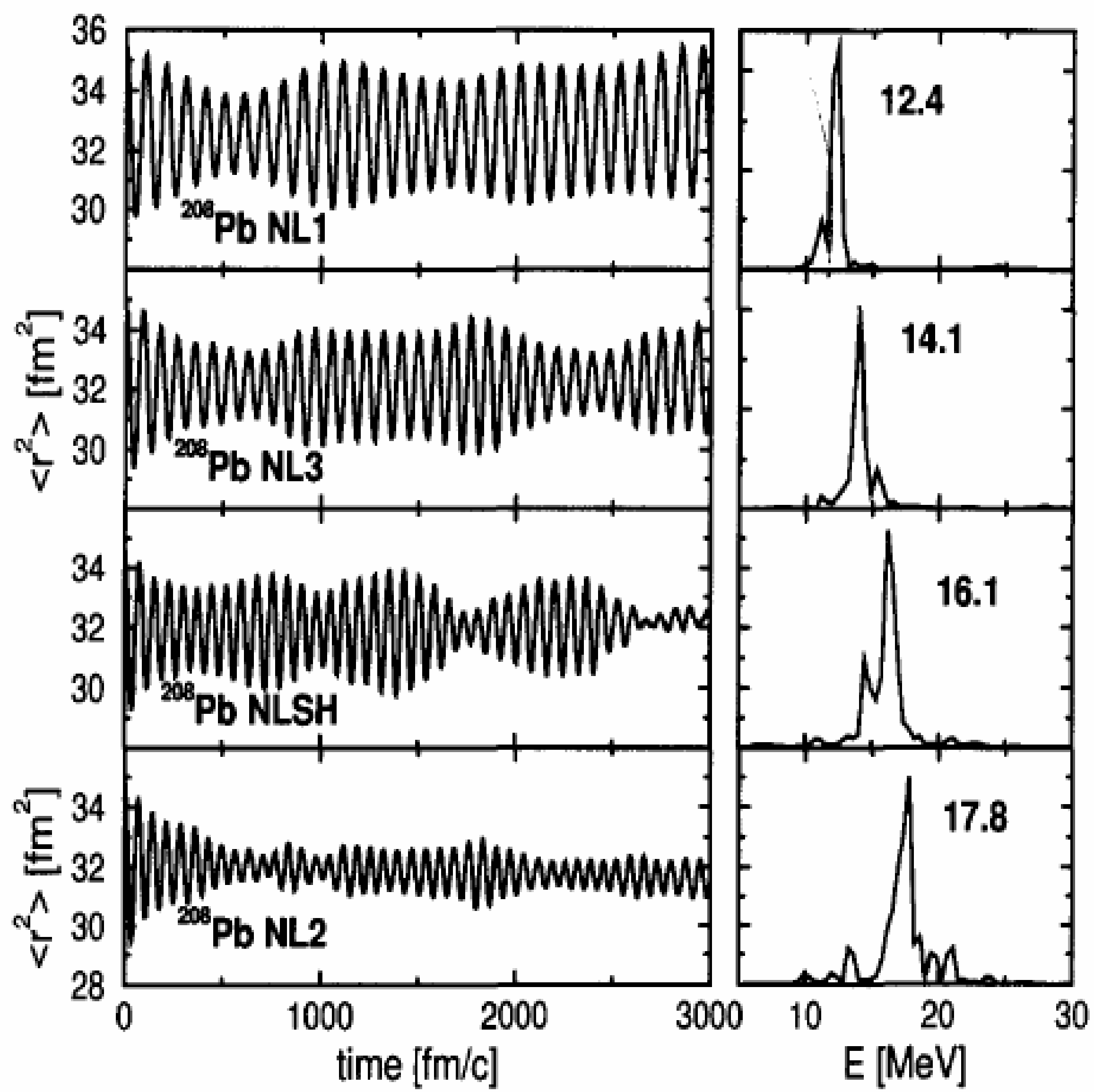
$$\left[-\Delta + m_\omega^2 \right] \omega_0(t) = g_\omega \rho_B(t) \qquad \rho_B = \sum_{i=1}^{A} \psi_i^+ \psi_i$$

$$\left[-\Delta + m_\omega^2 \right] \vec{\omega}(t) = g_\omega \vec{j}_B(t) \qquad \vec{j}_B = \sum_{i=1}^{A} \bar{\psi}_i \vec{\alpha} \psi_i$$

and similar equations for the ρ- and A-field

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

breathing mode: ^{208}Pb



K_∞=211

K_∞=271

K_∞=355

order and chaos

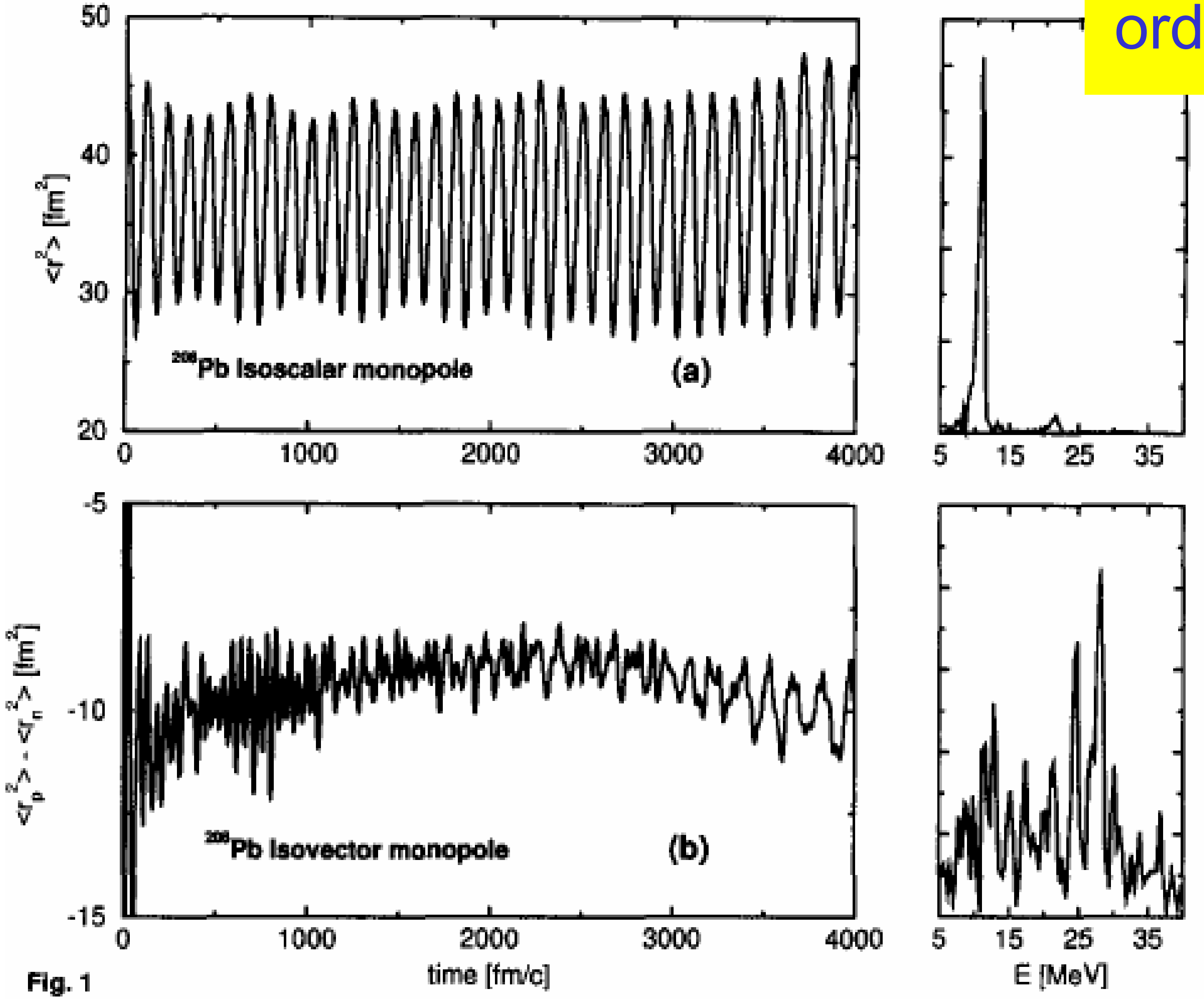


Fig. 1

GMR: T=0

GMR: T=1

D. Vretenar et al., PRE 56(1997) 6418

Relativistic RPA for excited states

Small amplitude limit:

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

ground-state density

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

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

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

RRPA 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

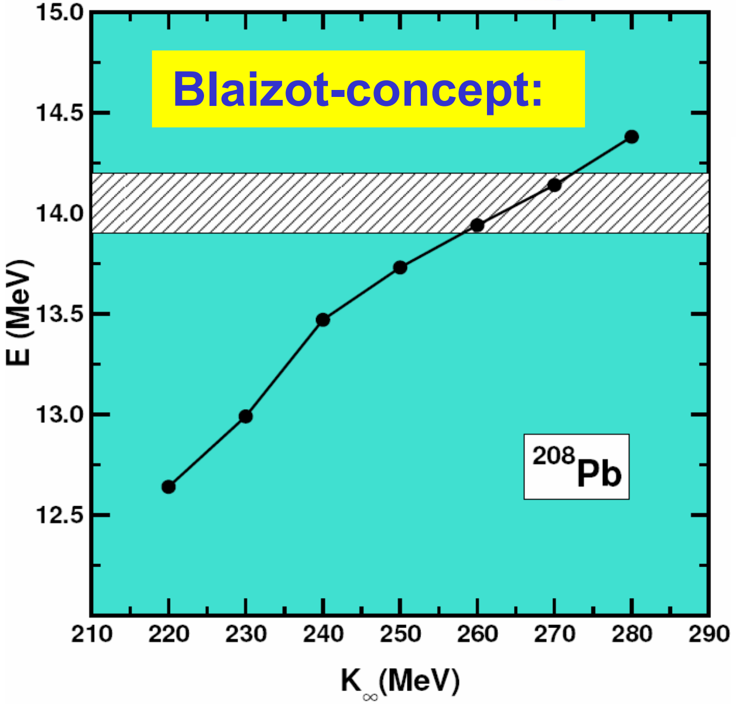
Interaction:

