TECHNISCHE UNIVERSITÄT MÜNCHEN

Pairing in Covariant Density Functional Theory

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Content

- Relativistic pairing in nuclear matter
- Applications of RHB-theory in finite nuclei
- Applications of rel. QRPA-theory in finite nuclei
- Rel. methods beyond mean field

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

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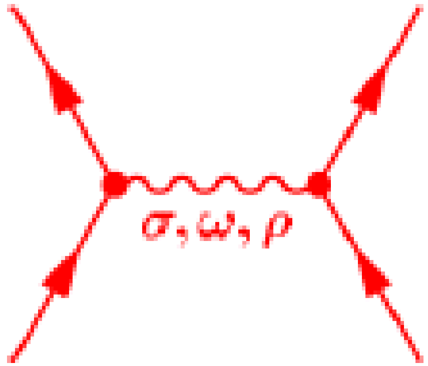
General remarks about nuclear pairing

1) There is plenty of experimental evidence
2) In principle pairing is a small effect ($\Delta << M$)
3) Most important close to the Fermi surface
4) Smearing of the Fermi surface (v^2)
5) Gap in the spectrum $E_k = \sqrt{(\varepsilon_k - \lambda)^2 + \Delta^2}$
6) Influence on response functions (e.g. moments of inertia)
7) Phase transition normal fluid → superfluid (with λ, ω, T)
8) Few exp. data on details of pairing (one parameter Δ)
9) Crucial quantity: pairtransfer matrix elements

$$J^{(2)} = \sum_{\nu} \frac{\left|\langle \nu | J_x | 0 \rangle\right|^2}{E_\nu - E_0} \approx \sum_{k<k'} \frac{\left|\langle k | J_x | k' \rangle\right|^2 (u_k v_{k'} - v_k u_{k'})}{E_k + E_{k'}}$$

Relativistic Pairing:

One has to quantize the meson fields:



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

Meson fields: $\sum_{\mu} \omega_{\mu}\, a_{\mu}^{+} a_{\mu}$

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

neglect retardation

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

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 Hartree Bogoliubov (RHB)

⇨ Unified description of mean-field and pairing correlations

Dirac hamiltonian

chemical potential

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

quasiparticle wave function

$$h_D(\vec{r}) = \vec{\alpha}(\vec{p} - \vec{V}(\vec{r})) + \beta(m - S(\vec{r})) + V(\vec{r})$$

$$\Delta_{ab}(\vec{r},\vec{r}\,') = \frac{1}{2}\sum_{c,d} V^{pp}_{abcd}(\vec{r},\vec{r}\,')\kappa_{cd}(\vec{r},\vec{r}\,') = \begin{pmatrix} \Delta_{++} & 0 \\ 0 & 0 \end{pmatrix}$$

H. Kucharek, P. Ring, Z. Phys. A339 (1991) 23

Gogny D1S

Pairing in nuclear matter

$^1S_0 - Channel$

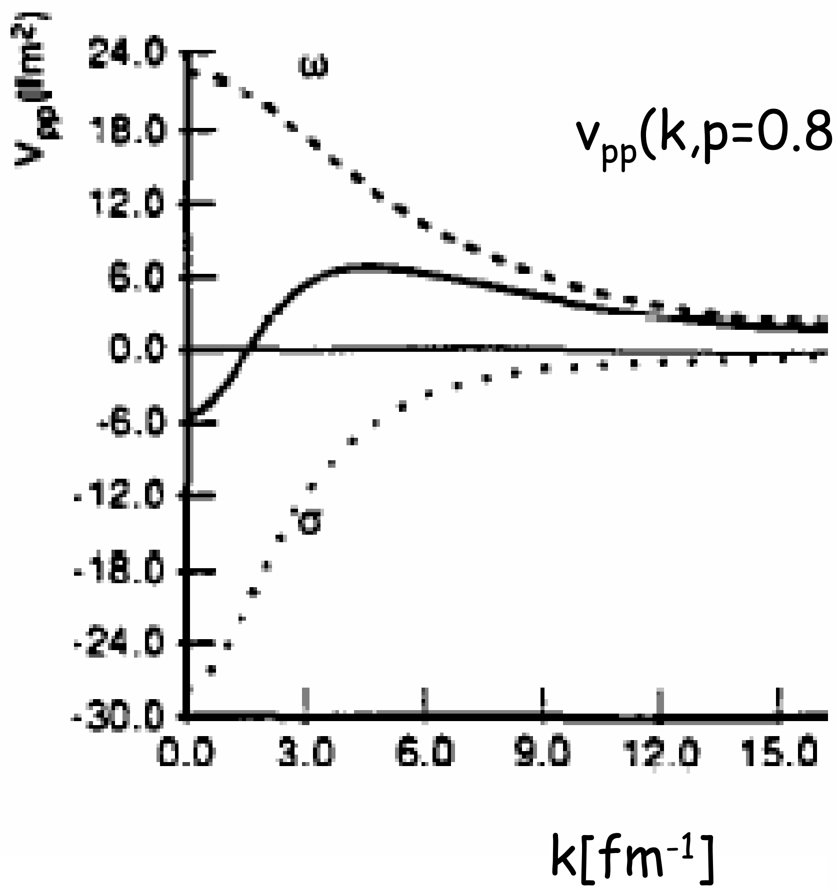
RMF+BCS
Gap equation:

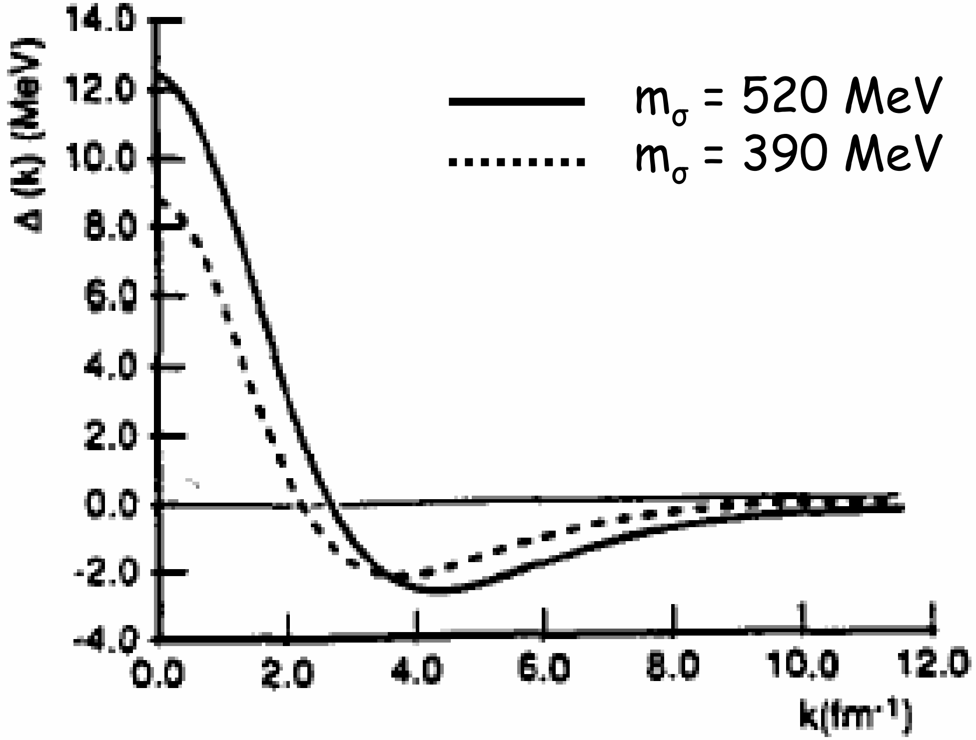
$$\Delta(p) = -\frac{1}{4\pi^2}\int_0^\infty v_{pp}(p,k)\frac{\Delta(k)}{\sqrt{(\varepsilon(k)-\lambda)^2+\Delta^2(k)}}k^2dk$$

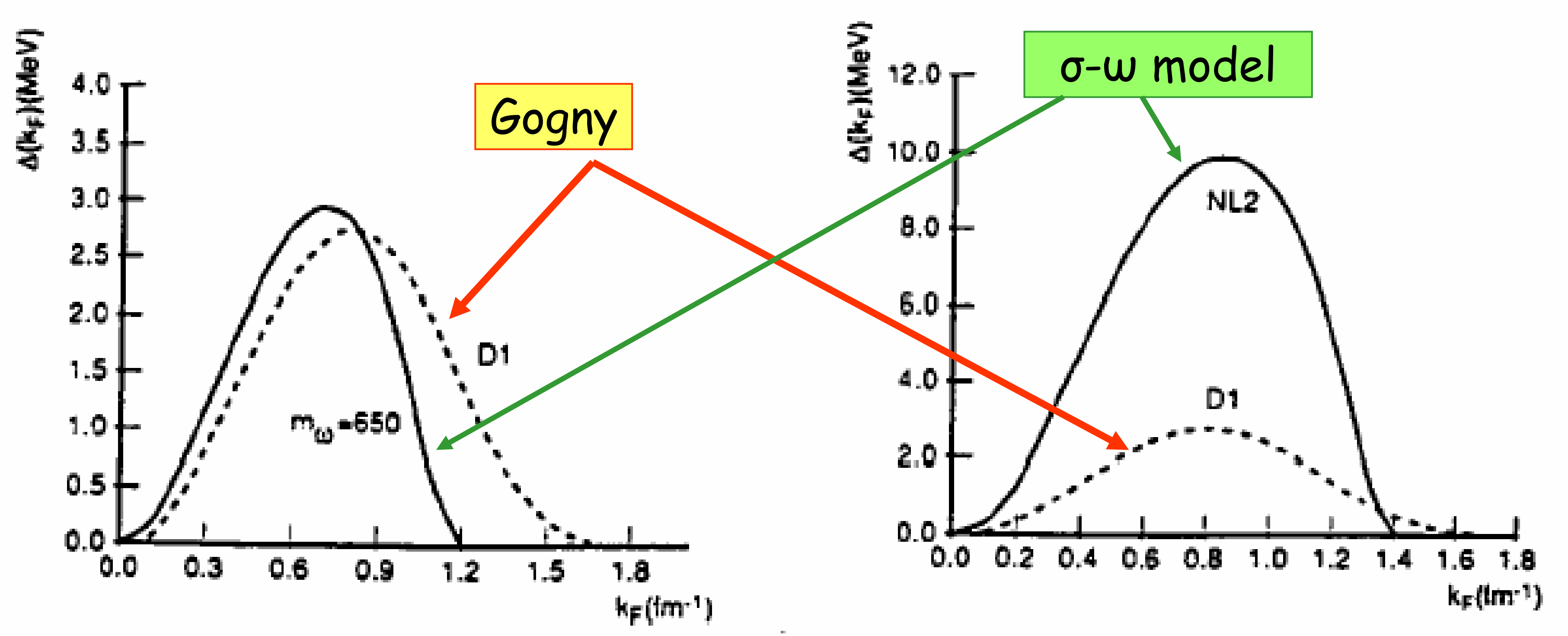
e.g.:

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

Pairing matrix elements:

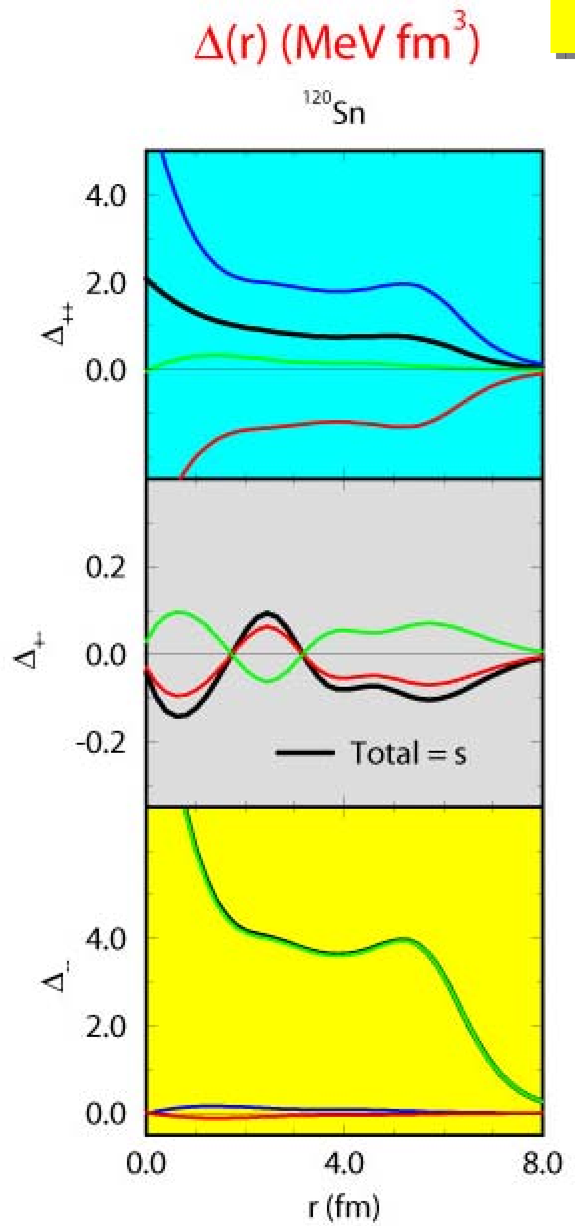






All relativistic forces, e. g. NL1, NL2,NL3 … overestimate nuclear pairing by a factor 3, because they do not have a cut off in momentum space

Relativistic structure of pairing:



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

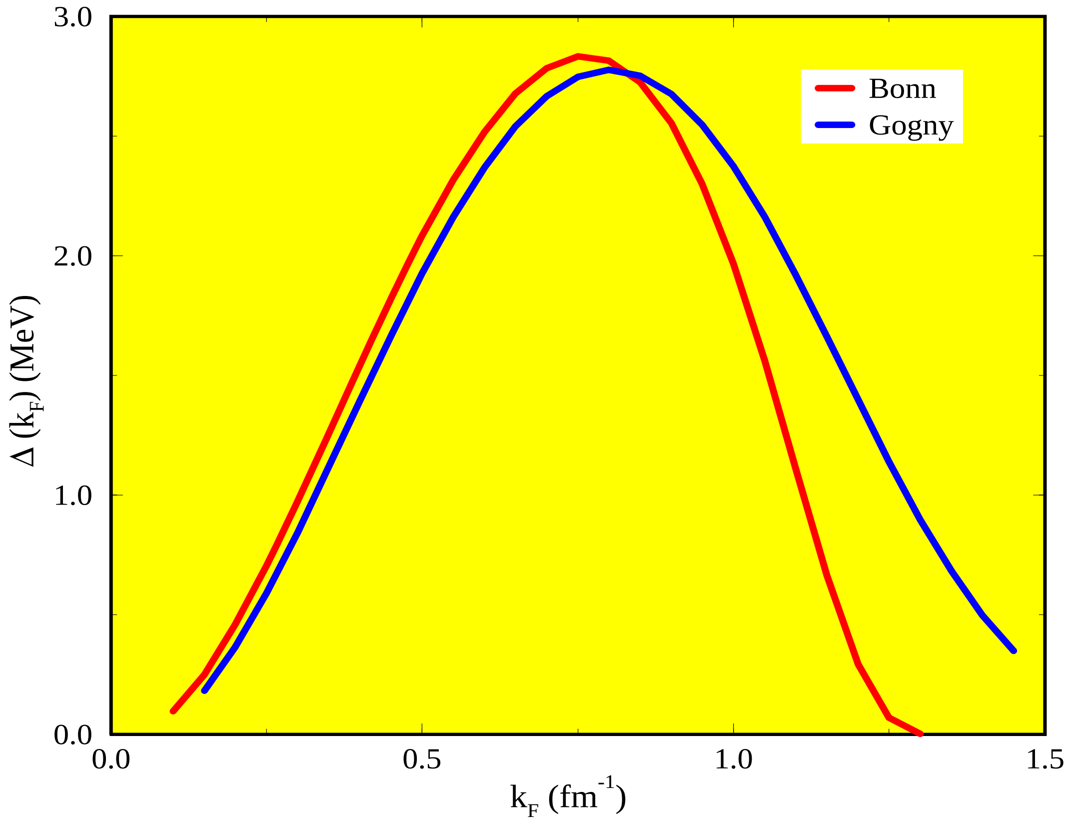
$$\Delta_{-+} \ll \Delta_{++} \ll \boldsymbol{\sigma}\mathbf{p}$$