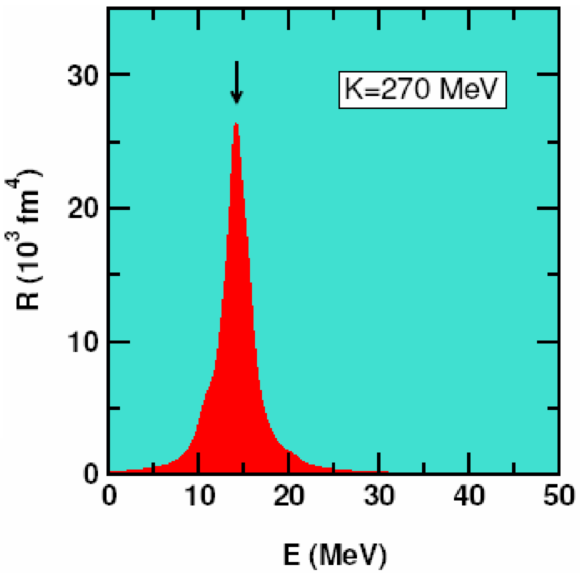
$$\hat{V} = \frac{\delta^2 E}{\delta\hat{\rho}\,\delta\hat{\rho}}$$

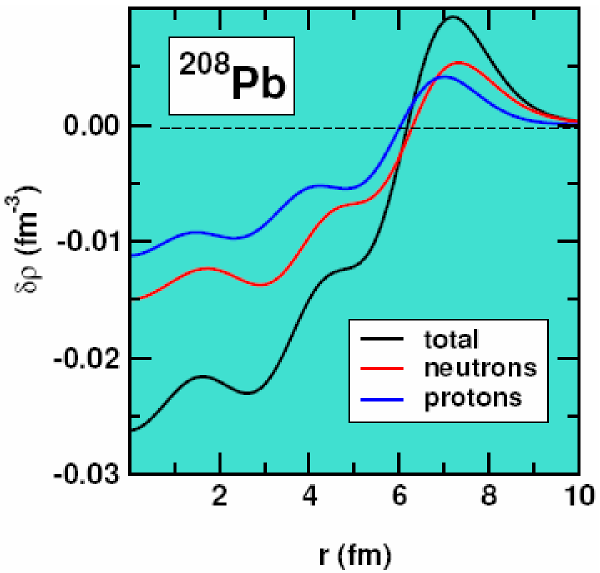
Isoscalar Giant Monopole Resonance: IS-GMR

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

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







constraining the nuclear matter compressibility

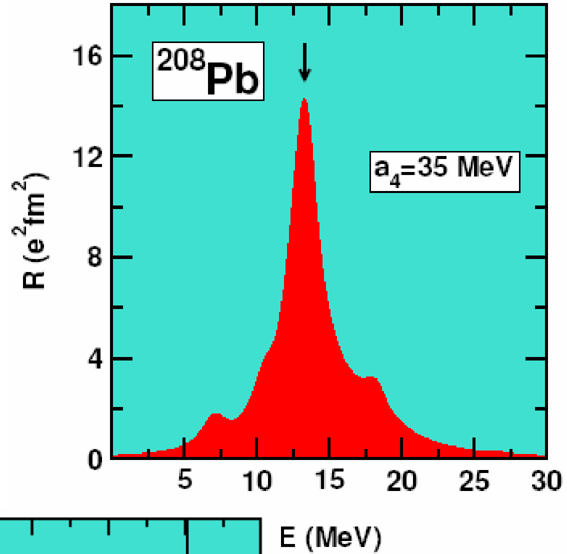
RMF models reproduce the experimental data only if

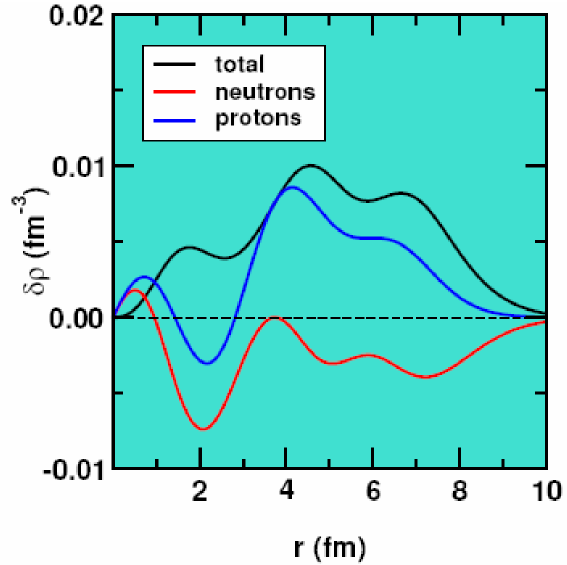
$$250\ \text{MeV} \leq K_0 \leq 270\ \text{MeV}$$

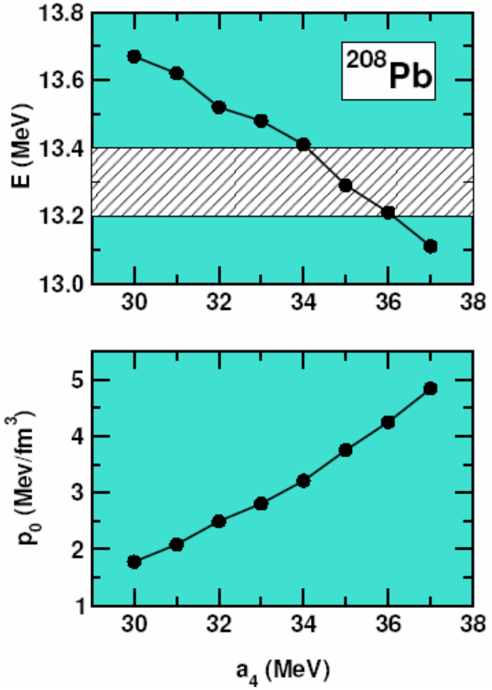
T. Niksic et al., PRC 66 (2002) 024306

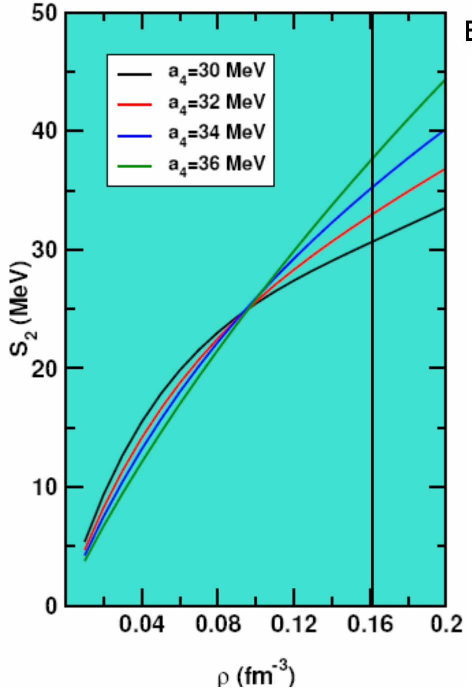
Isovector Giant Dipole Resonance: IV-GDR

the IV-GDR represents one of the sources of experimental informations on the nuclear matter symmetry energy