therefore we neglect Δ_{+-}

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

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

The pairing gap at the Fermi surface

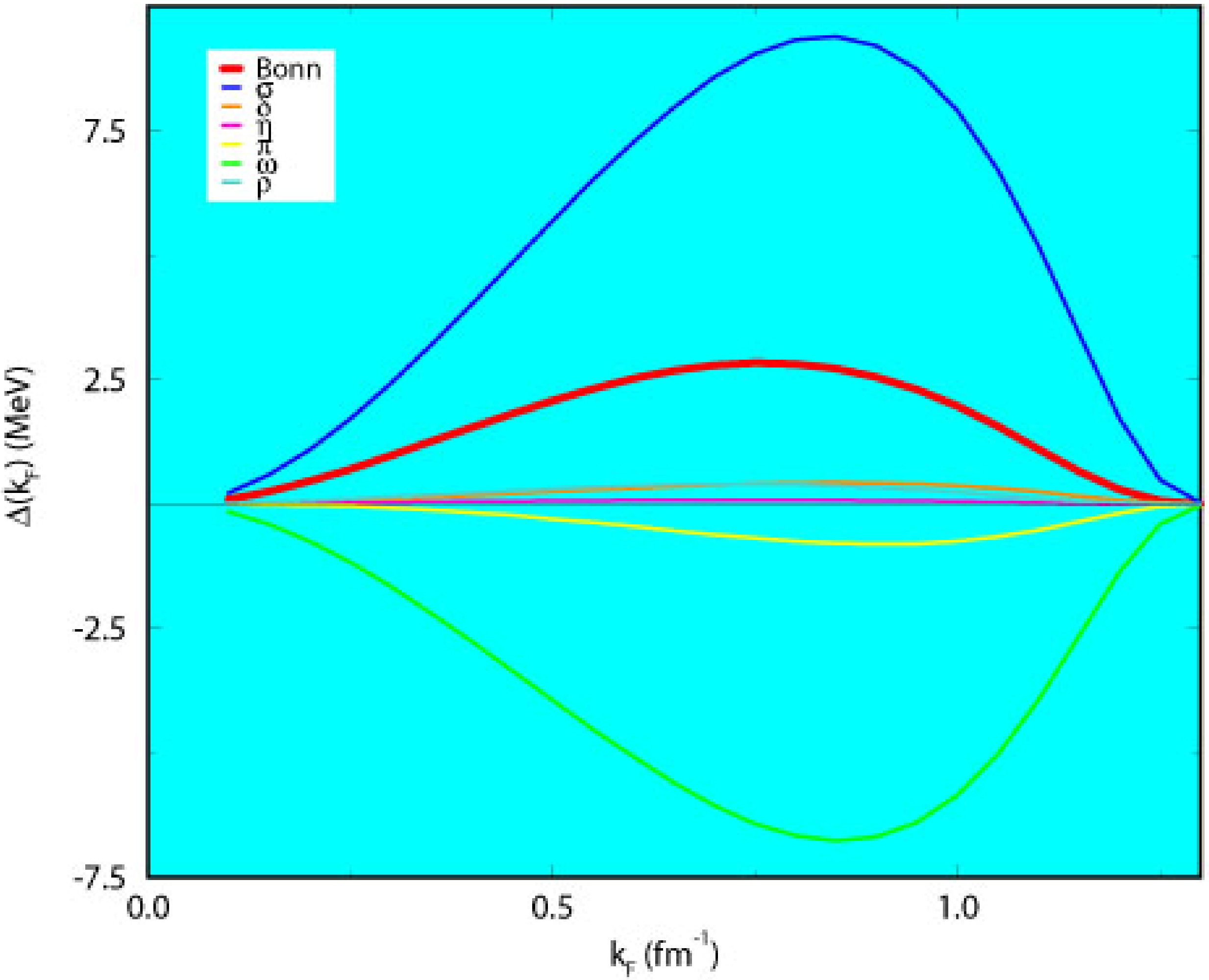


maximal pairing at the Fermi surface:

potential	Δ_F(MeV)	k_F(fm^{-1})
Bonn *A*	2.80	0.76
Bonn *B*	2.84	0.76
Bonn *C*	2.83	0.76
Gogny *D1S*	2.78	0.80

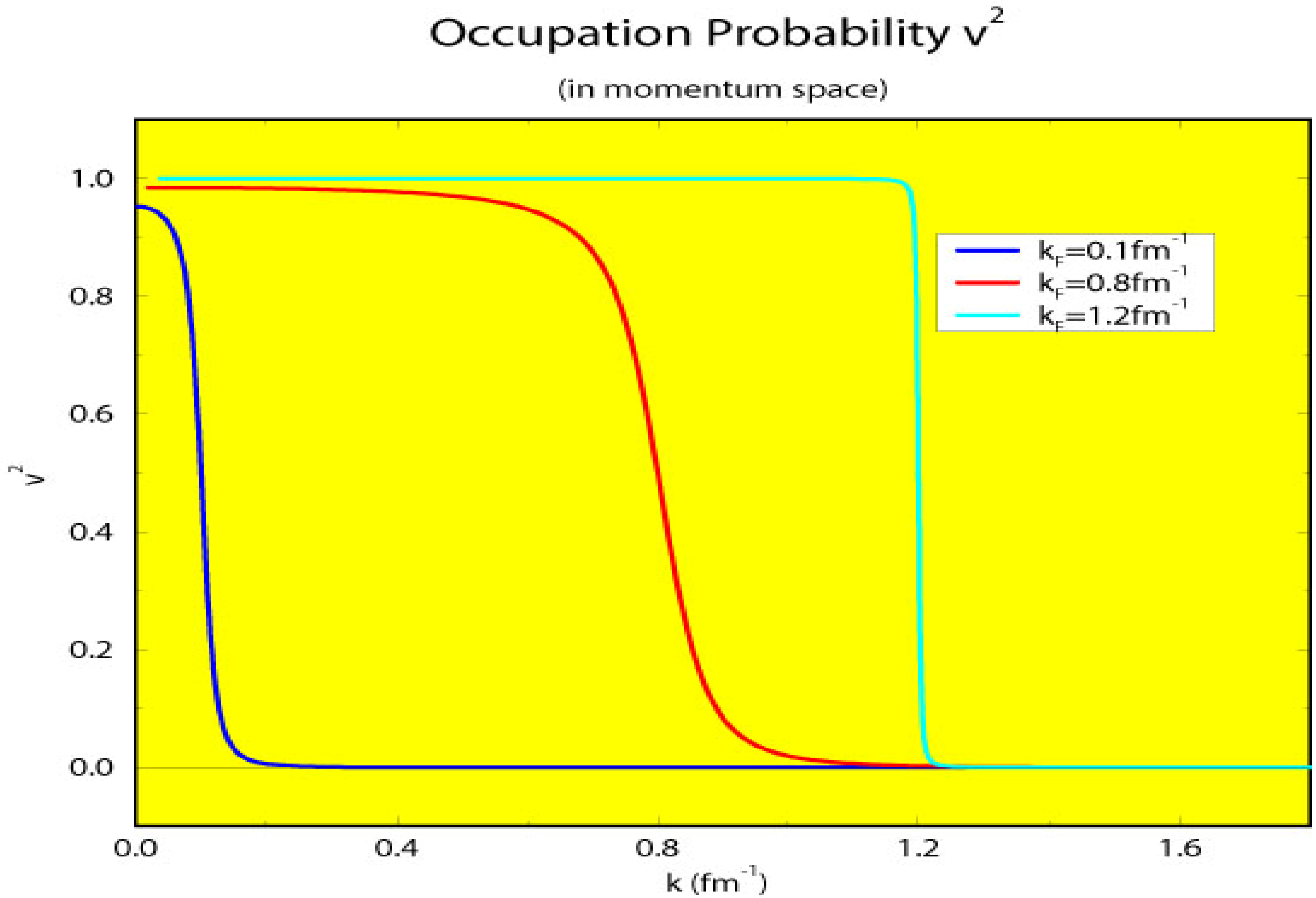
free NN-forces, which reproduce the phase shift in the $^1S_0$ channel give pairing similar to the Gogny force

Contributions of the various mesons in the Bonn-potential to pairing:

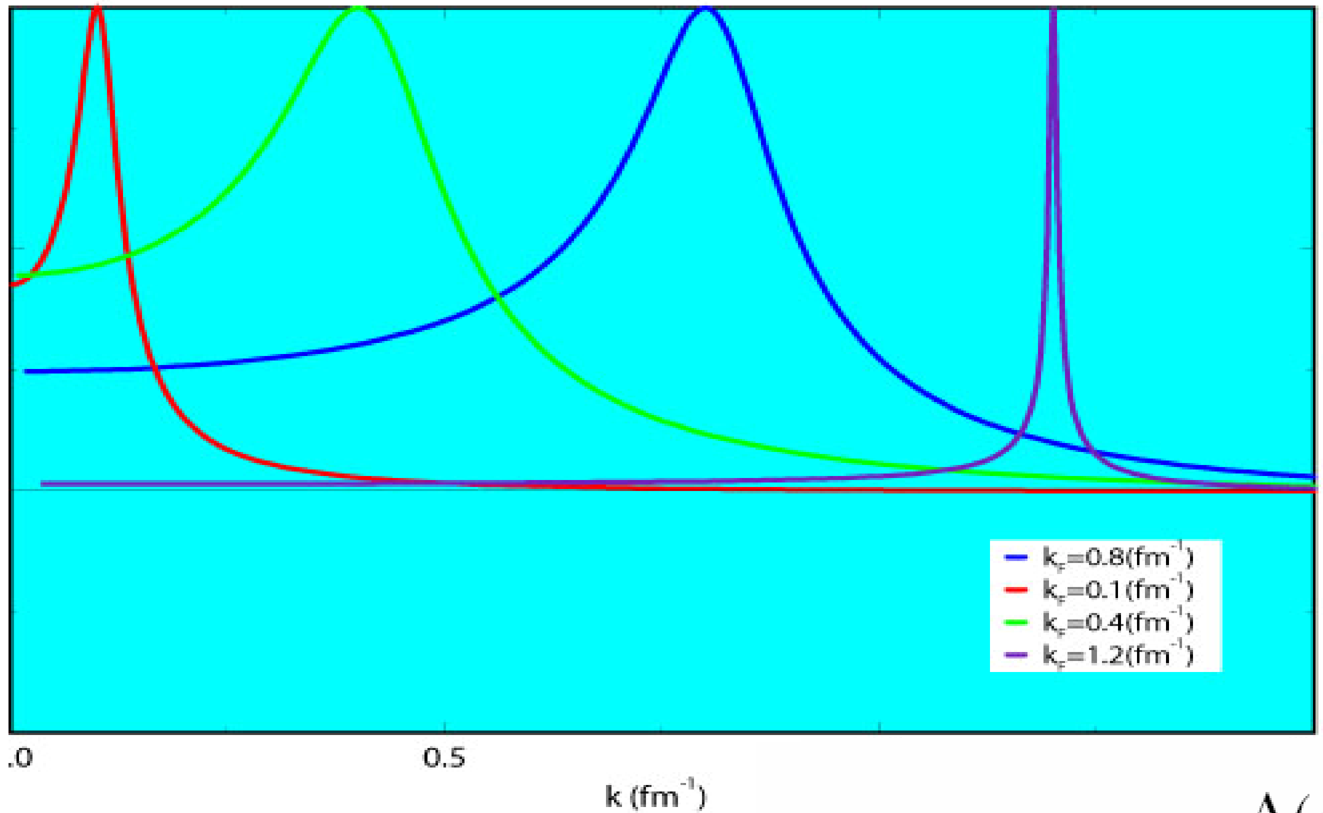


M. Serra, A. Rummel, P. Ring, PRC 65 (2002) 014304

Gogny *D1S*

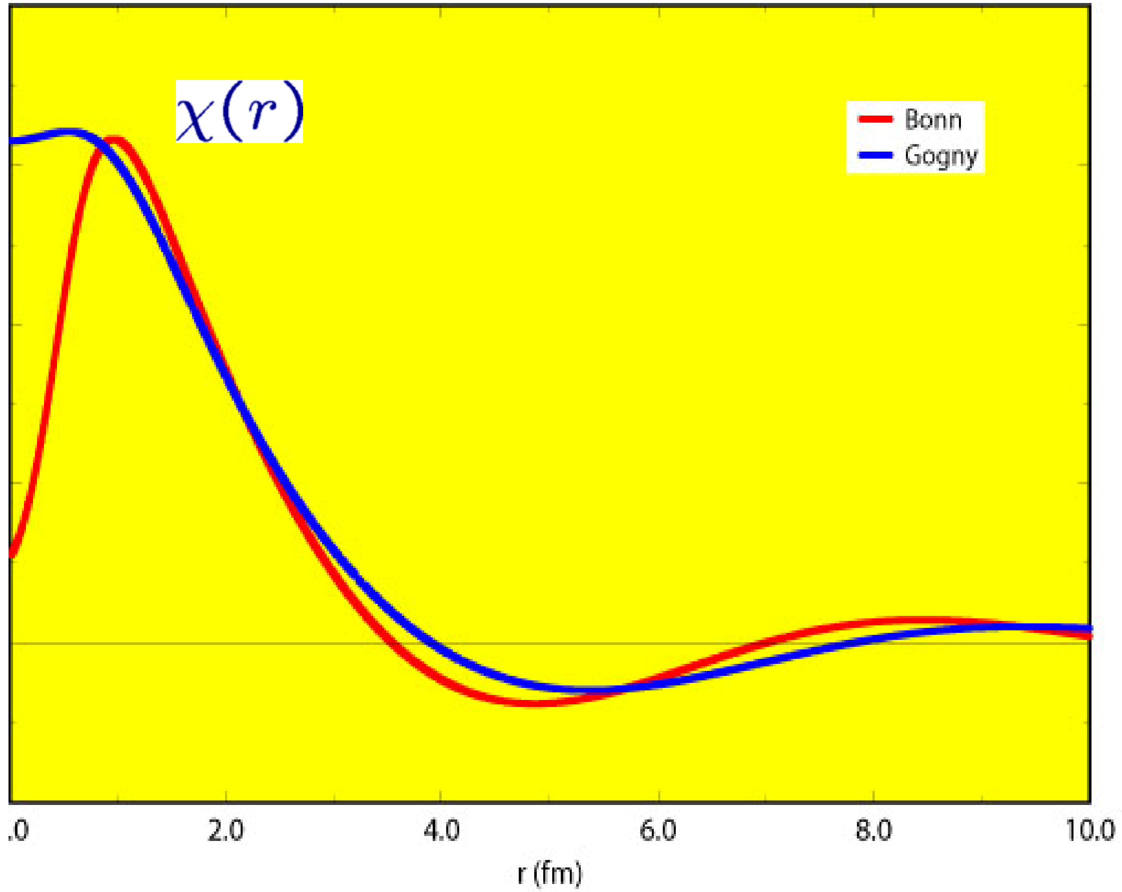

Occupation Probability v²
(in momentum space)
1.0
0.8
0.6
0.4
0.2
0.0
v²
0.0
0.4
0.8
1.2
1.6
k (fm⁻¹)
k_F=0.1fm⁻¹
k_F=0.8fm⁻¹
k_F=1.2fm⁻¹