constraining the nuclear matter symmetry energy

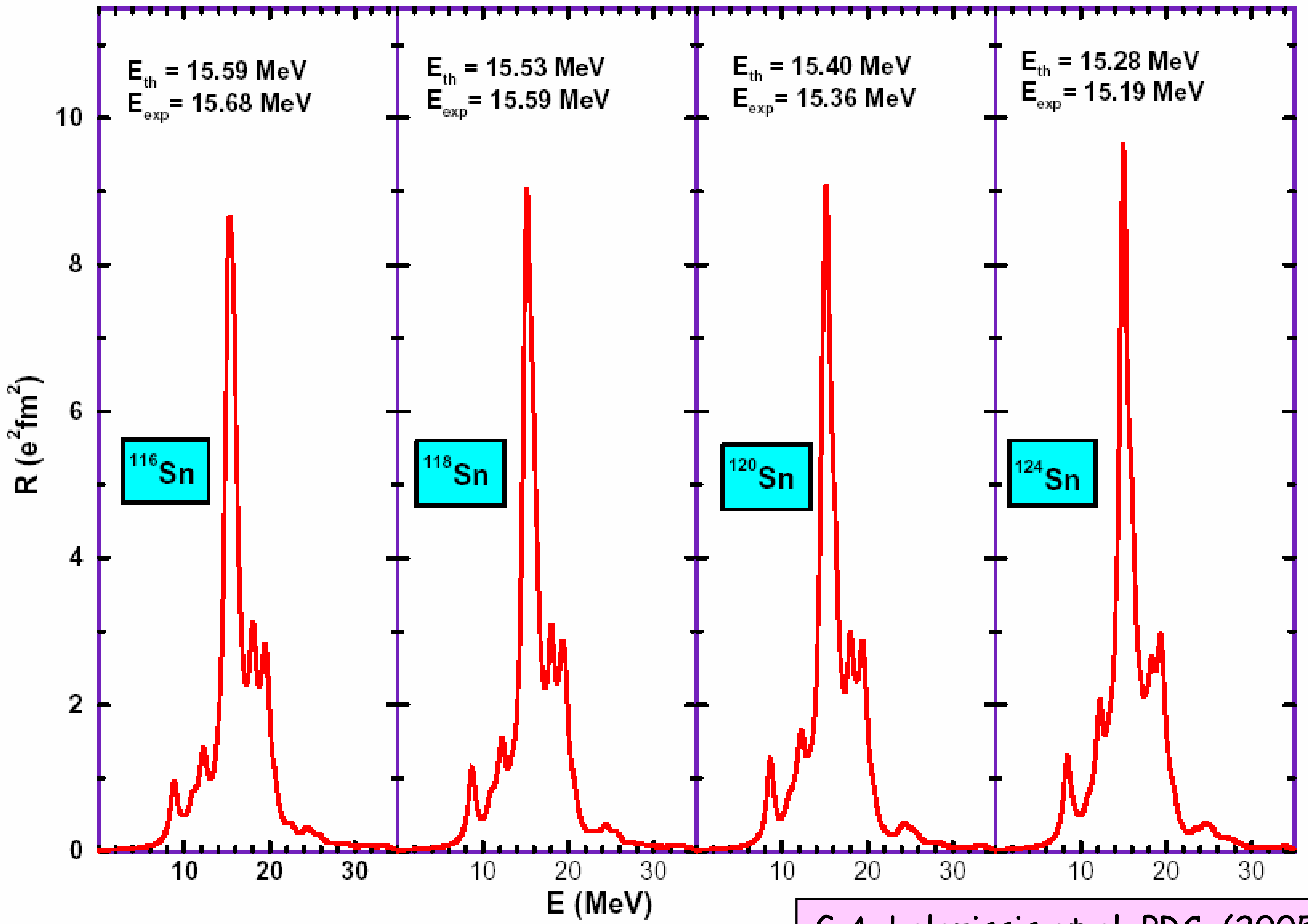
the position of IV-GDR is reproduced if

$$32 \text{ MeV} \leq a_4 \leq 36 \text{ MeV}$$

T. Niksic et al., PRC 66 (2002) 024306

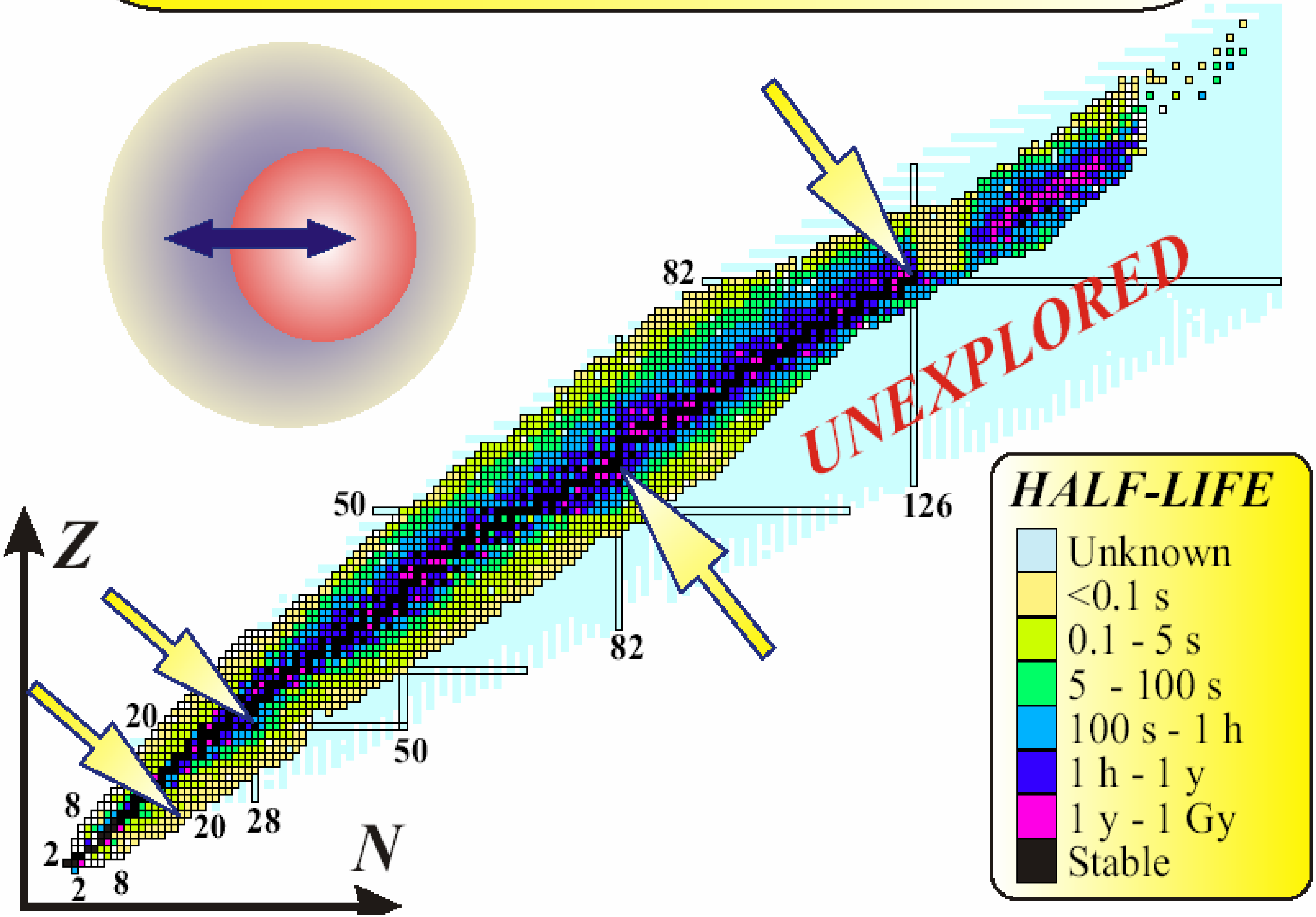
IV-GDR in Sn-isotopes

DD-ME2



G.A. Lalazissis et al, PRC (2005) in print

Experimental indications of the soft dipole mode



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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(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 und
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, 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].

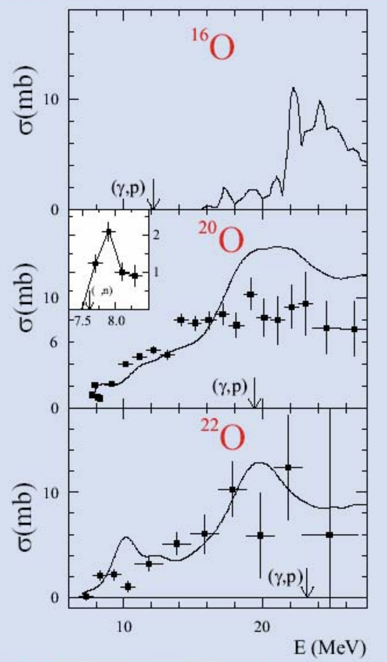
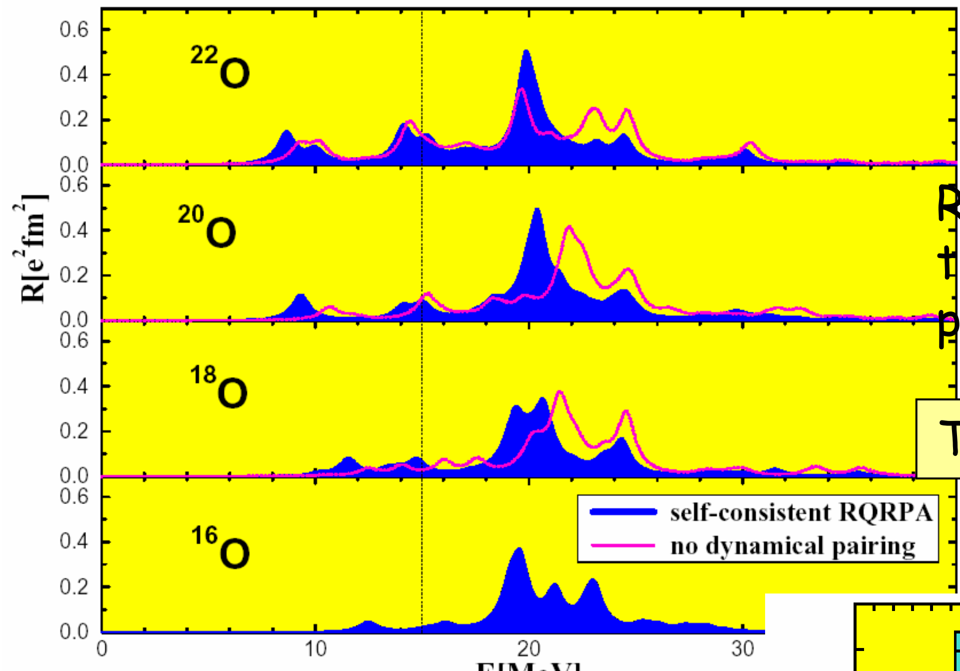


FIG. 2. Photoneutron cross sections for O16 (upper panel) and for the unstable isotopes ^{20,22}O (lower panels) as extracted from the measured electromagnetic excitation cross section (symbols). The inset displays the cross section for near the neutron threshold on an expanded energy scale. The thresholds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