Wave functions of the Cooper pair in momentum space:



$$\chi(k) = \frac{\Delta(k)}{2\sqrt{[\epsilon(k)-\lambda]^2+\Delta^2(k)}}.$$

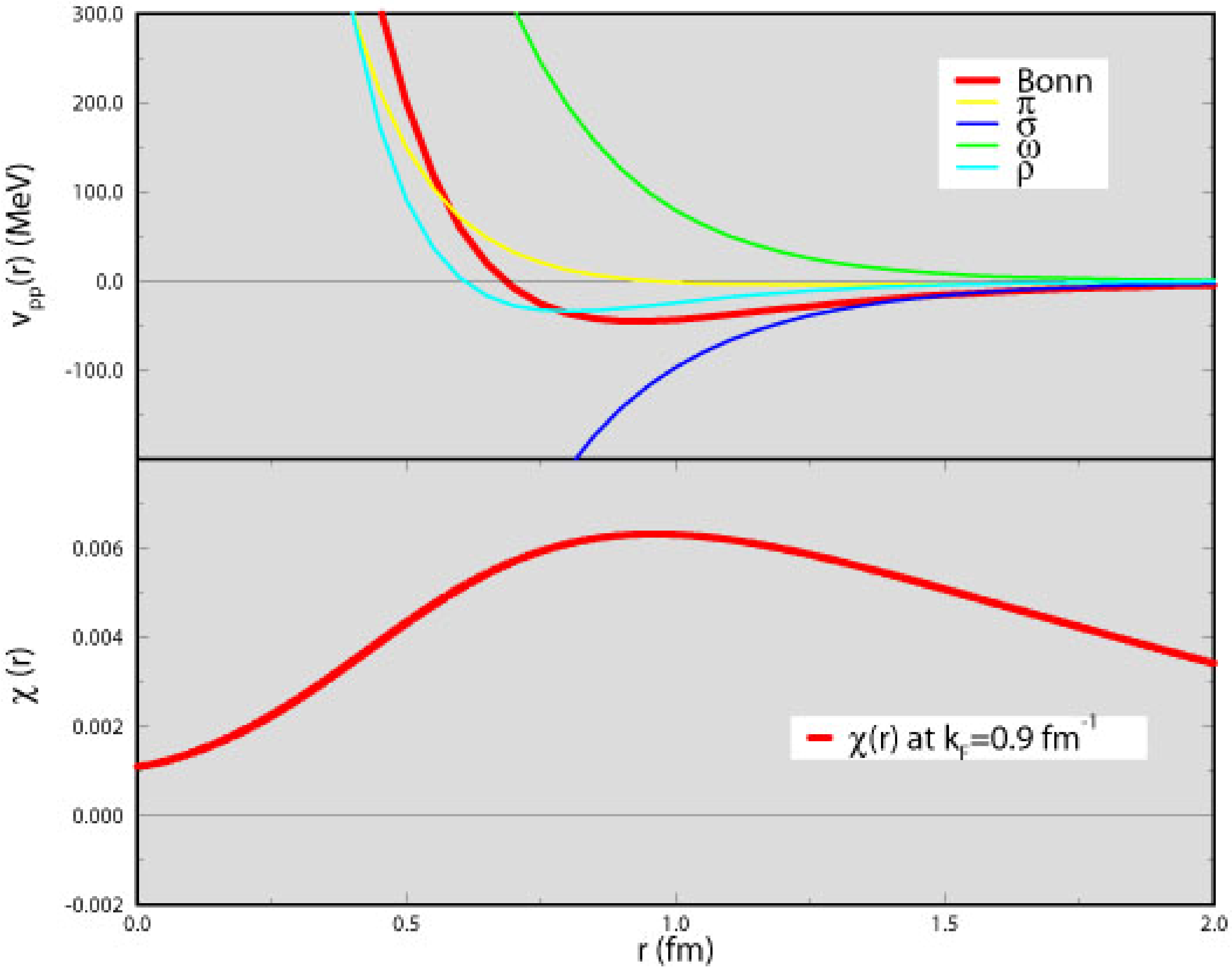
Wave functions of the Cooper pair in r-space:



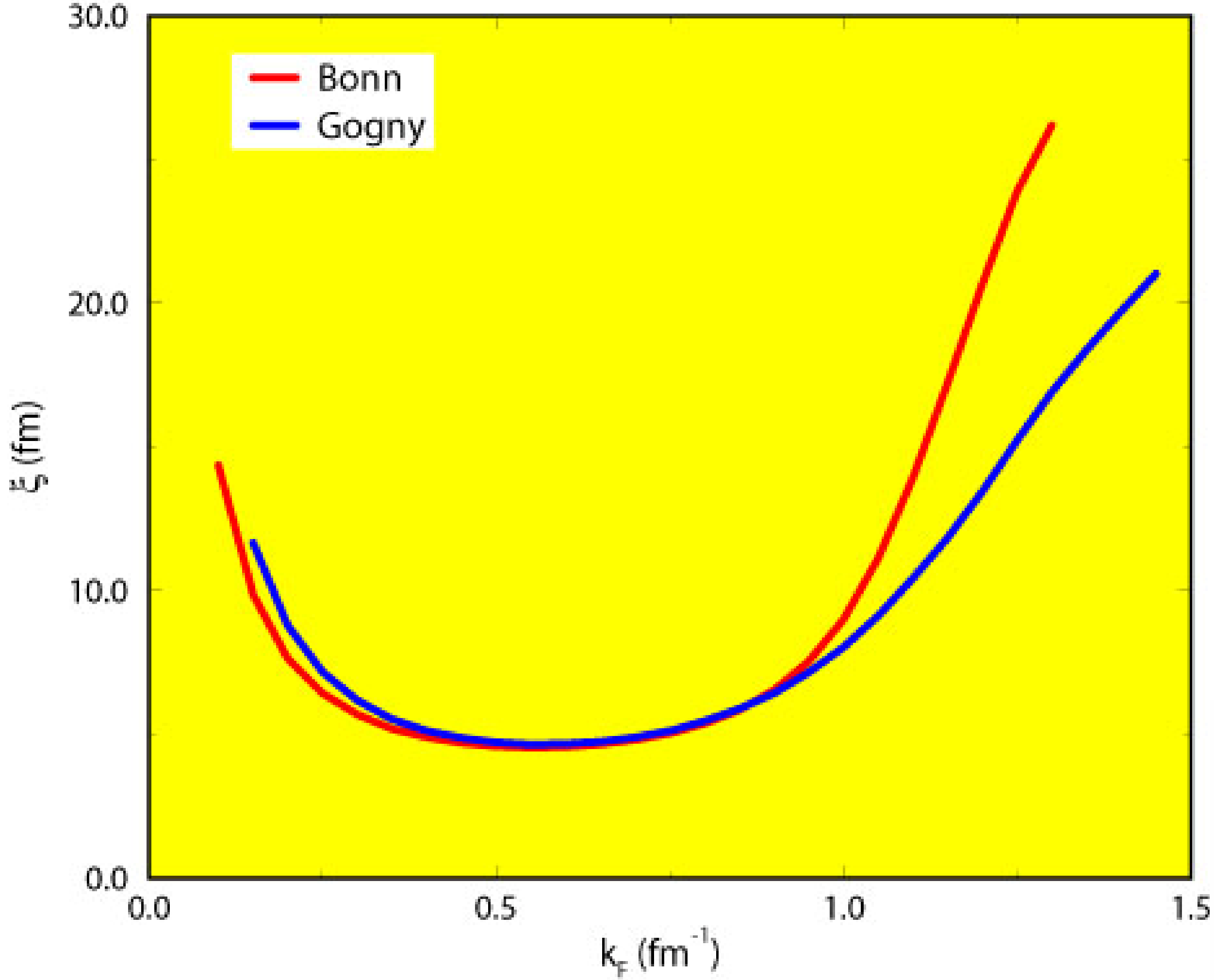
$$k_F = 0.8 \ fm^{-1}$$

$$\chi(\vec{r}) = \langle \Phi | \psi^\dagger_\uparrow(\vec{R} + \frac{1}{2}\vec{r}) \psi^\dagger_\downarrow(\vec{R} - \frac{1}{2}\vec{r}) | Phi \rangle$$

Influence of the repulsive core in Bonn-pot.:



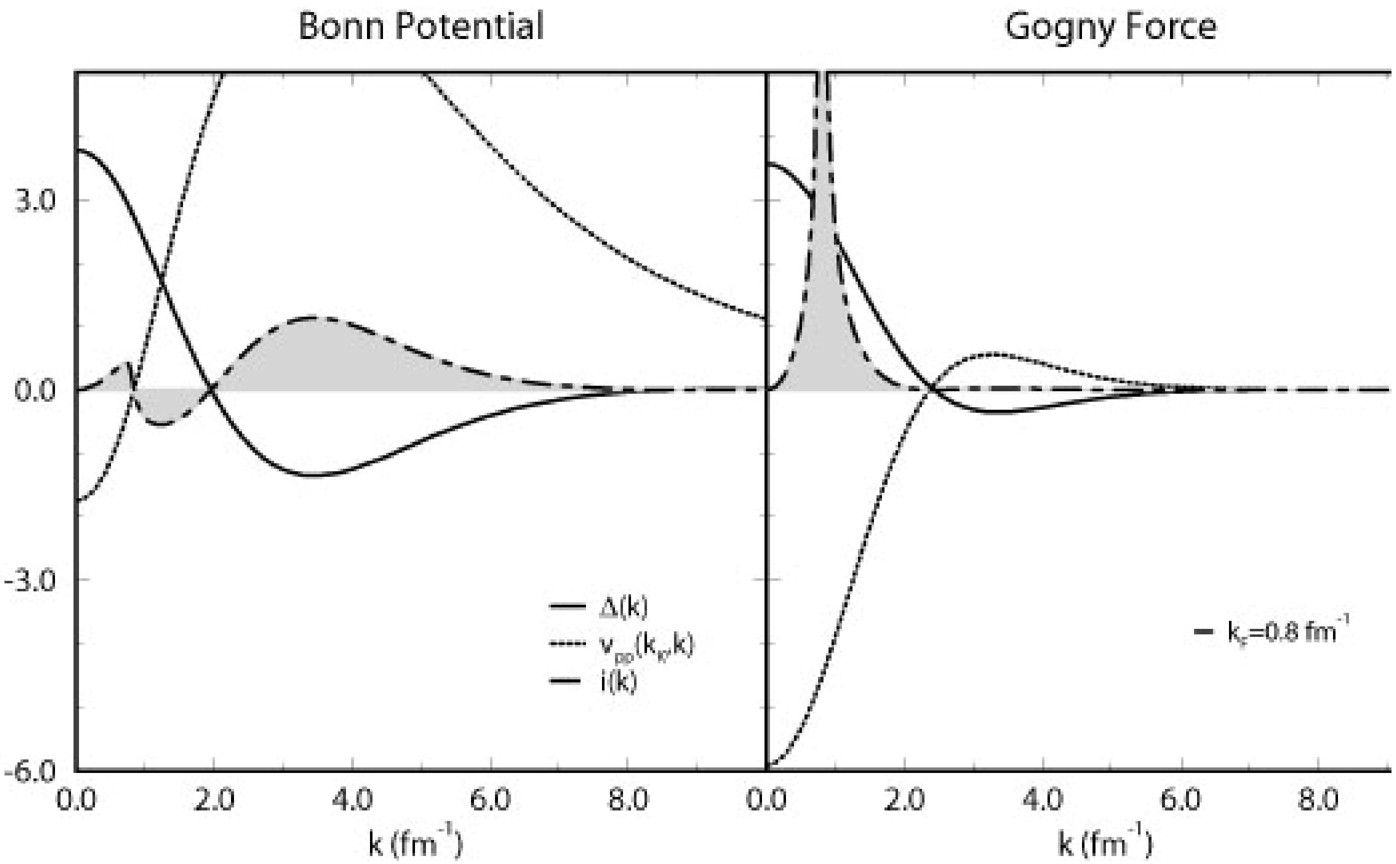
Coherence length:



$$\xi^2 = \frac{\int d^3r |\chi(\mathbf{r})|^2 r^2}{\int d^3r |\chi(\mathbf{r})|^2}:$$

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

Is the gap caused by the repulsive part of the: force?



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

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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

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

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

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

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

Density functional:

$$\hat{\rho} = \langle \Phi | \psi^\dagger \psi | \Phi \rangle$$

$$\hat{\kappa} = \langle \Phi | \psi^\dagger \psi^\dagger | \Phi \rangle$$

$$\phi = \sigma, \omega^\mu, \vec{\rho}^\mu, A^\mu$$

$$E[\hat{\rho}, \hat{\kappa}, \phi] = E_{RMF}[\hat{\rho}, \phi] + E_{pair}[\hat{\kappa}]$$

$$E_{RMF}[\rho, \phi] = \int d^3r \, \{ H_D(\mathbf{r}) + H_{mes}(\mathbf{r}) + H_{int}(\mathbf{r}) \}$$

$$E_{pair}[\hat{\kappa}] = \langle \Phi | V^{pp} | \Phi \rangle = \frac{1}{2} \mathrm{Tr} \, (\hat{\kappa} V^{pp} \hat{\kappa}^*)$$

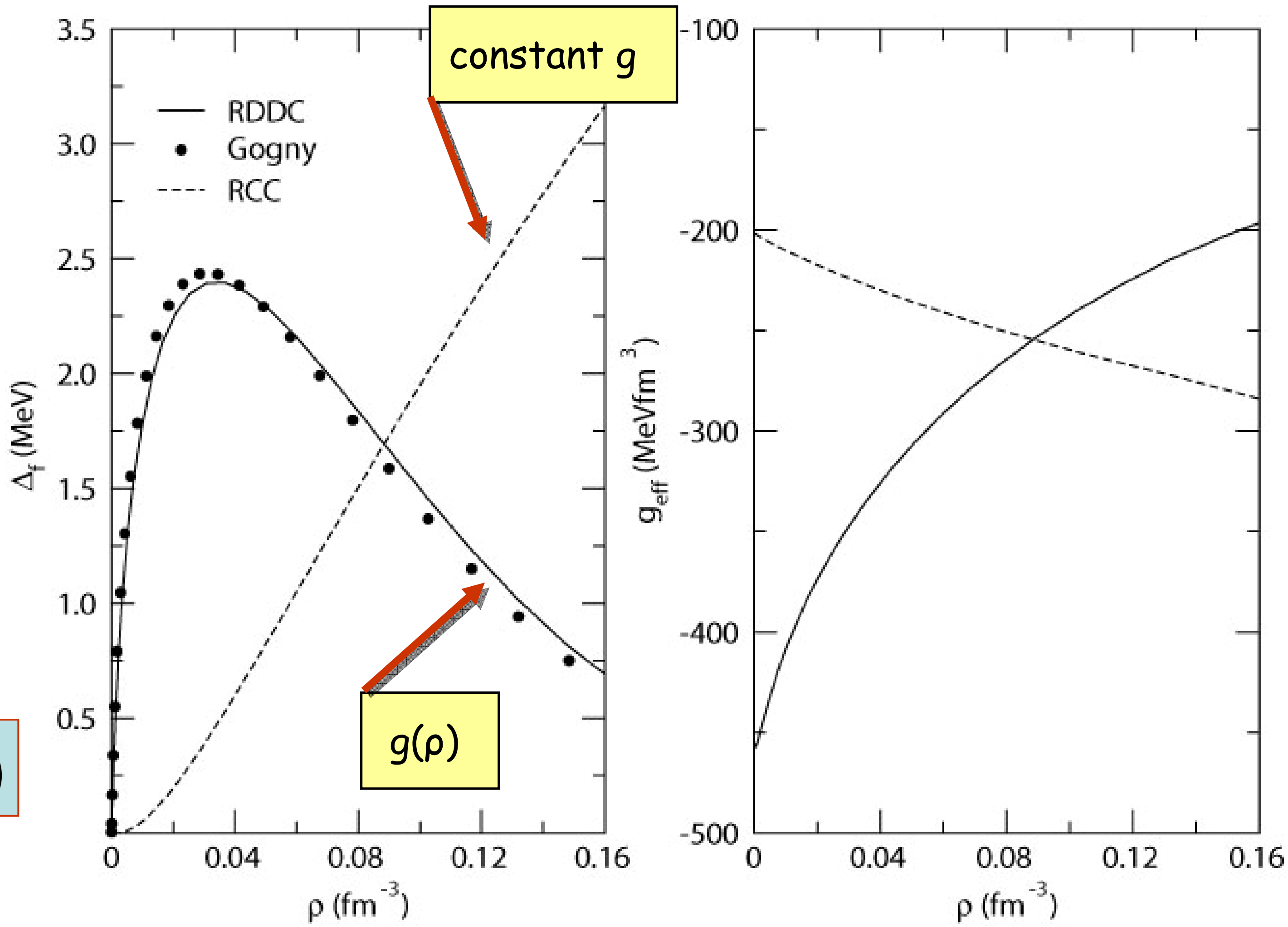
$$H_D(\mathbf{r}) = J(\mathbf{r}) + m_N [\rho_s(\mathbf{r}) - \rho(\mathbf{r})]$$

$$H_{mes}(\mathbf{r}) = \frac{1}{2} |\nabla \sigma(\mathbf{r})|^2 + \frac{1}{2} m_\sigma \sigma(\mathbf{r})^2 + \ldots$$

$$H_{int}(\mathbf{r}) = g_\sigma \rho_s(\mathbf{r}) \sigma(\mathbf{r}) + g_\omega j_B^\mu(\mathbf{r}) \omega_\mu(\mathbf{r}) + \ldots$$

$$J(\mathbf{r}) = -i \sum_i V^\dagger(\mathbf{r}) \boldsymbol{\alpha} \boldsymbol{\nabla} V(\mathbf{r})$$