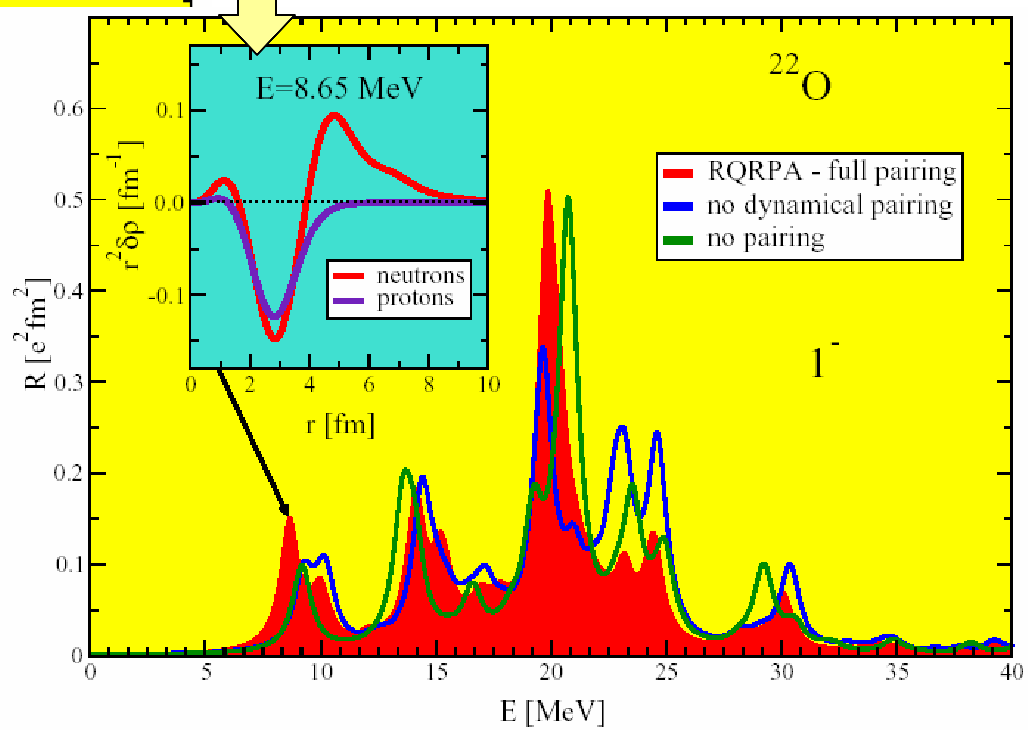
gmy resonance, may arise
neutrons vibrate against
passing that a systematic
le strength in neutron-rich
sical aspects, e.g., calcu-
es in the -process of the
21].
t resonances and lower ly-
investigated systematically
s of all neutron-rich oxygen
rongly bound doubly magic
pes, one may expect a de-
ns from the inert O core.
st neutron is 7–8 MeV for
, and about 4 MeV for the
16 MeV for O. Thus the
might be good candidates for
ion.
we use the electromagnetic
high targets. Similar to
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

olution of IV dipole rength in Oxygen isotopes



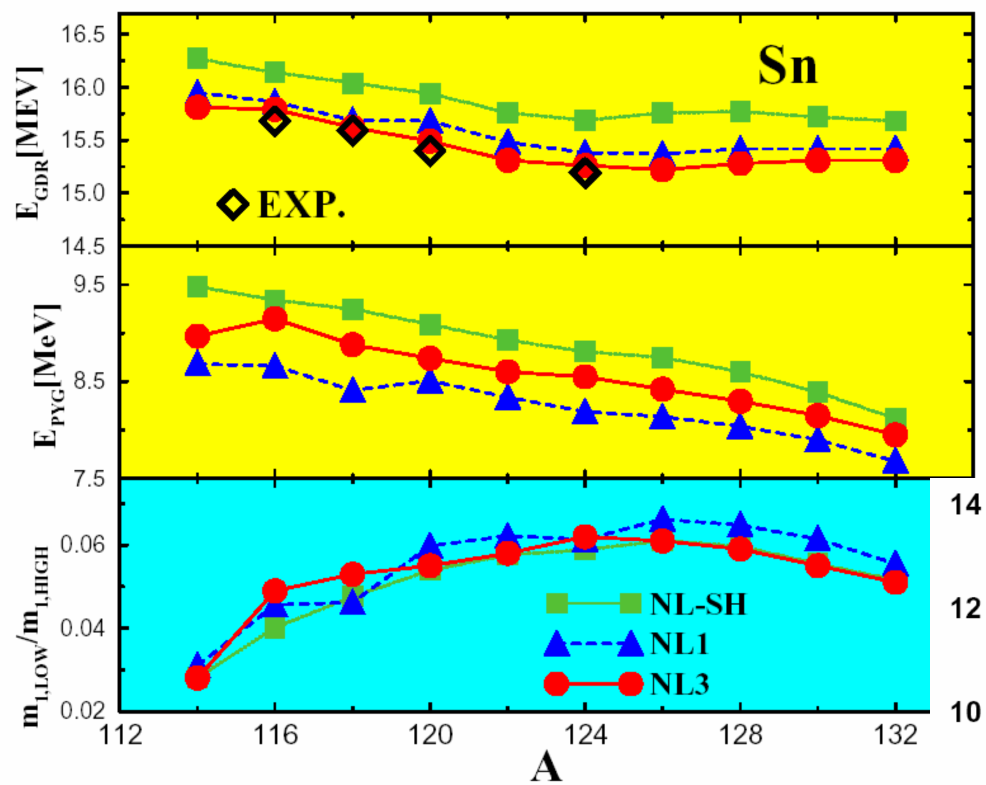
RHB + RQRPA calculations with the NL3 relativistic mean-field plus D1S Gogny pairing interaction.

Transition densities



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

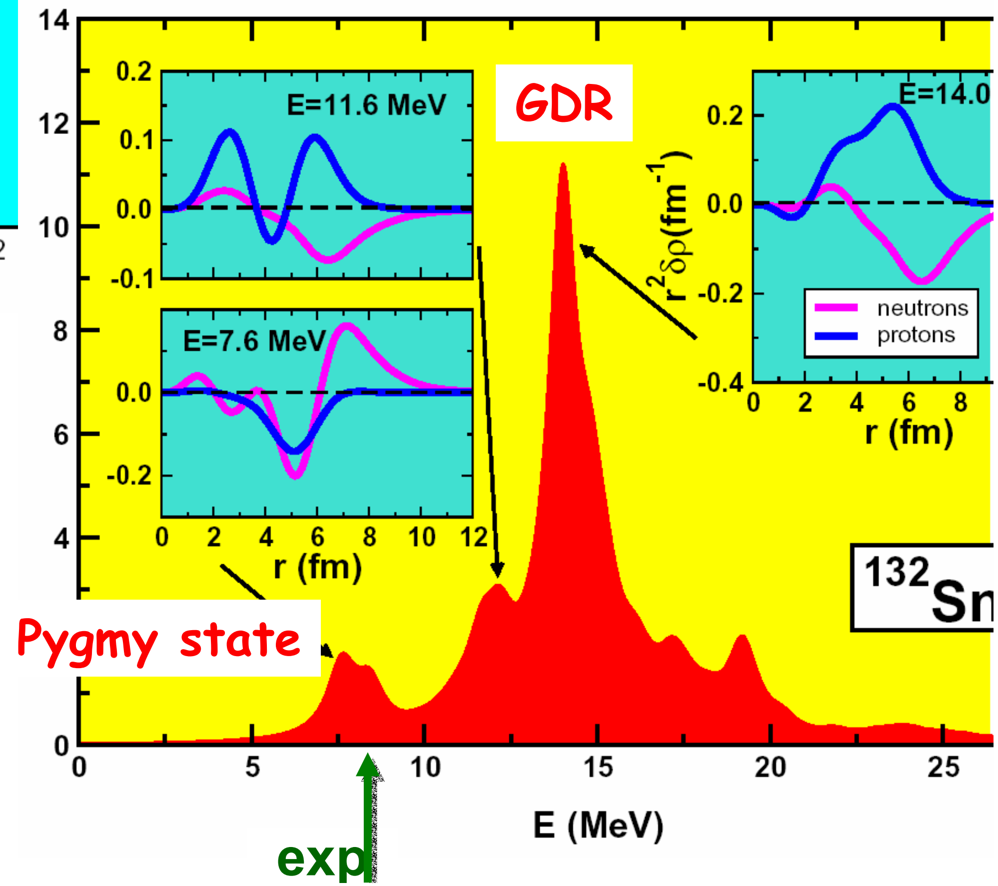
Effect of pairing correlations on the dipole strength distribution



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)