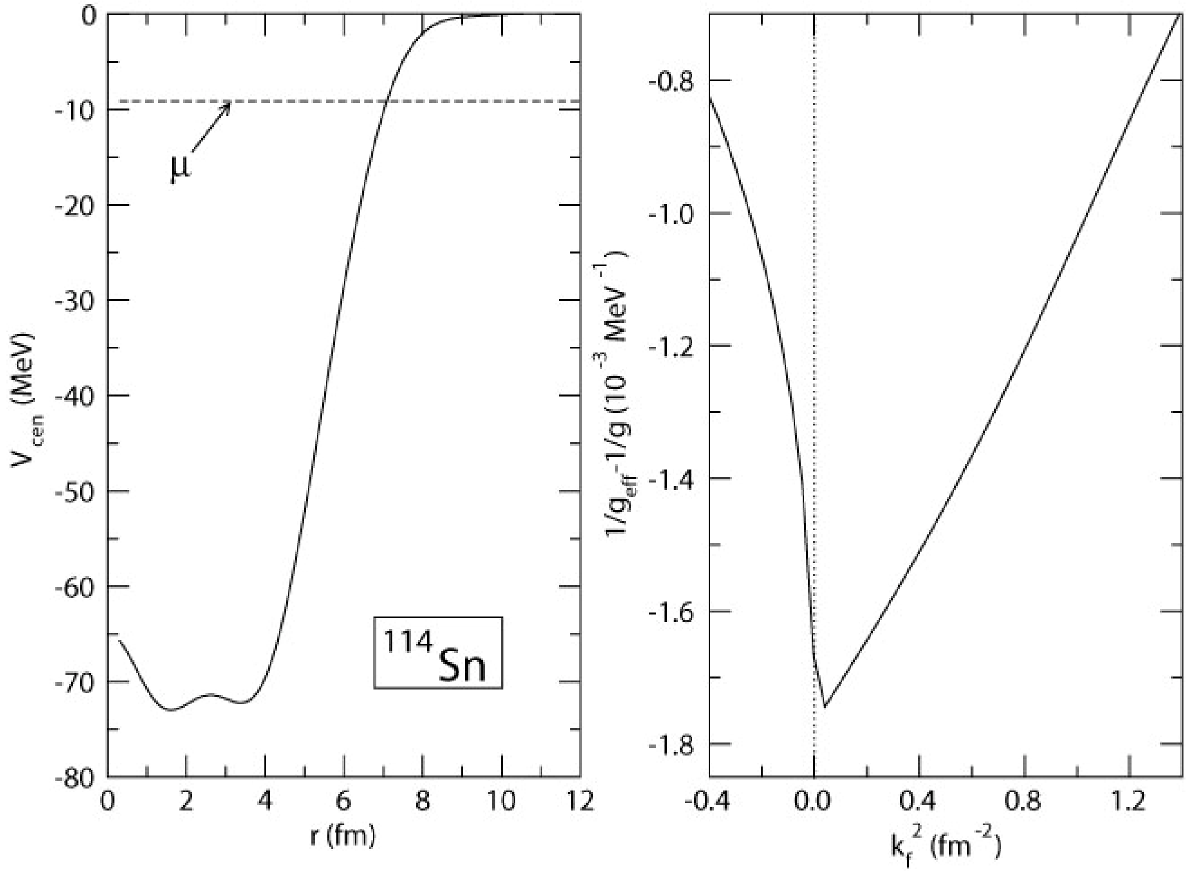
renormalized relativistic RHB for zero range pairing



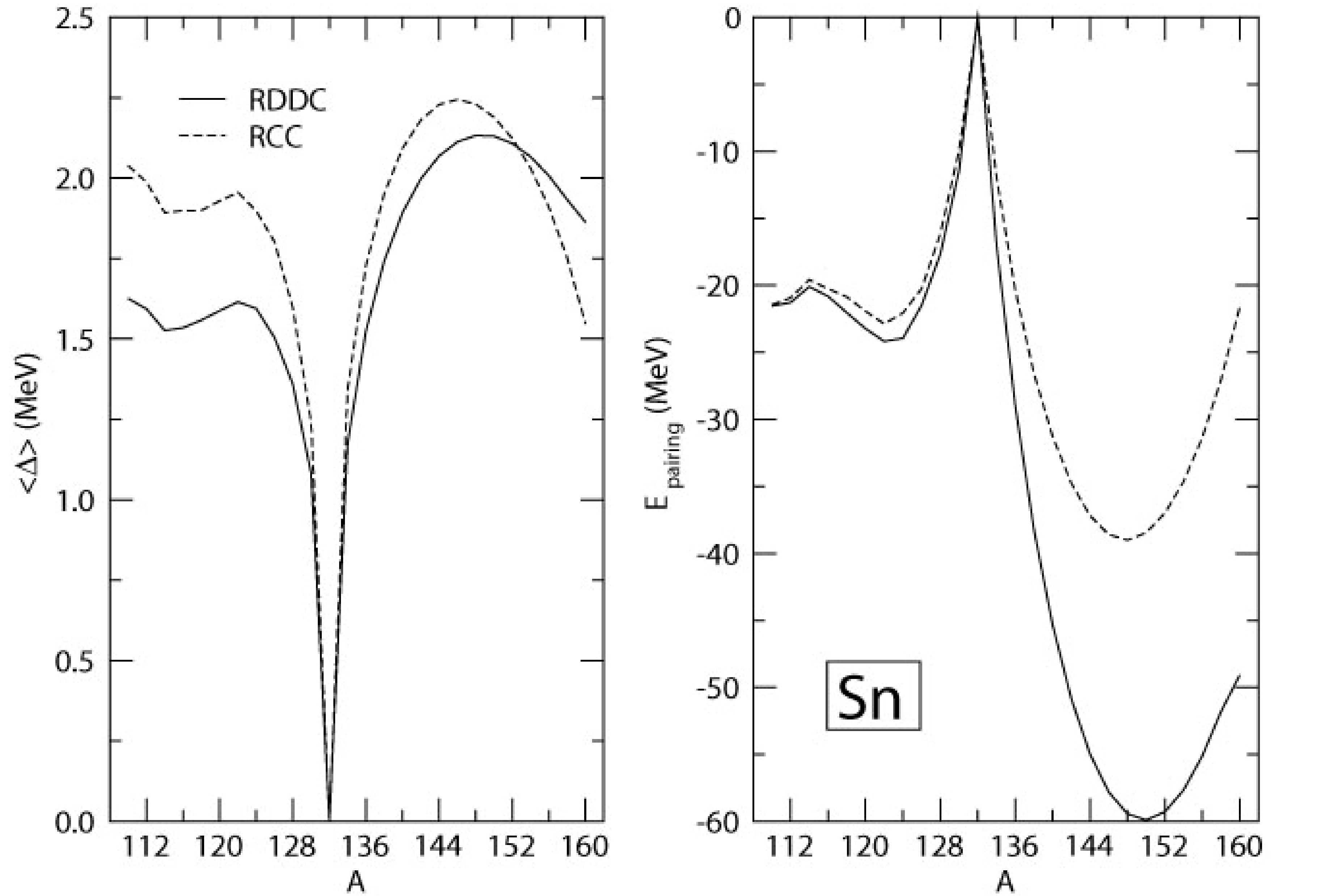
$V^{pp} = g(\rho)\delta(r-r')$

Bulgac, Yu, PRC **65**, 051305 (2002)
Niksic, Ring, Vretenar, PRC **71**, 044320 (2005)

renormalized δ-pairing in finite nuclei



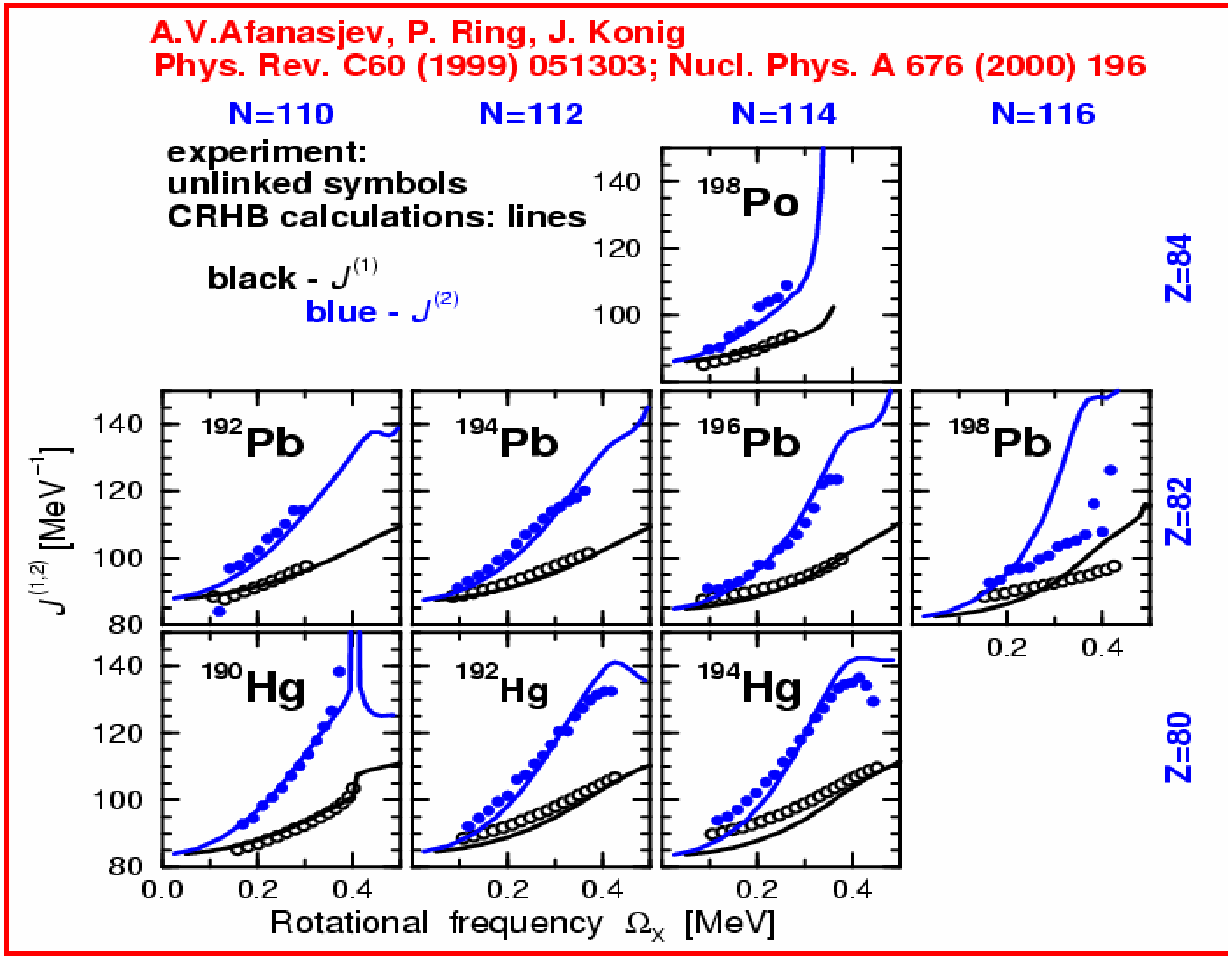
for density dependend g(ρ) the effective coupling shows a peak at the surface


RDDC
RCC
<Δ> (MeV)
A
E pairing (MeV)
Sn
112 120 128 136 144 152 160
0.0 0.5 1.0 1.5 2.0 2.5
0 -10 -20 -30 -40 -50 -60

Applications of pairing in finite nuclei

- **Moments of inertia in rotating nuclei**
- **Halo phenomena at the neutron drip line**
- **Quasiparticle-RPA for excited states**
  - IVGDR in Sn-isotopes
  - Pygmy modes
- **Methods beyond mean field**
  - projected density functionals (PDFT)
  - relativistic GCM
  - particle vibrational coupling
  - decay width of Giant resonances

D. Vretenar, A. V. Afanasjiev, G. A. Lalazissis, P. Ring, Phys. Rep. 409 (2005) 101 pairing in superdeformed bands:



Pairing important: Gogny D1S (no free parameter).
With Skyrme-forces one needs surface pairing
Does surface pairing compensate for finite range?

Excitation of the superdef. minimum:

^{194}Hg

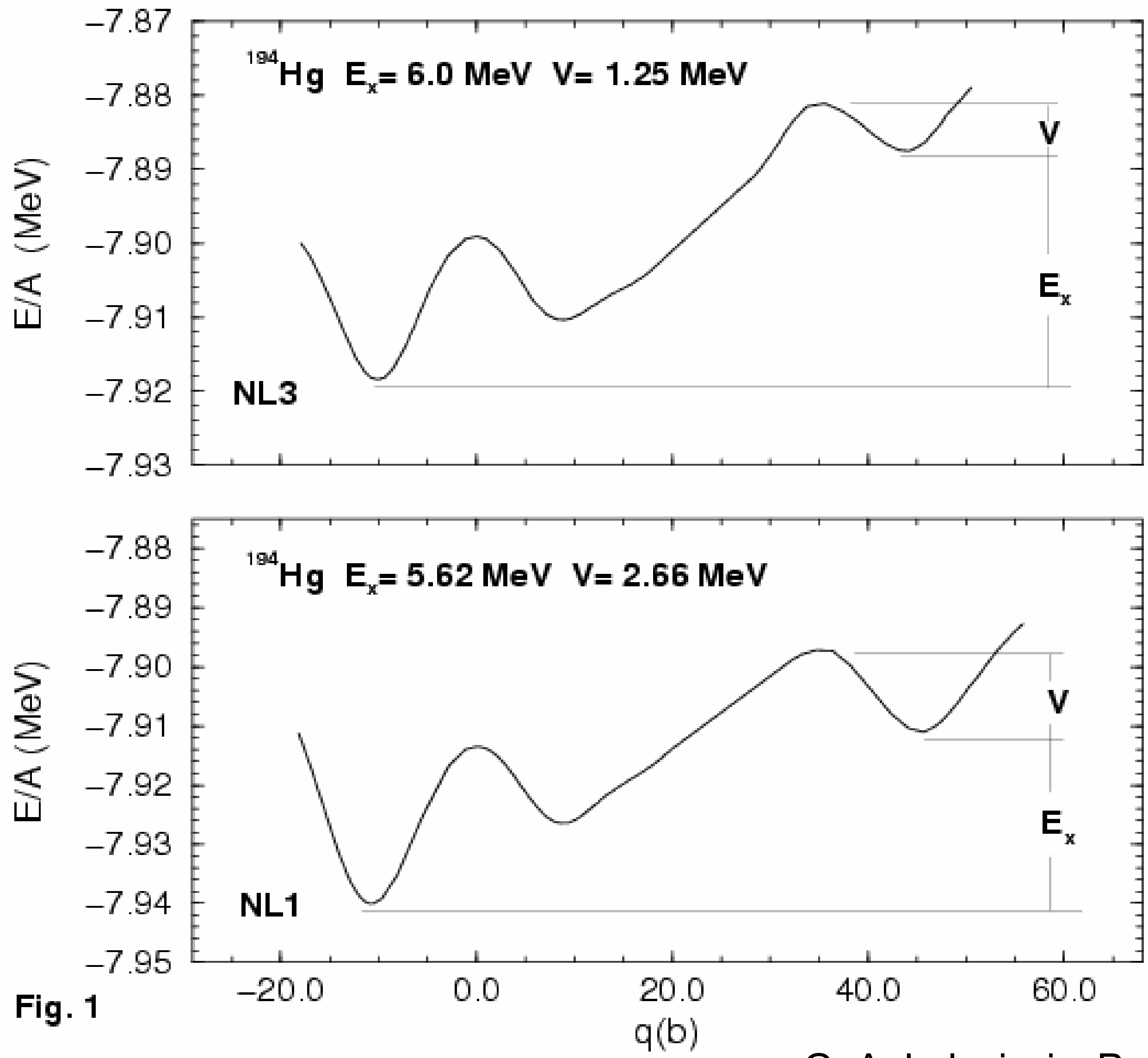
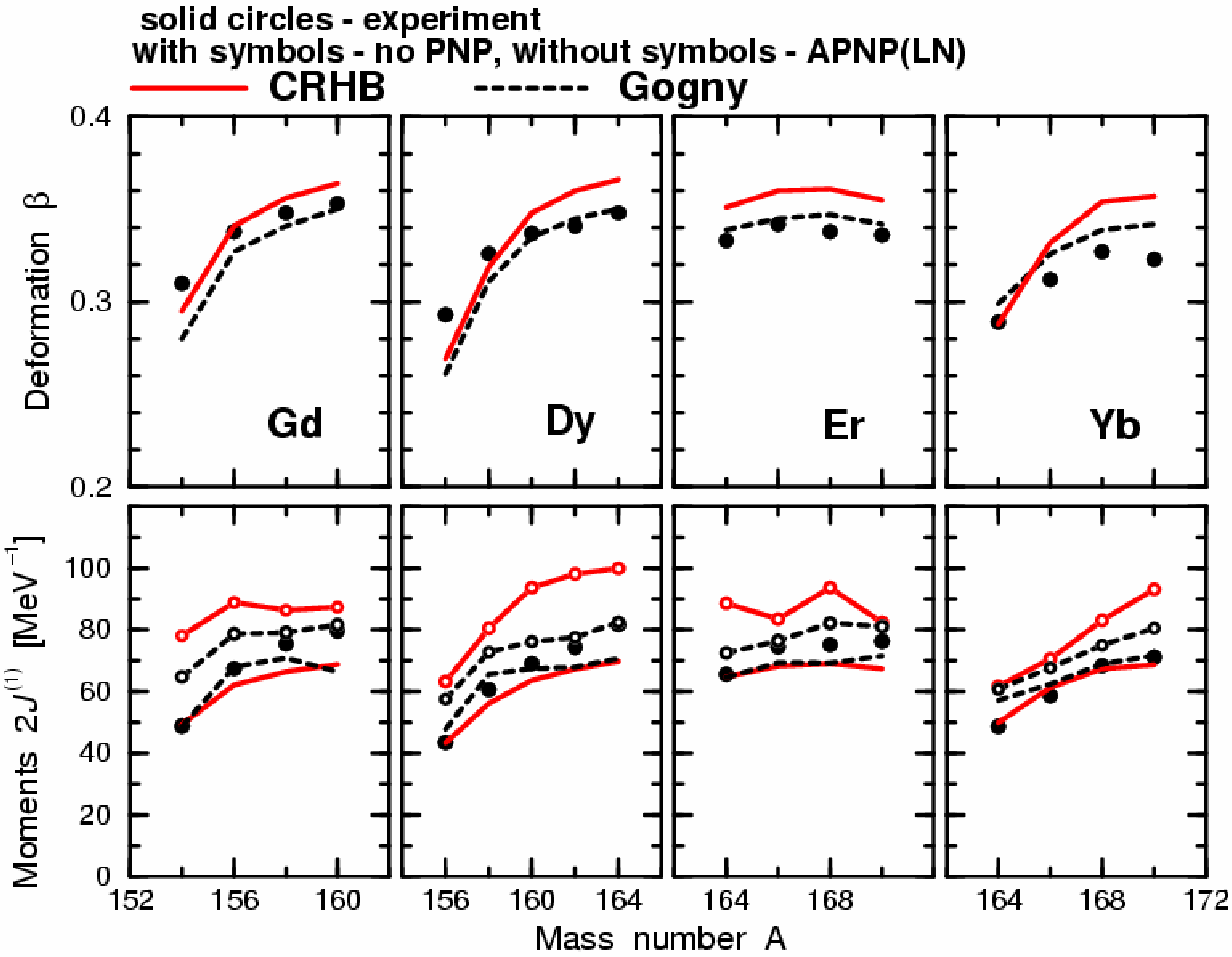


Fig. 1

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

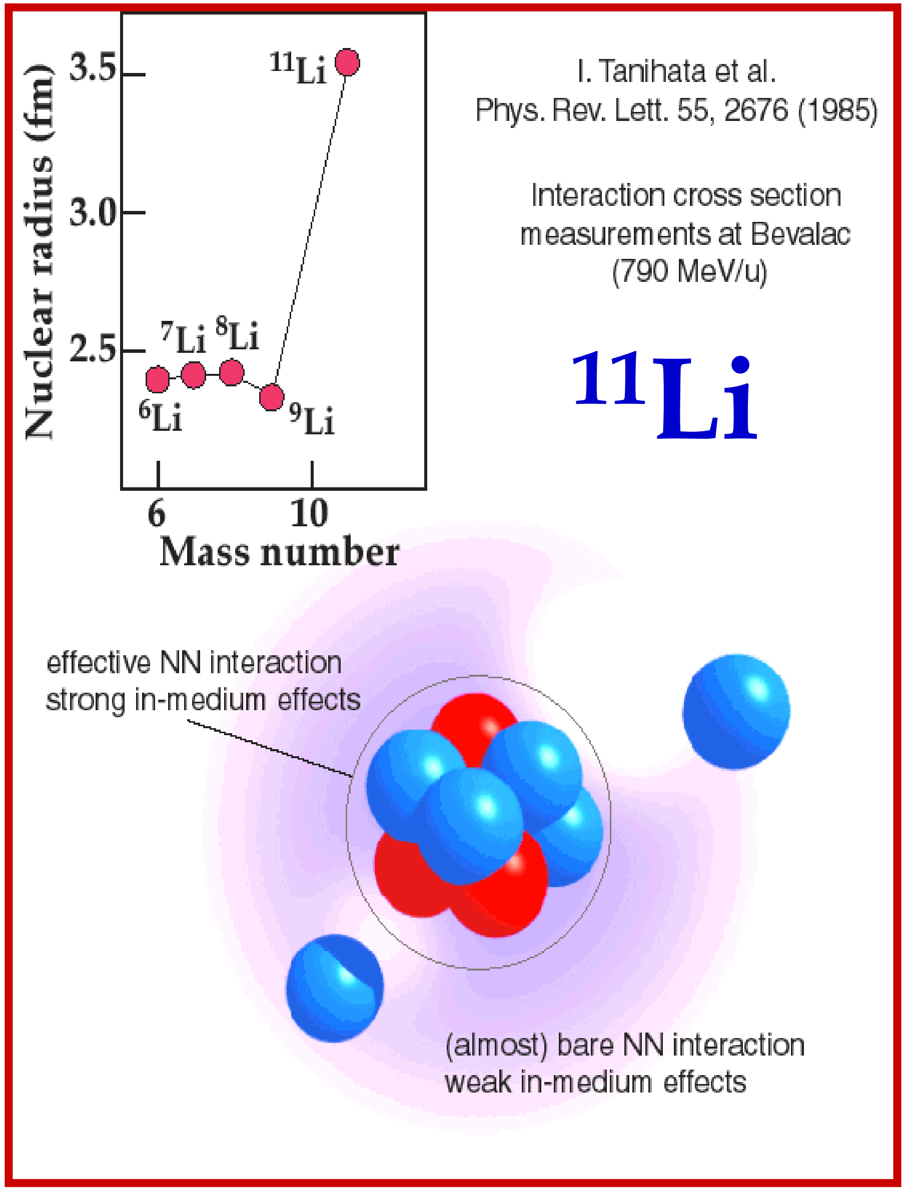
G. A. Lalazissis, P. Ring, PLB 427 (1998) 225

normal deformed bands in the rare earth region



A.V. Afanasjev et al., PRC 62, 054306 (2000)

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

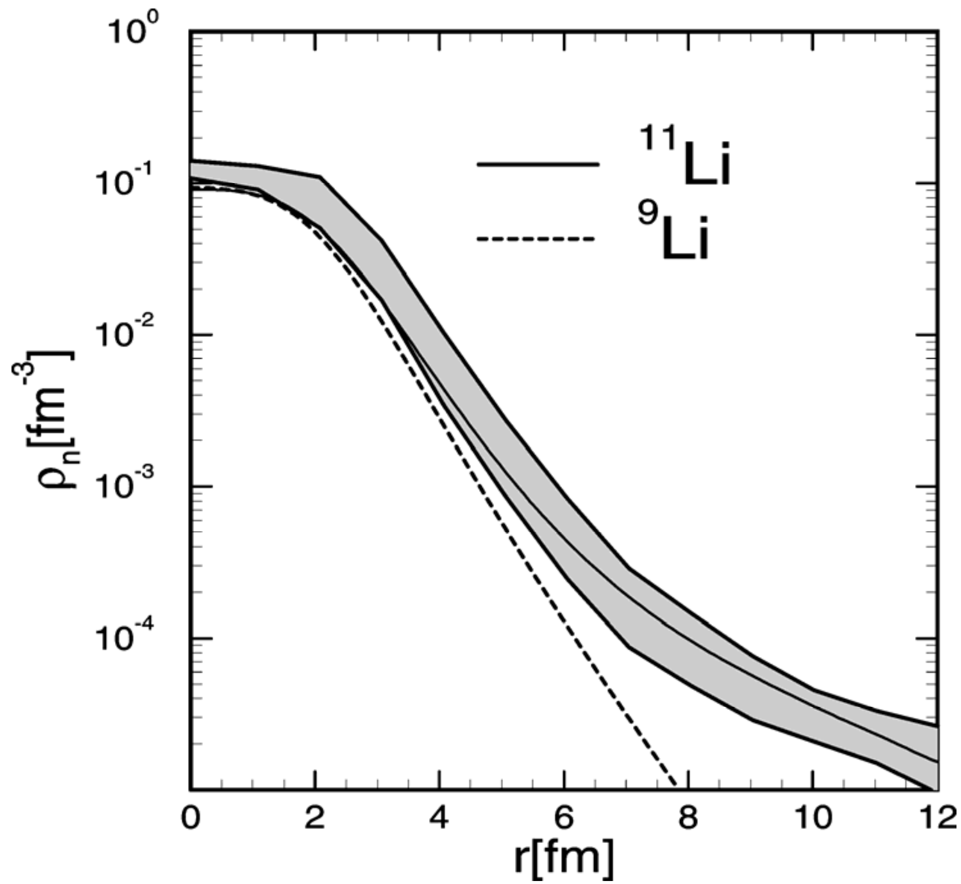
problems:

*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,

parameter set NL2

density dependent δ–pairing

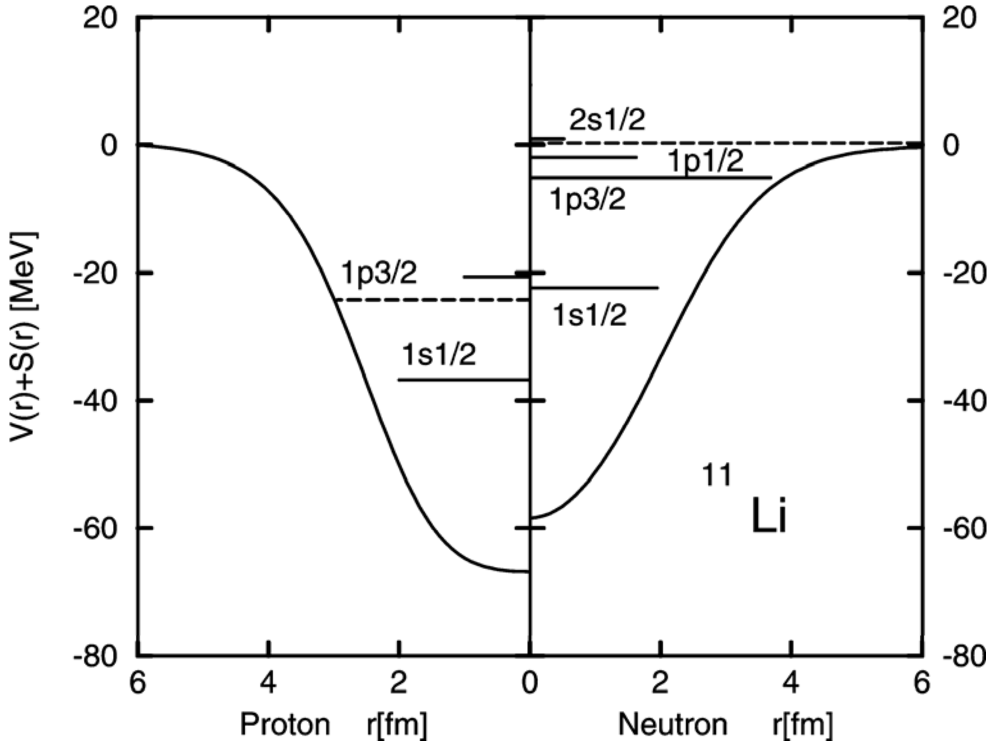
(adjusted to Gogny)