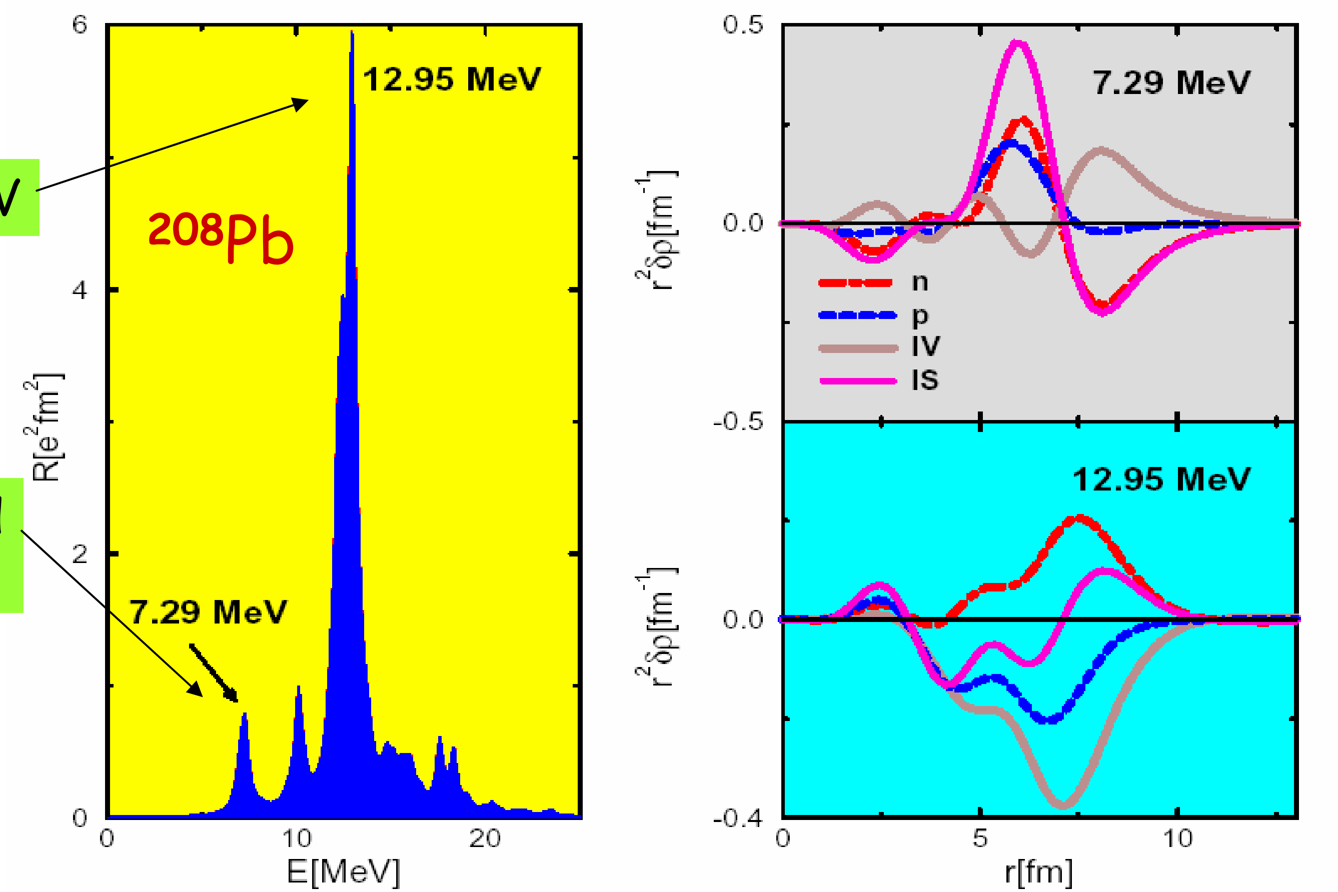
^{132}Sn at 7.6 MeV	
28.2%	$2d_{3/2} \rightarrow 2f_{5/2}$
21.9%	$2d_{5/2} \rightarrow 2f_{7/2}$
19.7%	$2d_{3/2} \rightarrow 3p_{1/2}$
10.5%	$1h_{11/2} \rightarrow 1i_{13/2}$
3.5%	$2d_{5/2} \rightarrow 3p_{3/2}$
1.9%	$1g_{7/2} \rightarrow 2f_{5/2}$
1.5%	$1g_{7/2} \rightarrow 1h_{9/2}$
0.6%	$1g_{7/2}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

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.

Spin-Isospin Resonances: IAR - GTR

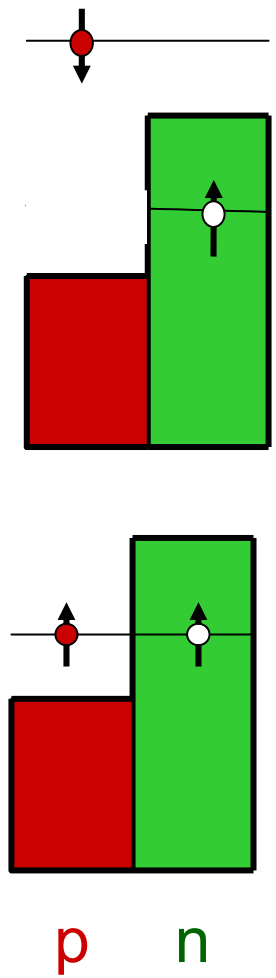
Z,N **Z+1,N-1**

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

spin flip σ

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

isospin flip τ



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

Spin-Isospin Resonances: IAS 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

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

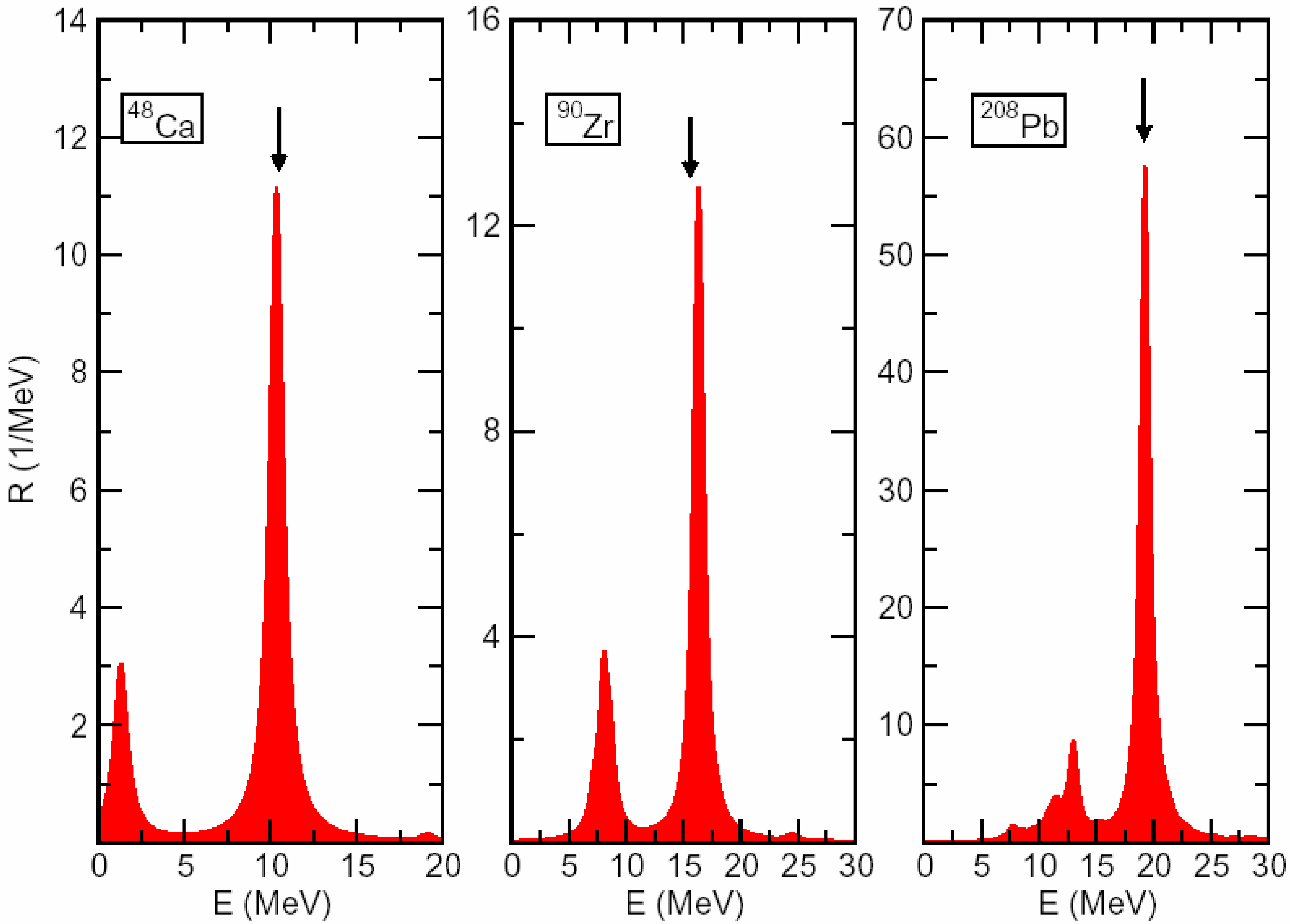
($g'_0=0.55$)