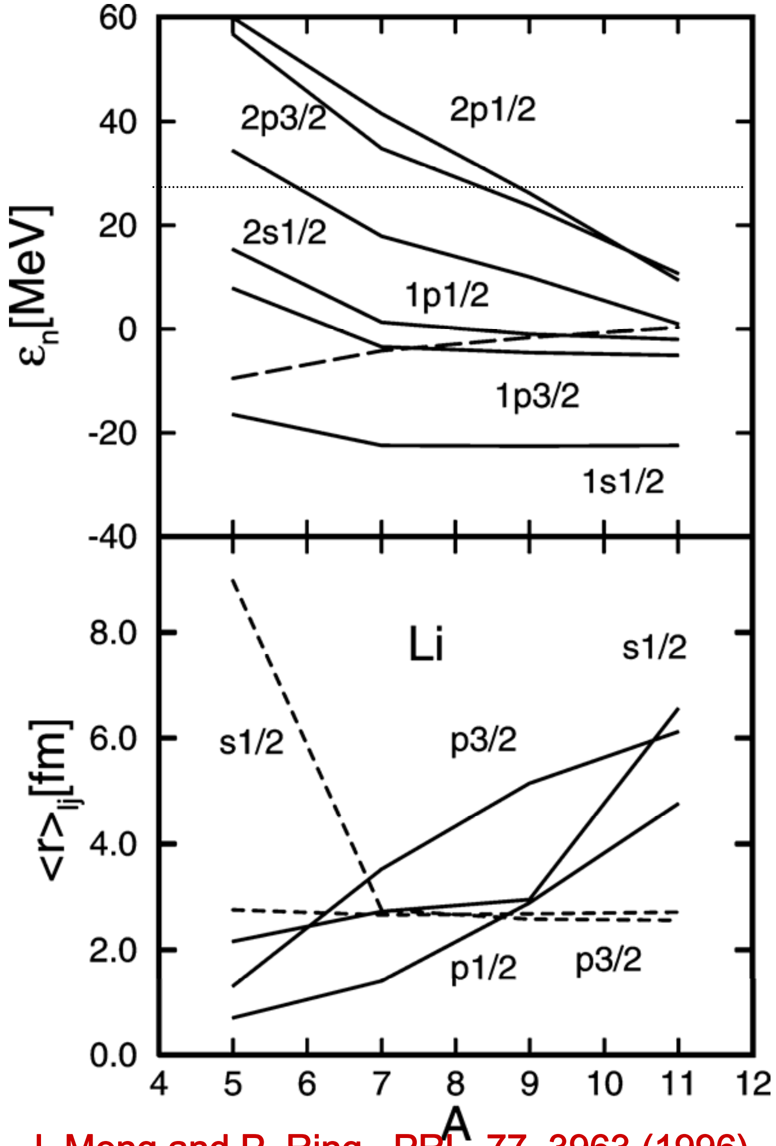
canonical basis in Li-isotopes

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

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

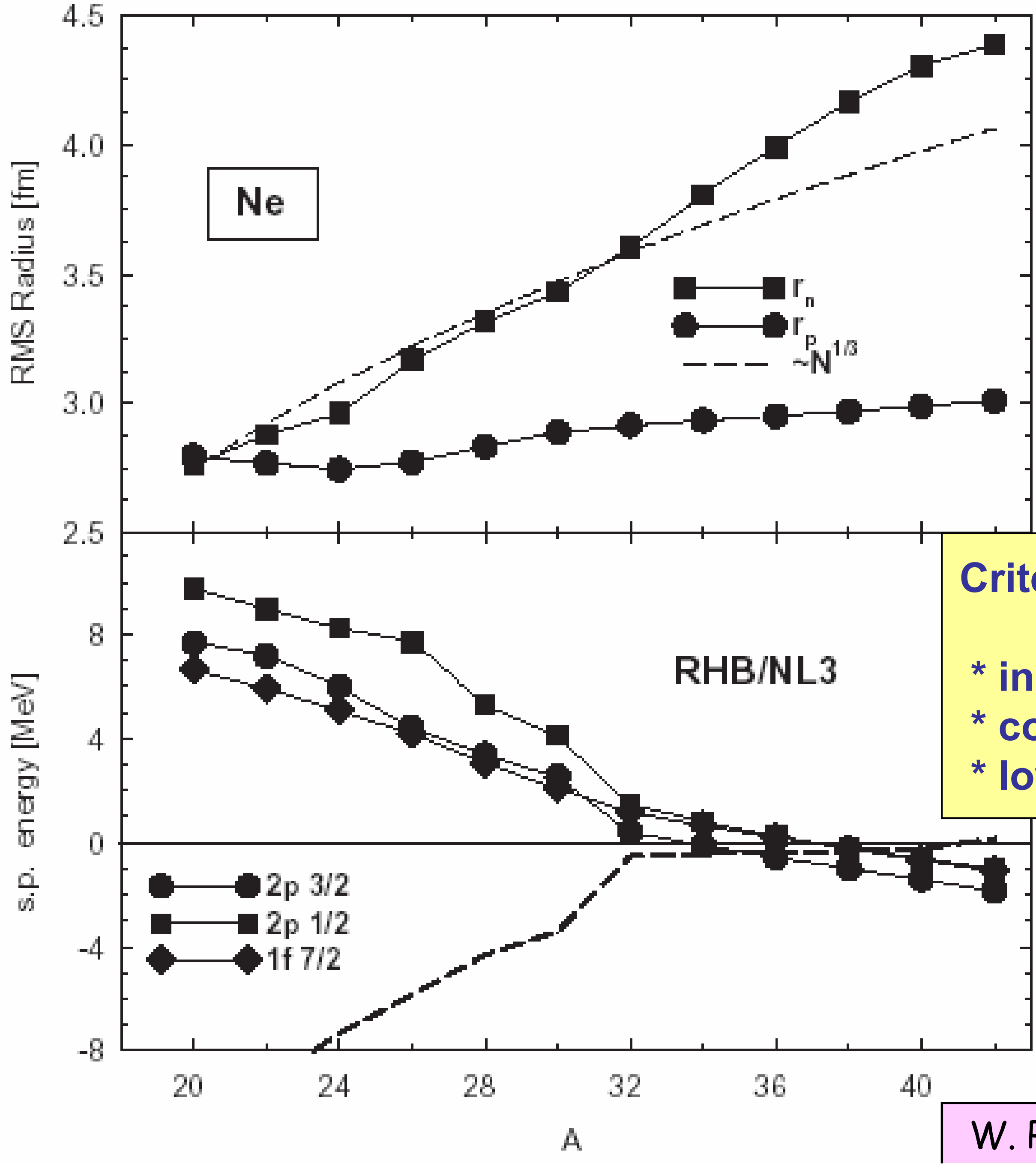
$$\varepsilon_n = \langle n|h|n\rangle, \quad \Delta_n = \langle n|\Delta|n\rangle$$





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

halo's in the Ne region

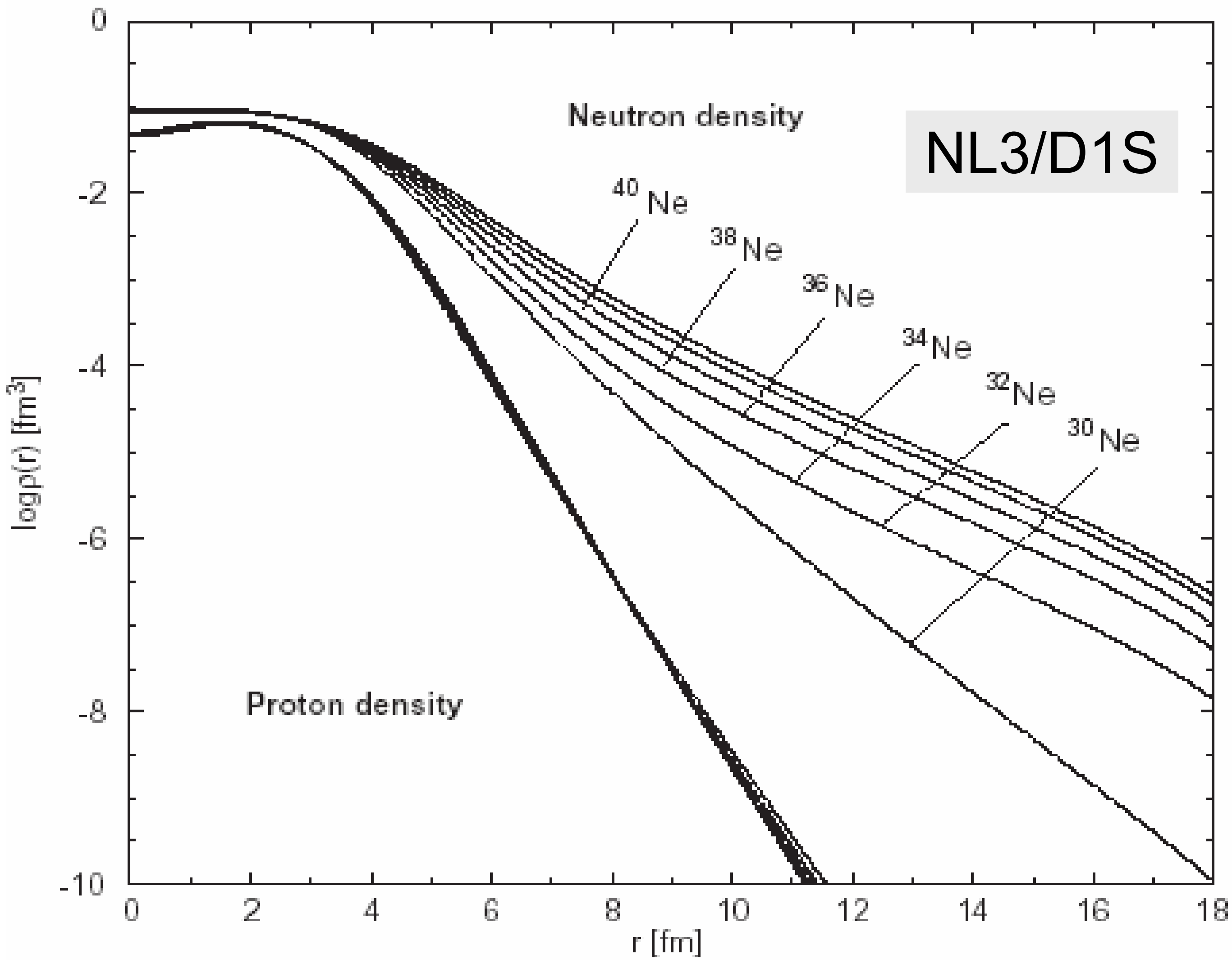


Criteria for halo formation:

* increasing level density
* coupling to the continuum
* low orbital angular momentum

W. Pöschl et al., PRL **79** (1997) 3841

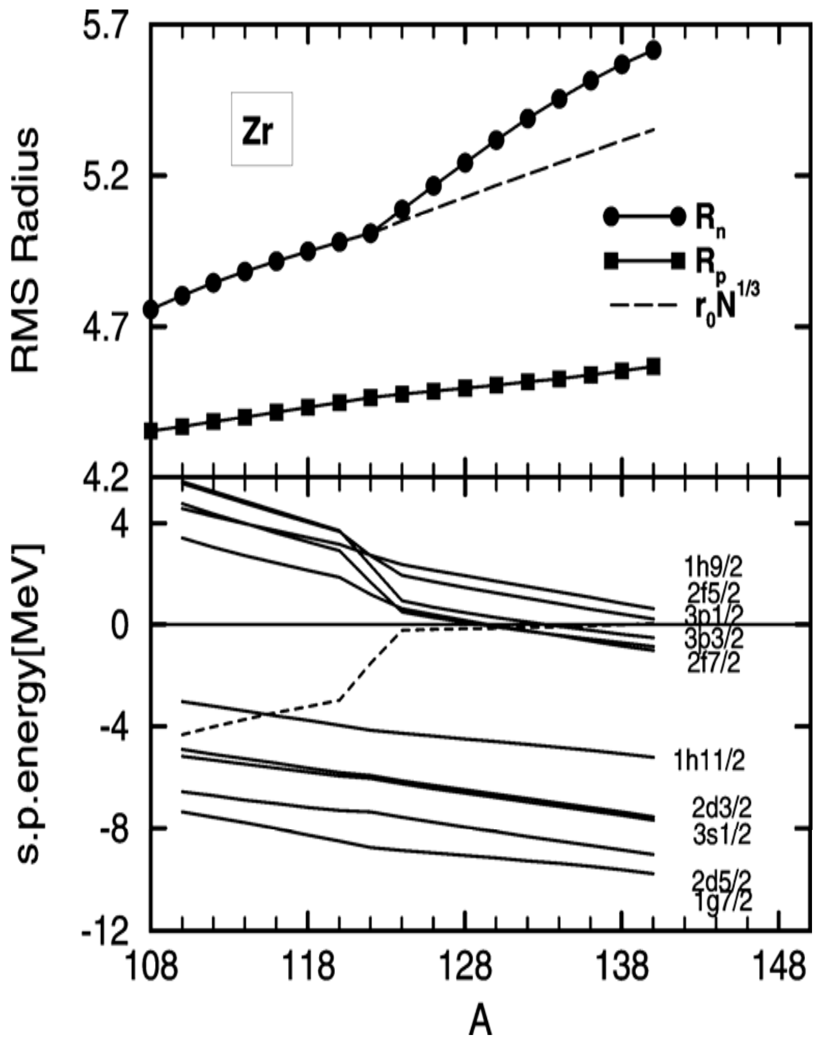
Densities in Ne-isotopes

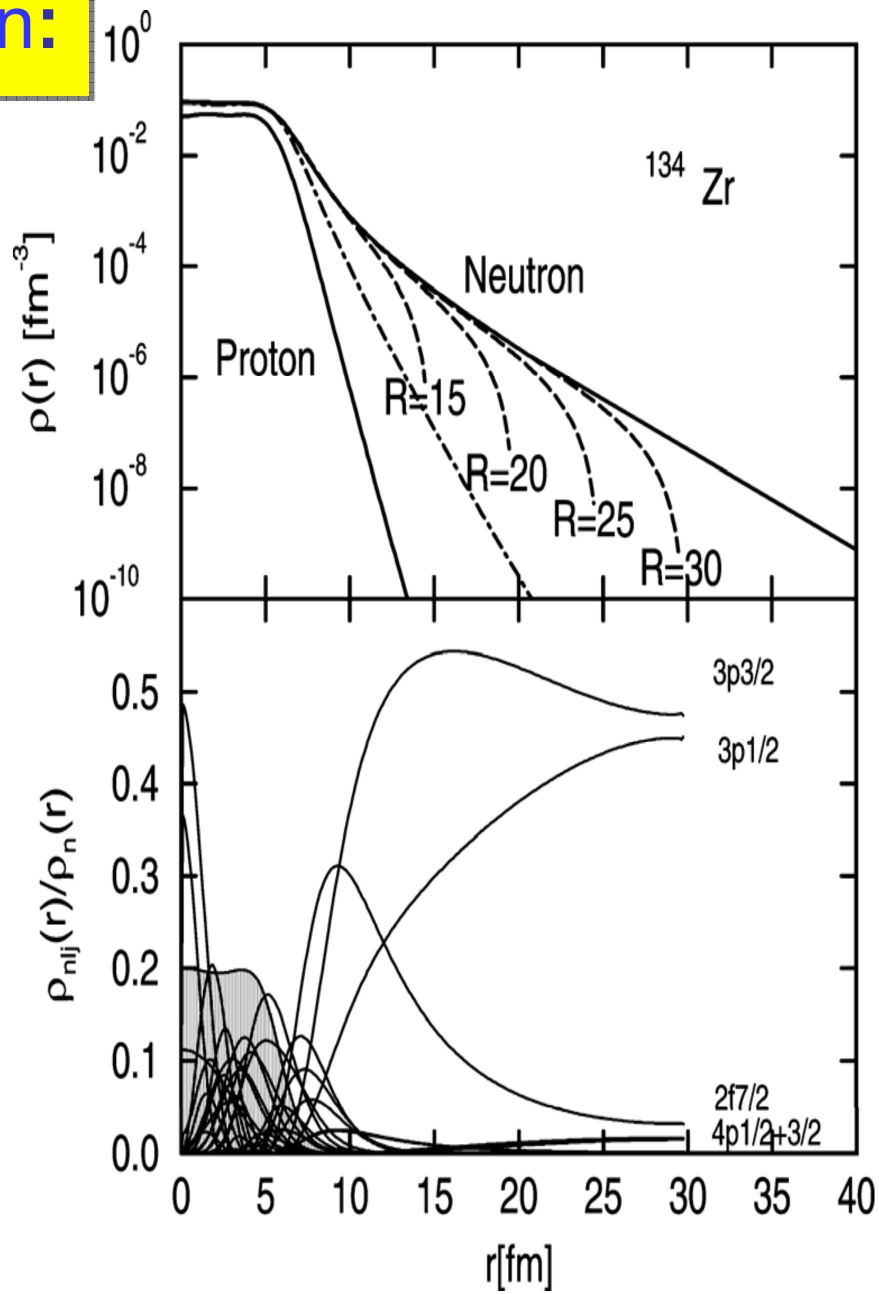


W. Pöschl et al., PRL **79** (1997) 3841

Giant halo in the Zr region:

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





Relativistic QRPA for excited states:

Small amplitude limit:

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

ground-state density

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

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

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

RRPA matrices:

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

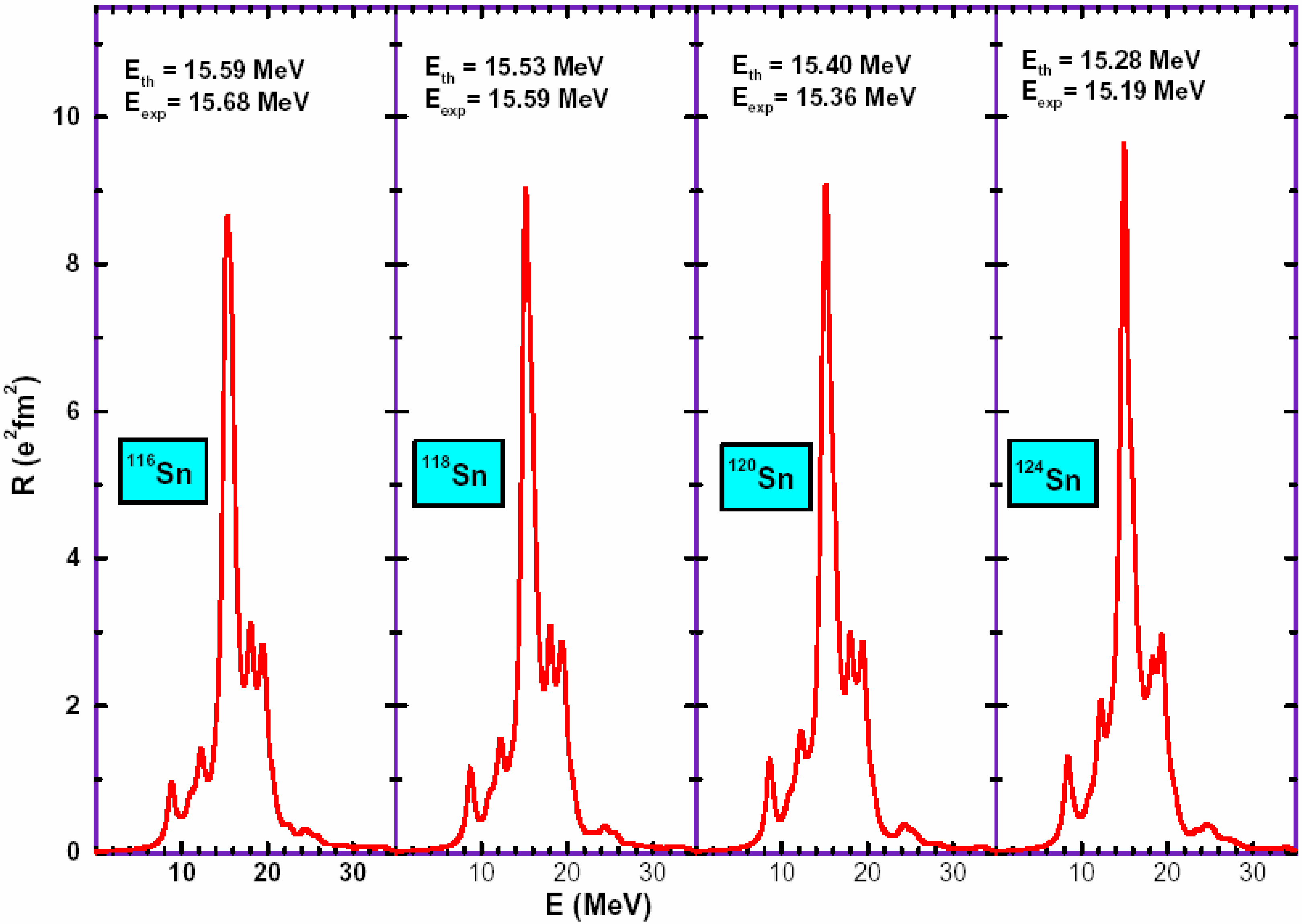
⇒ the same effective interaction determines the Dirac-Hartree single-particle spectrum and the residual interaction

Interaction:

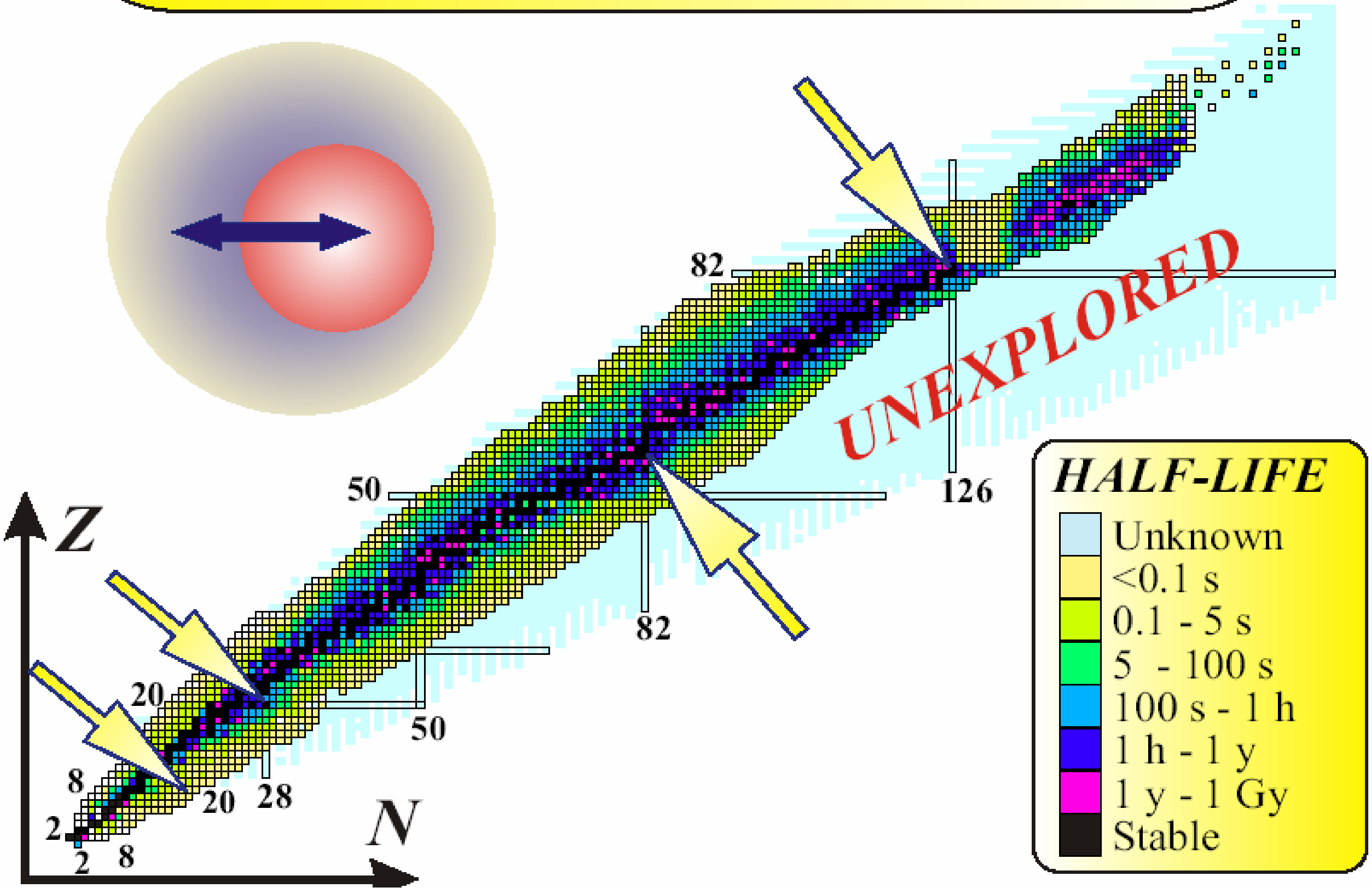
$$\hat{V}^{ph} = \frac{\delta^2 E}{\delta\hat{\rho}\delta\hat{\rho}} \qquad \hat{V}^{pp} = \frac{\delta^2 E}{\delta\hat{\kappa}\delta\hat{\kappa}}$$

IV-GDR in Sn-isotopes

DD-ME2



Experimental indications of the soft dipole mode



TECHNISCHE UNIVERSITÄT MÜNCHEN

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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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 r
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 non
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].

...my 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
...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
...e parameters by applying
...,24]. The high secondary
...eV nucleon allows for the

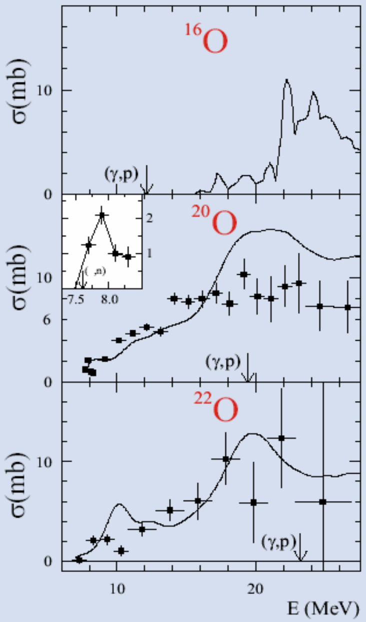
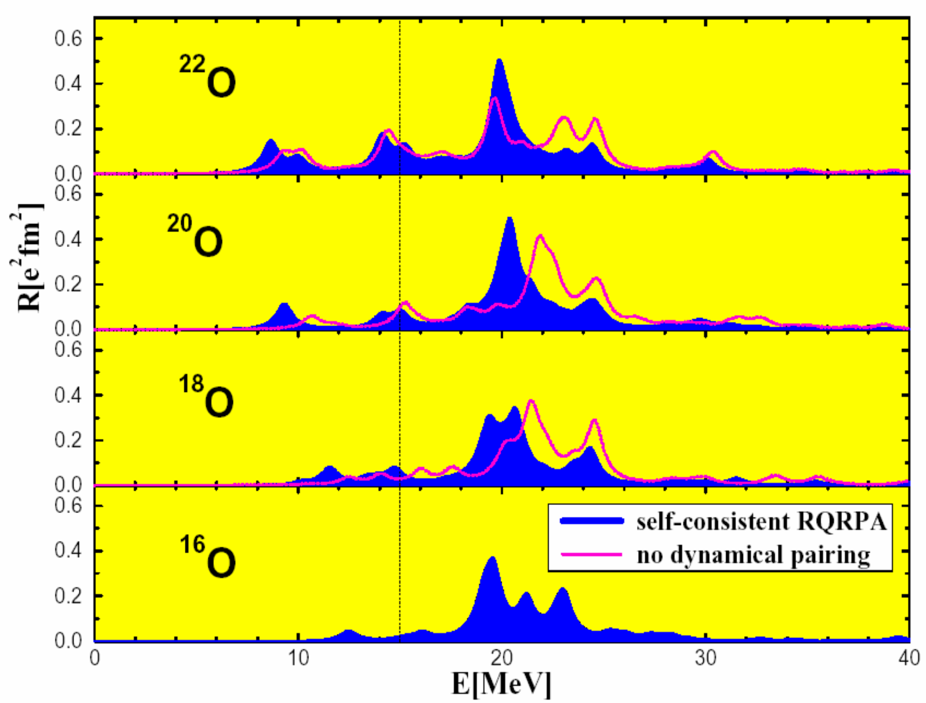


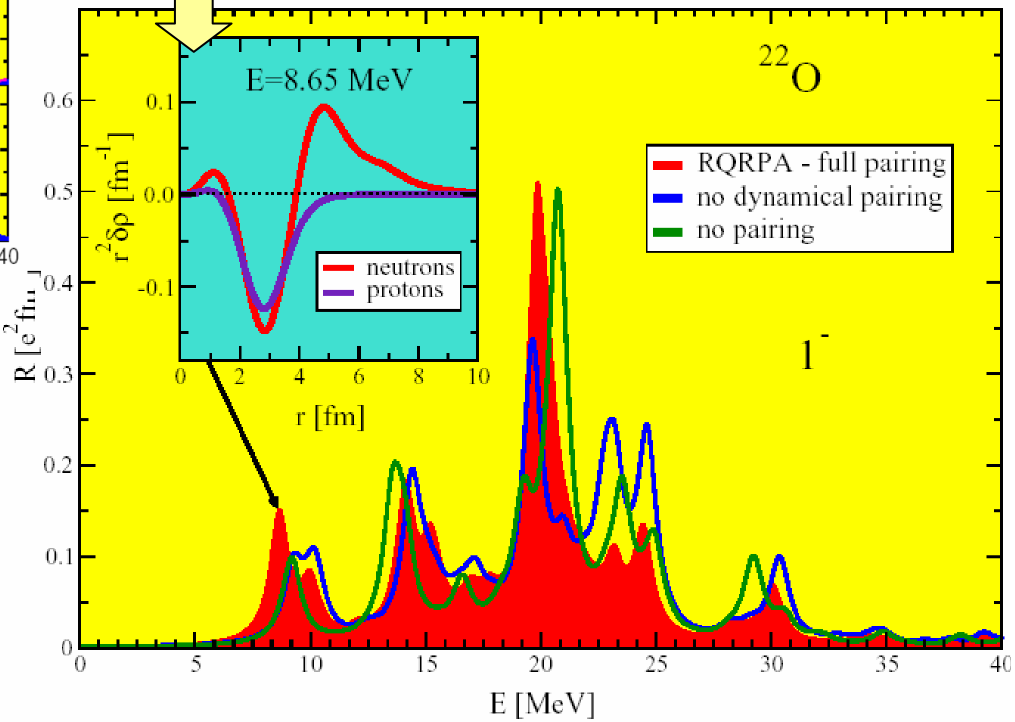
FIG. 2. Photoneutron cross sections for O16 (upper panel) and for the unstable isotopes ^{20,22}O (lower panels) as extracted from the measured electromagnetic excitation cross section (symbols). The inset displays the cross section for near the neutron threshold on an expanded energy scale. The thresholds 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



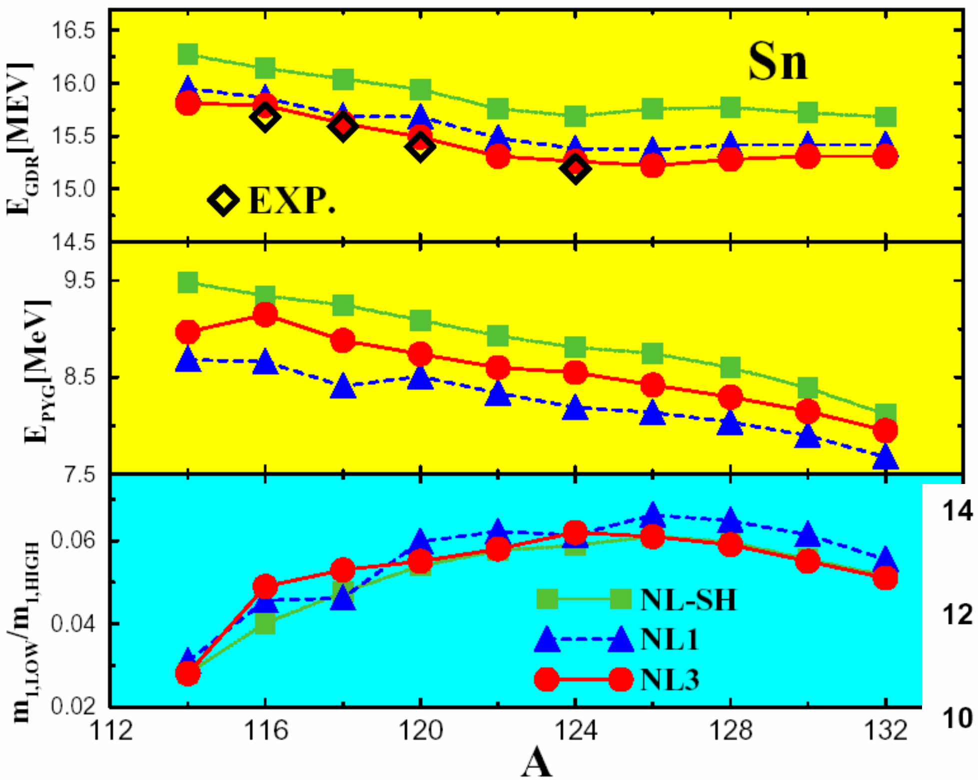
RHB + RQRPA calculations with the NL3 relativistic mean-field plus D1S Gogny pairing interaction.