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

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

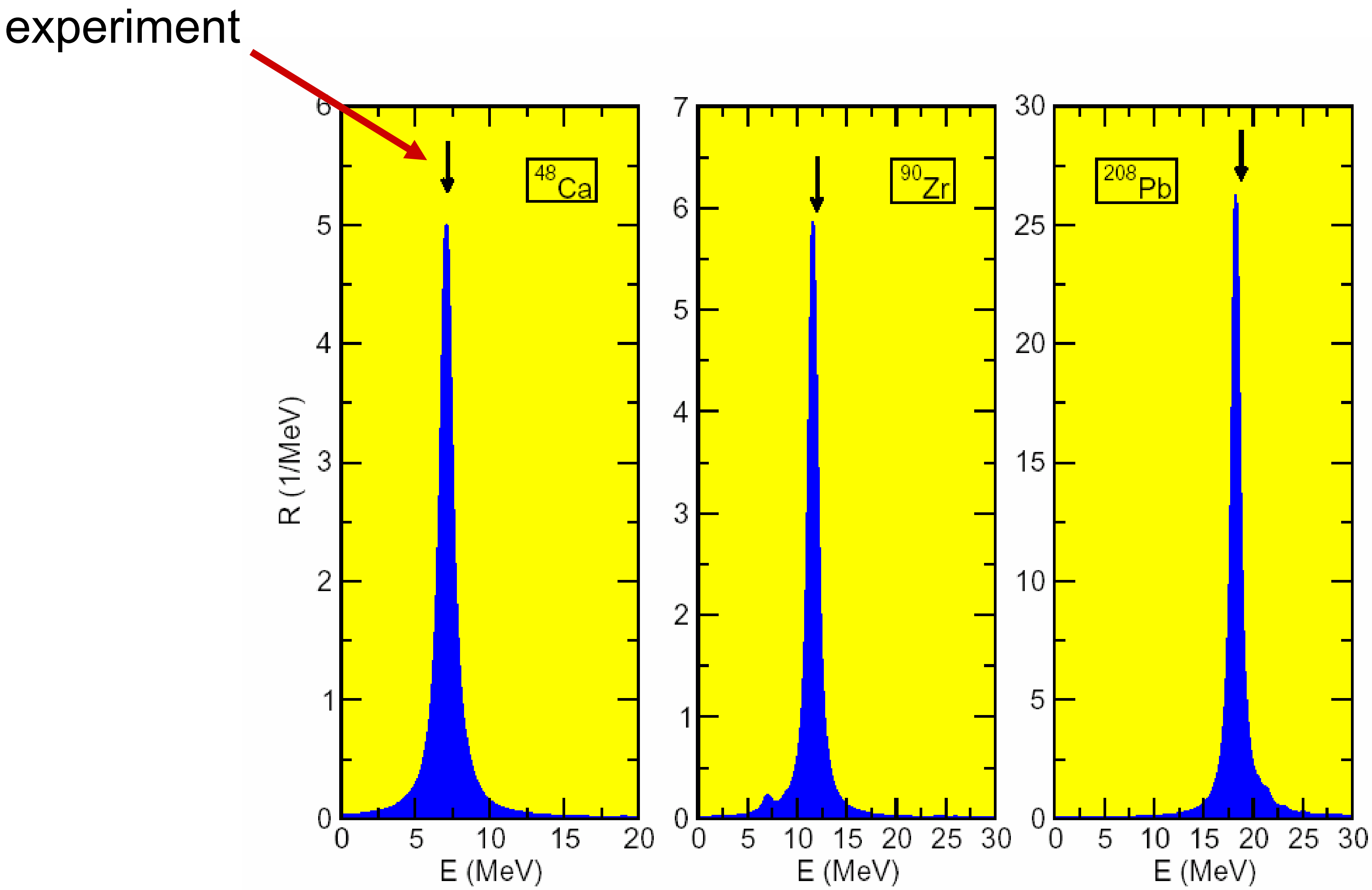
GT-Resonances

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

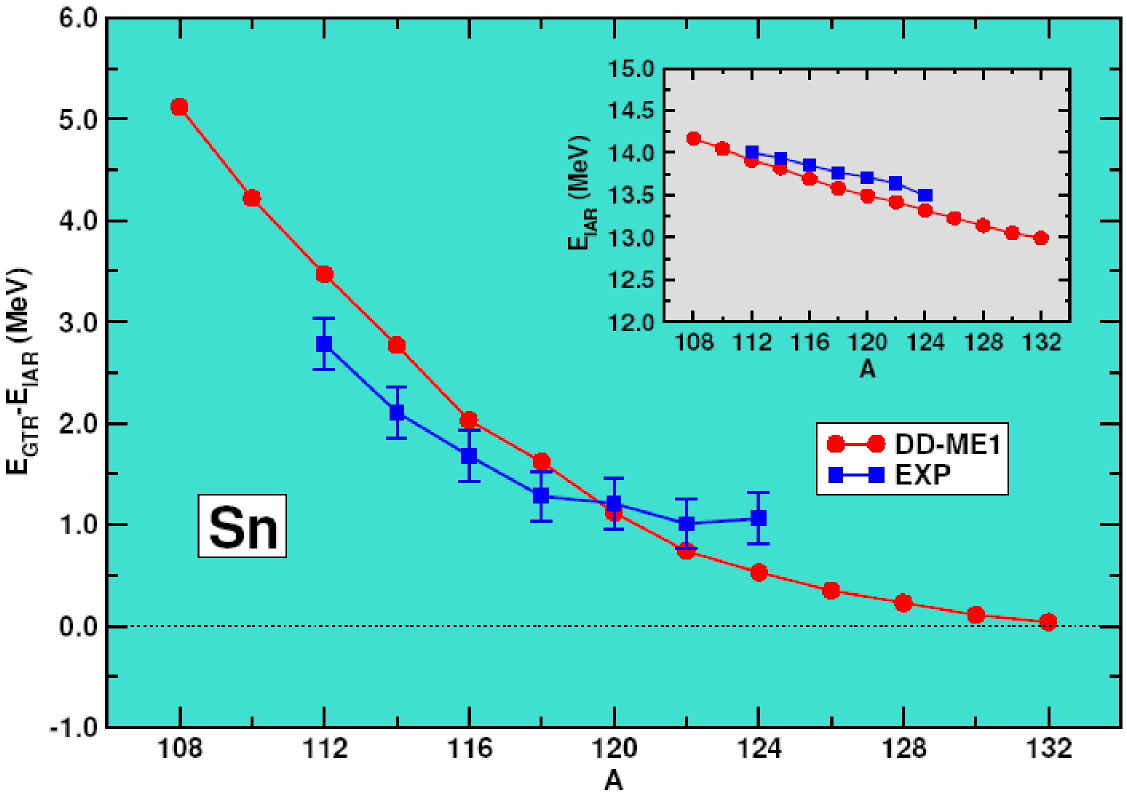


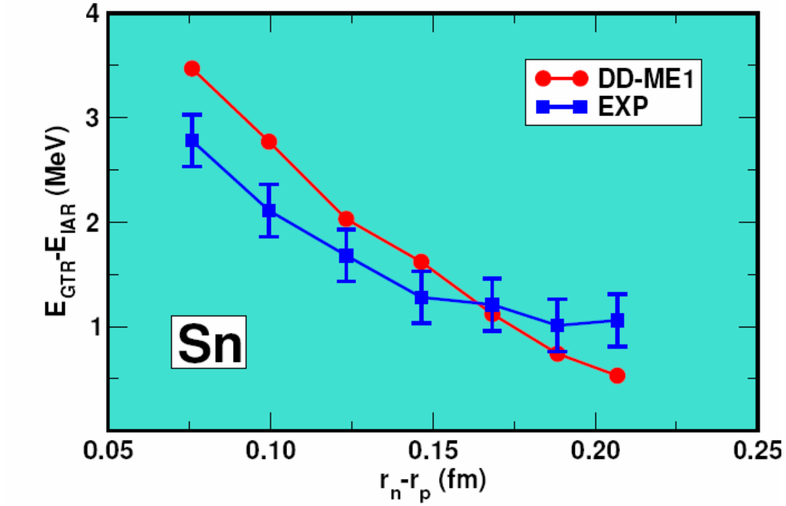
Isobaric Analog Resonance: IAR

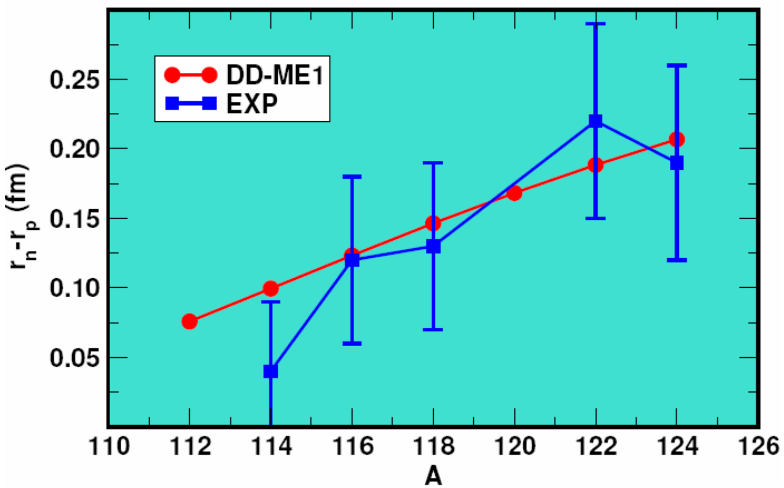
N. Paar, T. Niksic, D. Vretenar, P.Ring, PR C69, 054303 (2004)



Neutron skin and IAR/GRT



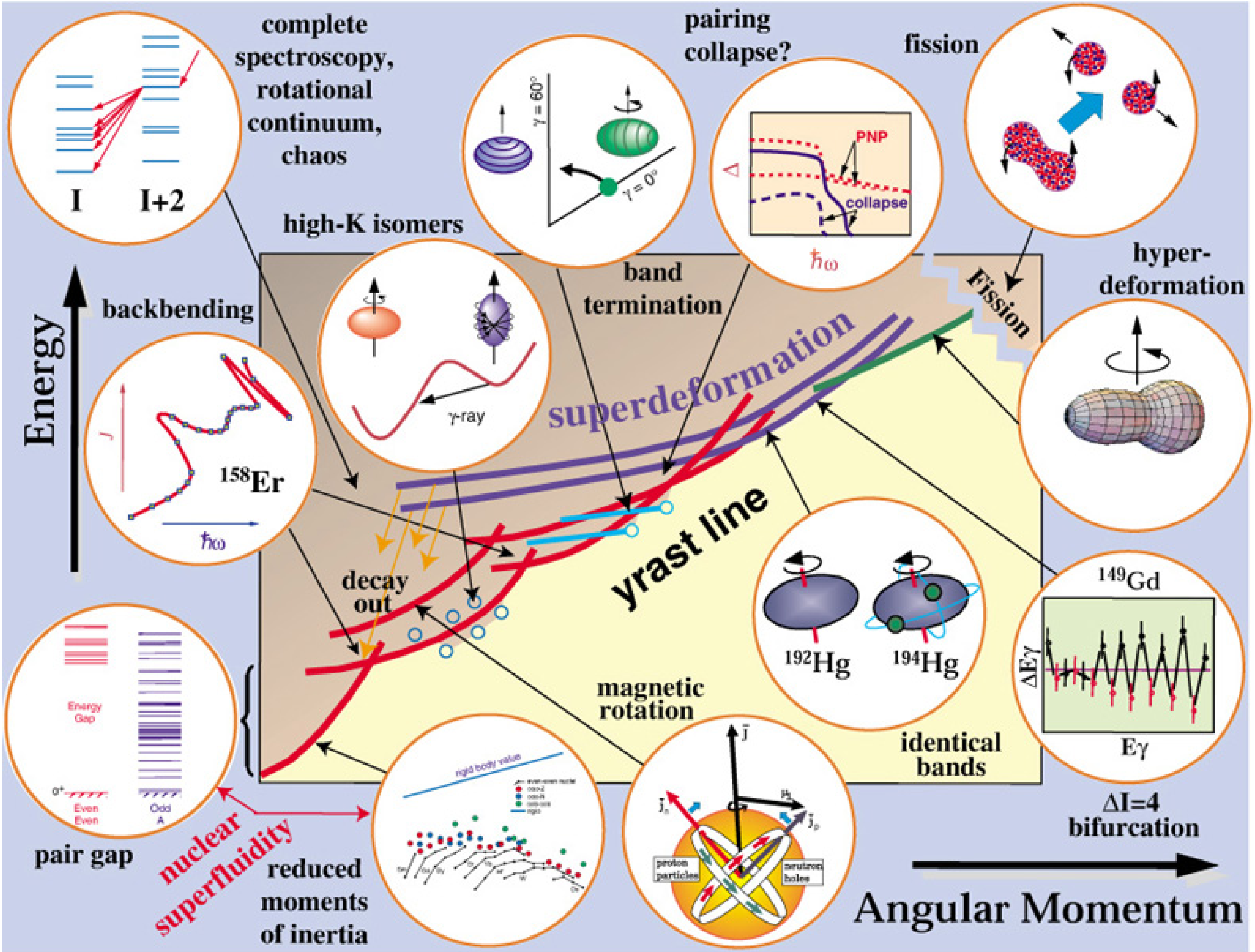




The isotopic dependence of the energy spacings between the GTR and IAS

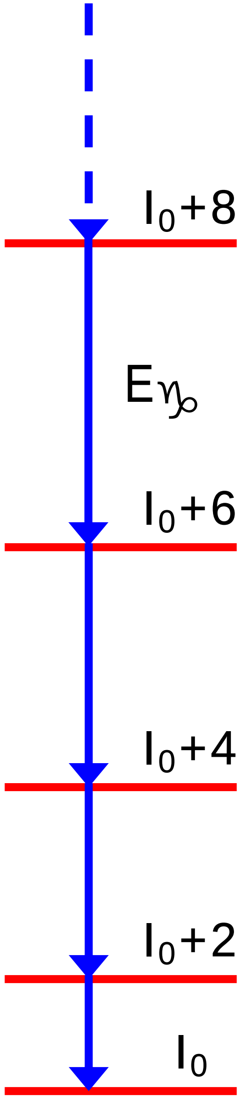
→ direct information on the evolution of the neutron skin along the Sn isotopic chain

nuclei at high large angular velocities:



Physical observables in rotating nuclei:

$$E_\gamma(I) = E(I+2) - E(I)$$



Angular velocity Ω:

$$\Omega = \frac{dE}{dJ} = \frac{\Delta E}{\Delta I} = \frac{E_\gamma(I)}{2}$$

Kinematic moment of inertia $J^{(1)}$

$$J^{(1)}(\Omega) = \frac{J}{\Omega} = \frac{2I-1}{E_\gamma}$$

Dynamic moment of inertia $J^{(2)}$

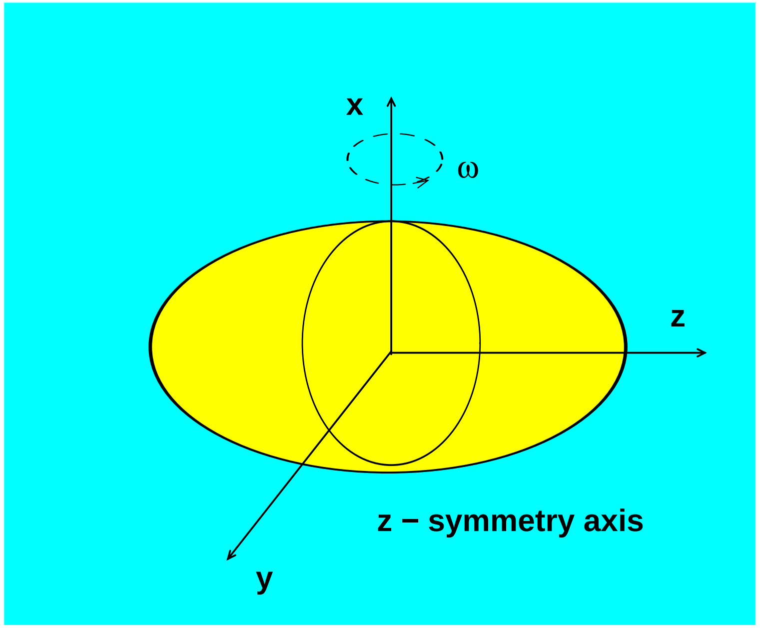
$$J^{(2)}(\Omega) = \frac{dJ}{d\Omega} = \frac{4}{E_\gamma(I) - E_\gamma(I-2)}$$

Charge quadrupole moment

Relative quantities: relative (effective) alignment, relative charge quadrupole moments:

1. measure an effect introduced by a particle(s) in single-particle orbital(s)
2. includes direct contribution (<i|O|i>) and polarization effects on “core”

How to describe rotating nuclei ?



Rigid rotor: rotational excitation energies *E(I)* obey 'the *I(I+1)* rule'; *I* is spin

$$E(I) = \frac{\hbar^2}{2J} I(I+1)$$

J is moment of inertia

- Nuclei do not rotate as rigid bodies
- Quantum mechanics forbids collective rotation around the symmetry axis

Laboratory frame: potential V is time-dependent
Rotating frame: potential V* is time-independent

Transformation to rotating frame → CRANKING MODEL

$$< \Psi | \hat{J}_x | \Psi > = \sqrt{I(I+1)}$$

$$\langle \Psi | \hat{J}_x | \Psi \rangle = \sum_i \langle i | \hat{j}_x | i \rangle$$

$$\hat{H}' = \hat{H} - \Omega \hat{J}_x$$

The cranked relativistic Hartree+Bogoliubov theory

1. The CRHB equations for the fermions in the rotating frame (one-dimensional cranking approximation)

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

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

2. Klein-Gordon equations for mesons:

$$\left\{-\Delta-(\Omega\hat{L}_x)^2+m_\omega{}^2\right\}\omega_0(\vec{r})=g_\omega\rho_V^{is}(\vec{r})$$

$$\left\{-\Delta-(\Omega\hat{L}_x)^2+m_\sigma^2\right\}\sigma(\vec{r})=-g_\sigma\rho_S(\vec{r})-g_2\sigma^2(\vec{r})-g_3\sigma^3(\vec{r})$$

$$\left\{-\Delta-(\Omega(\hat{L}_x+S_x))^2+m_\omega{}^2\right\}\vec{\omega}(\vec{r})=g_\omega j^{is}(\vec{r})$$

Two sources of time-reversal symmetry breaking:
- Coriolis term
- magnetic potential

“time-odd” mean fields in non-relativistic theory

^{194}Hg

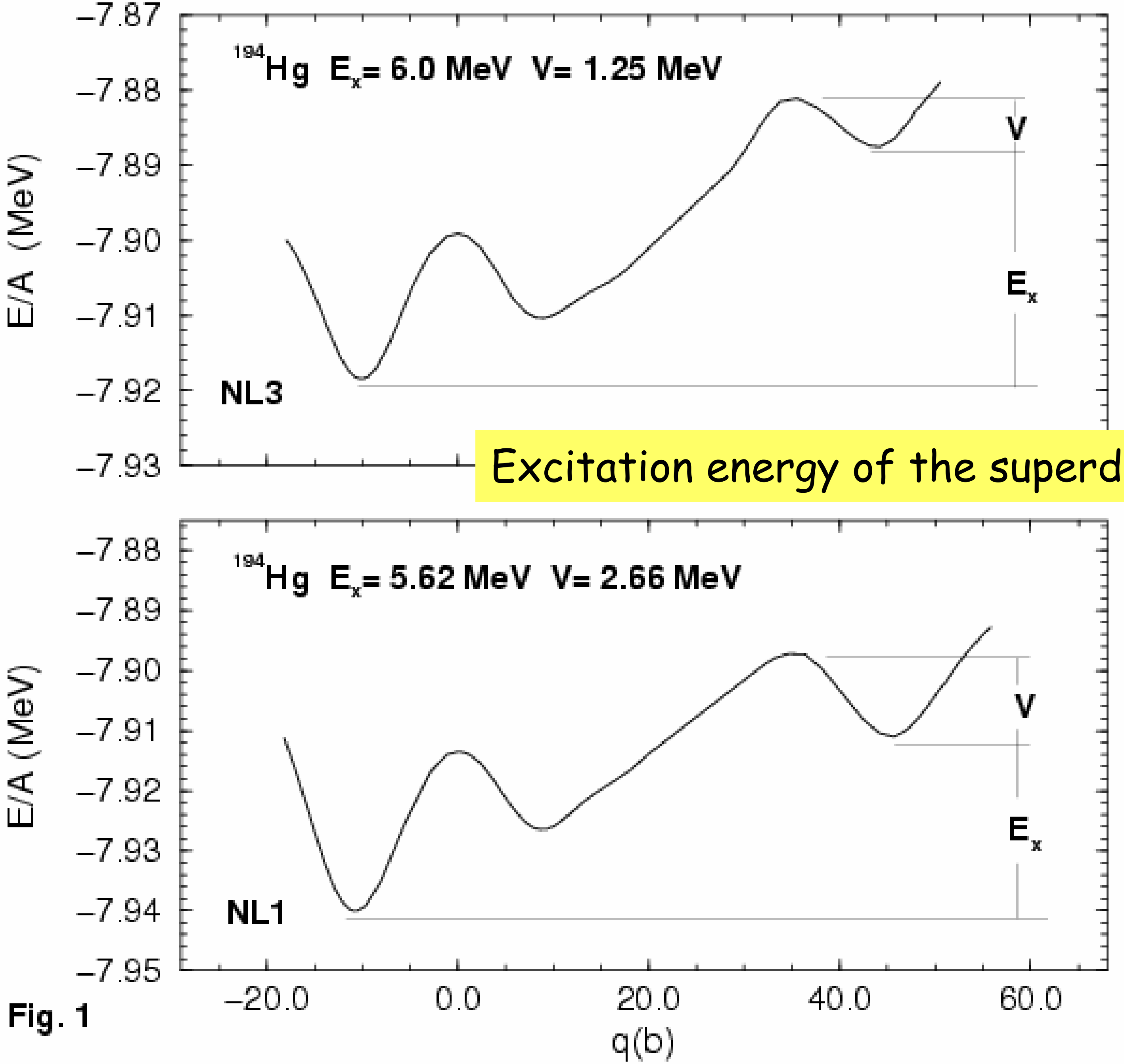


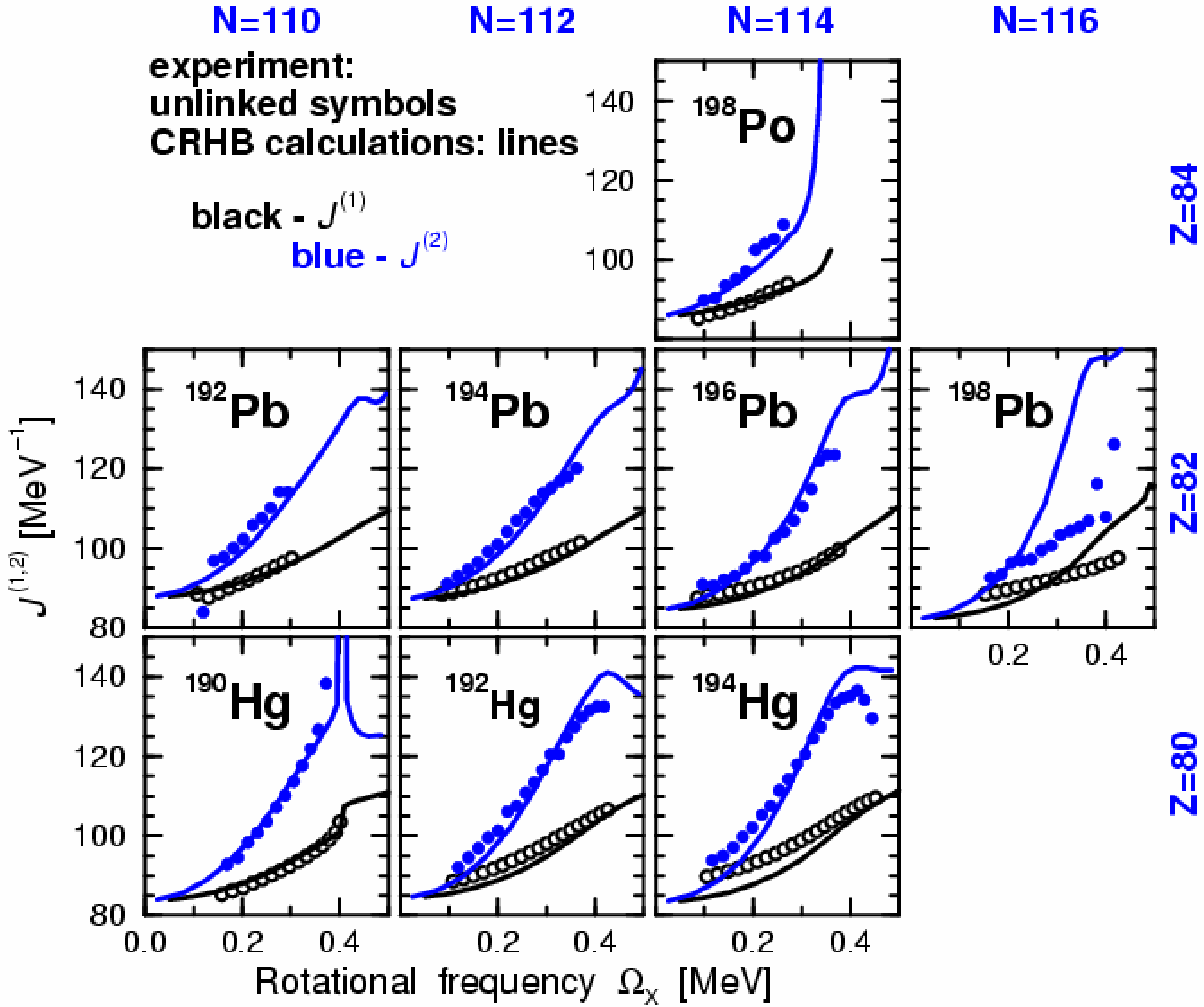
Fig. 1

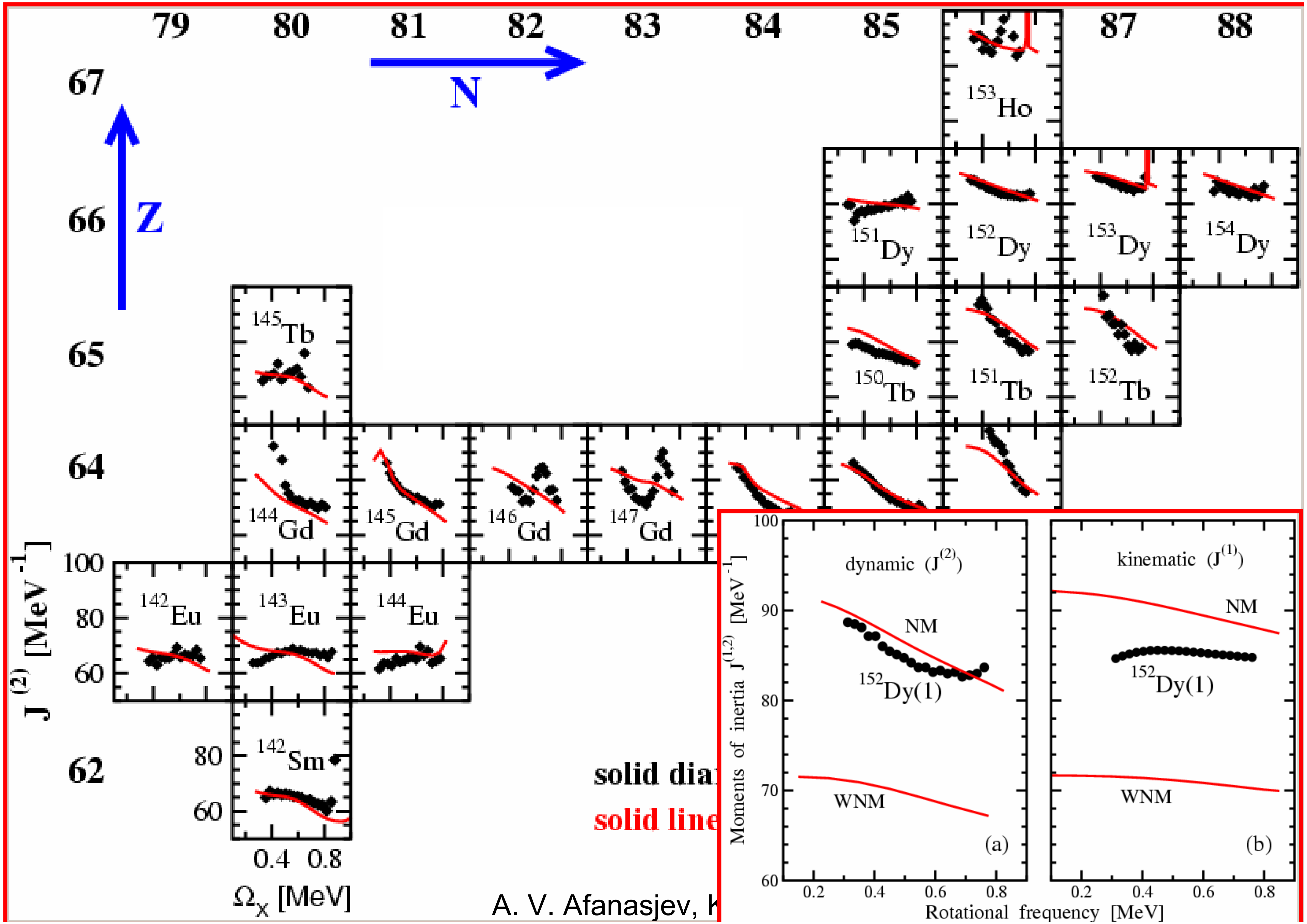
Excitation energy of the superdeformed minimum:

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

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

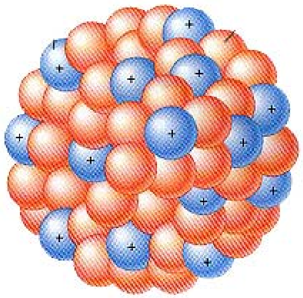




79
80
81
82
83
84
85
87
88
N
Z
67
66
65
64
62
^{153}Ho
^{151}Dy
^{152}Dy
^{153}Dy
^{154}Dy
^{145}Tb
^{150}Tb
^{151}Tb
^{152}Tb
^{144}Gd
^{145}Gd
^{146}Gd
^{147}Gd
^{142}Eu
^{143}Eu
^{144}Eu
^{142}Sm
$J^{(2)}$ [MeV^{-1}]
100
80
60
0.4
0.8
Ω_x [MeV]
solid dia
solid line
A. V. Afanasjev, K
dynamic ($J^{(2)}$)
kinematic ($J^{(1)}$)
NM
WNM
^{152}Dy(1)
(a)
(b)
Moments of inertia $J^{(1,2)}$ [MeV^{-1}]
Rotational frequency [MeV]
100
90
80
70
60
0.2
0.4
0.6
0.8

TOWARD THE UNIVERSAL ENERGY DENSITY FUNCTIONAL

Structure of heavy neutron-rich nuclei



→ Covariant Density Functional Theory

Next generation universal energy density functionals constrained by bulk properties of nuclei, nuclear excitations, nuclear and neutron matter EOS -> microscopic description of.

- ground-state properties of all nuclei
- extended asymmetric nuclear matter
- low-energy vibrations
- rotational spectra
- small-amplitude vibrations
- large-amplitude adiabatic properties

Applications in astrophysics
- r-process
- supernova explosions
- neutrino-matrix-elements

D.Vretenar,A.V.Afanasjev,G.A.Lalazissis,P.Ring, Physics Reports 409 (2005) 101

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