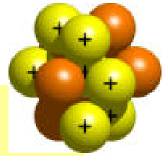
Transition densities



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

Effect of pairing correlations on the dipole strength distribution

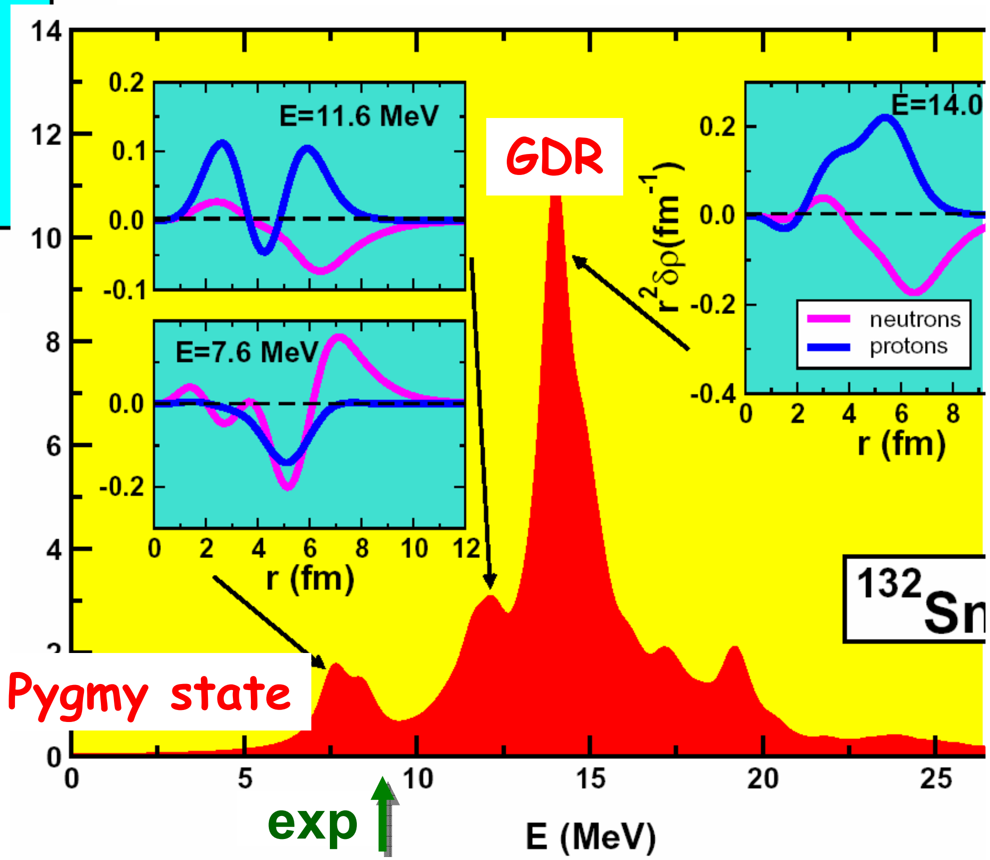




Mass dependence of GDR and Pygmy dipole states in Sn isotopes. Evolution of the low-lying strength.

Isovector dipole strength in ^{132}Sn.

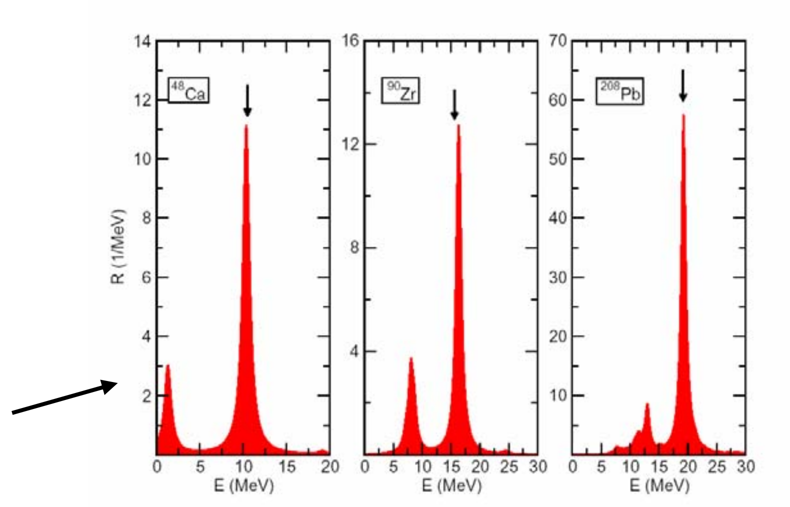
Nucl. Phys. A692, 496 (2001)



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%	$2d_{3/2} \rightarrow 3p_{3/2}$

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)

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

$$0.55m \leq m_D \leq 0.60m$$

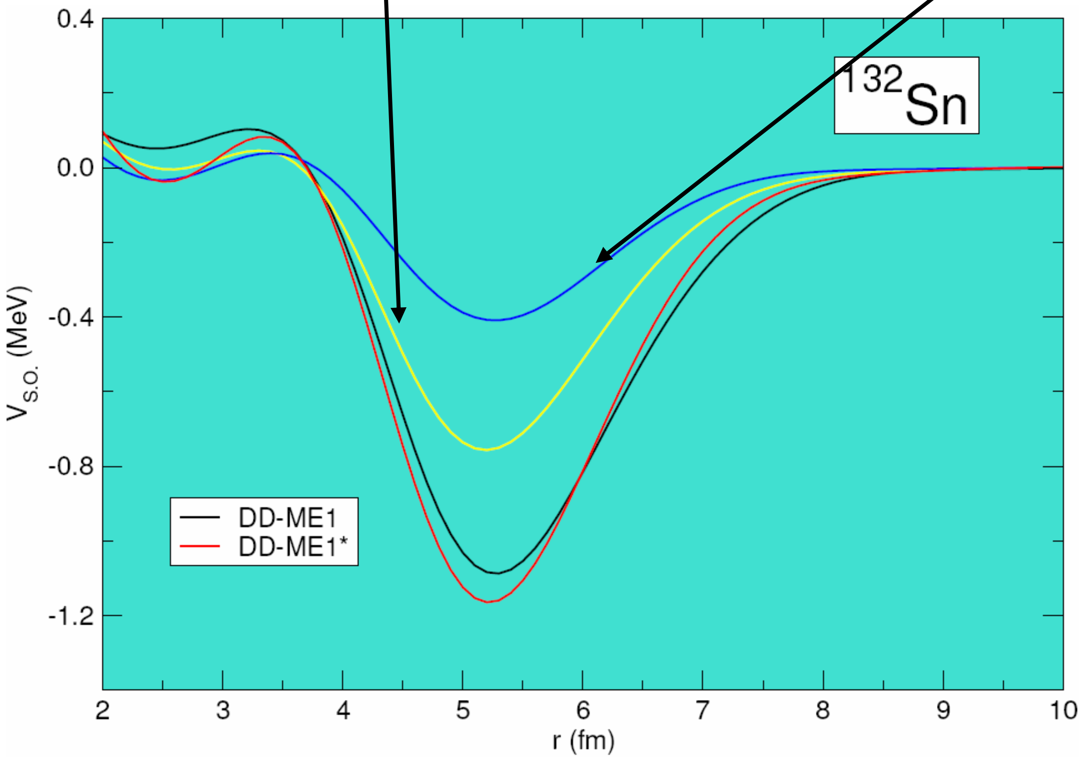
$$0.64m \leq m^* \leq 0.67m$$

small density of states -> overestimated β-decay lifetimes

tensor omega-nucleon coupling enhances the spin-orbit interaction

scalar and vector self-energies can be reduced

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



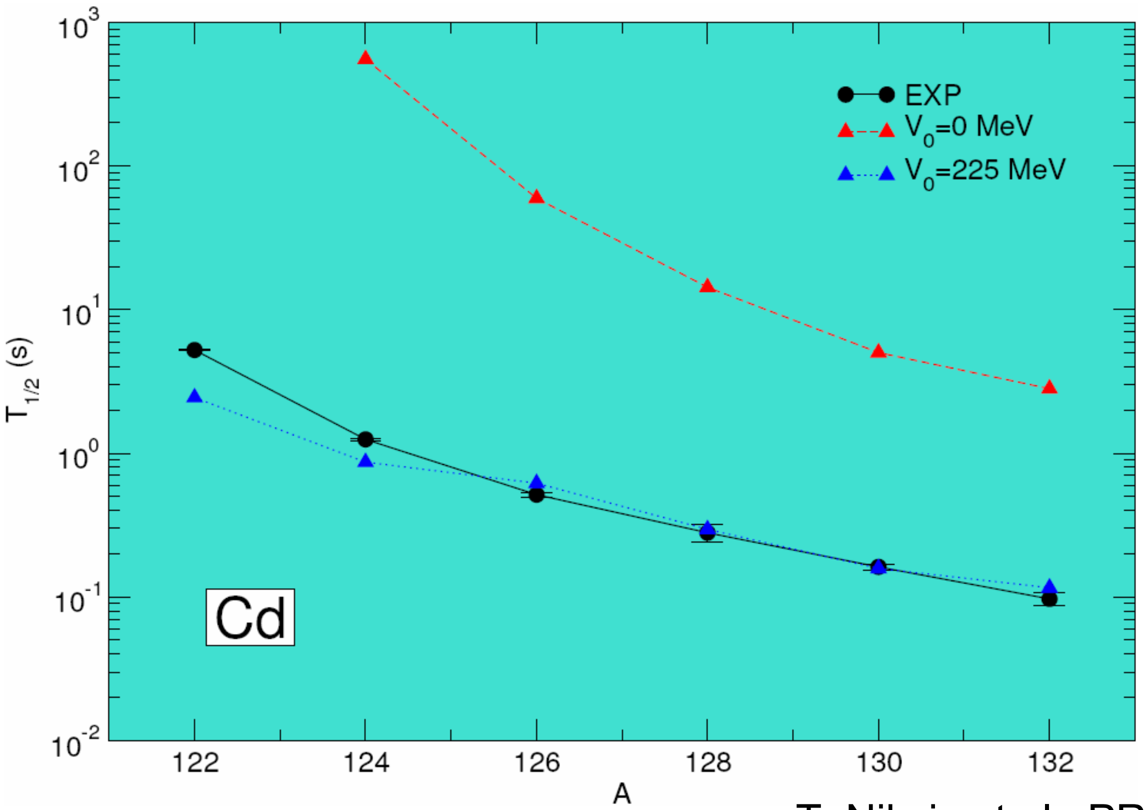
	DD-ME1	DD-ME1*
m_D/m	0.58	0.67
m^*/m	0.66	0.76

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

N≈82 region:

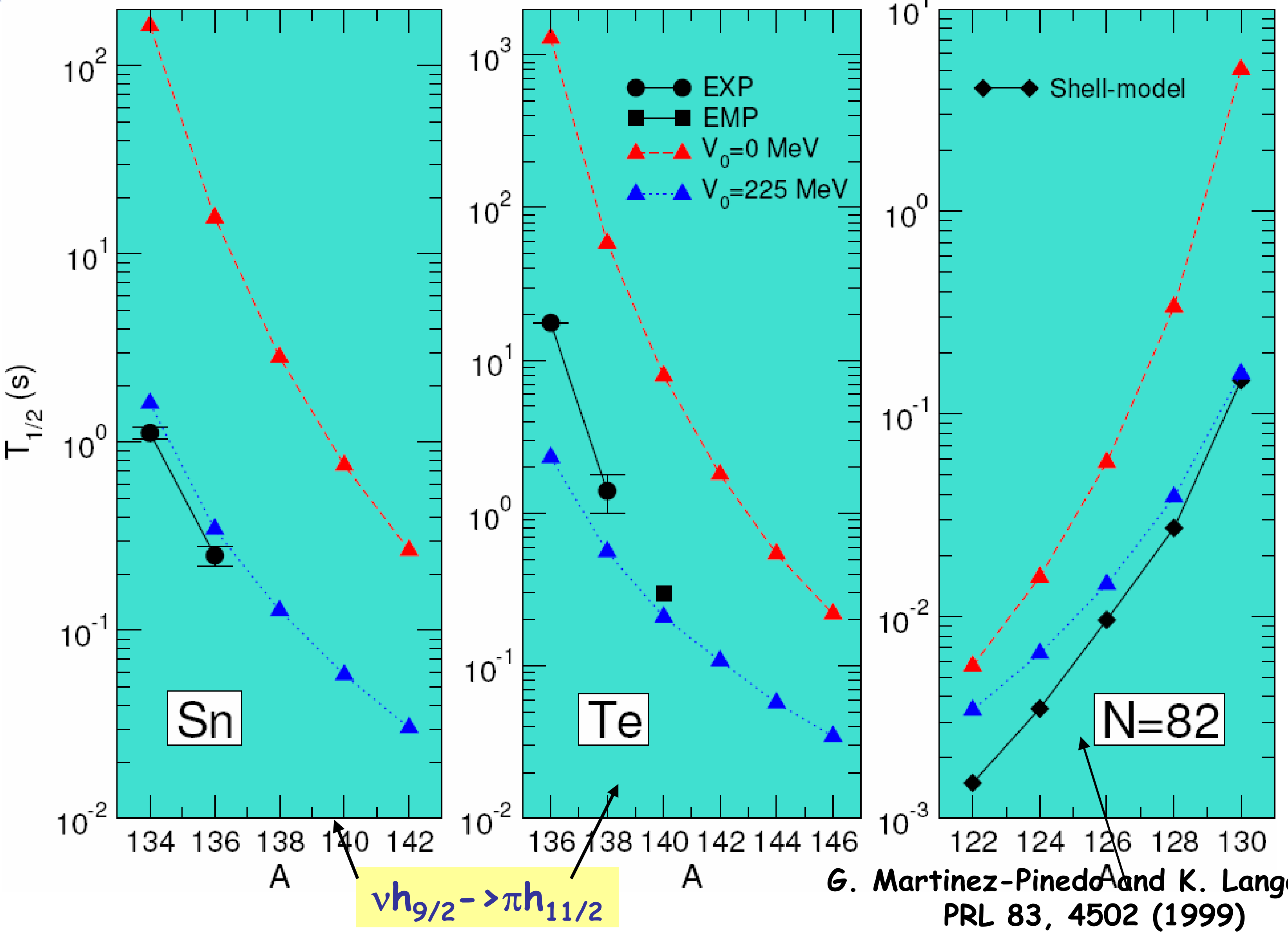
Cadmium isotopes: π1g9/2 level is partially empty

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



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

Correlations beyond mean field

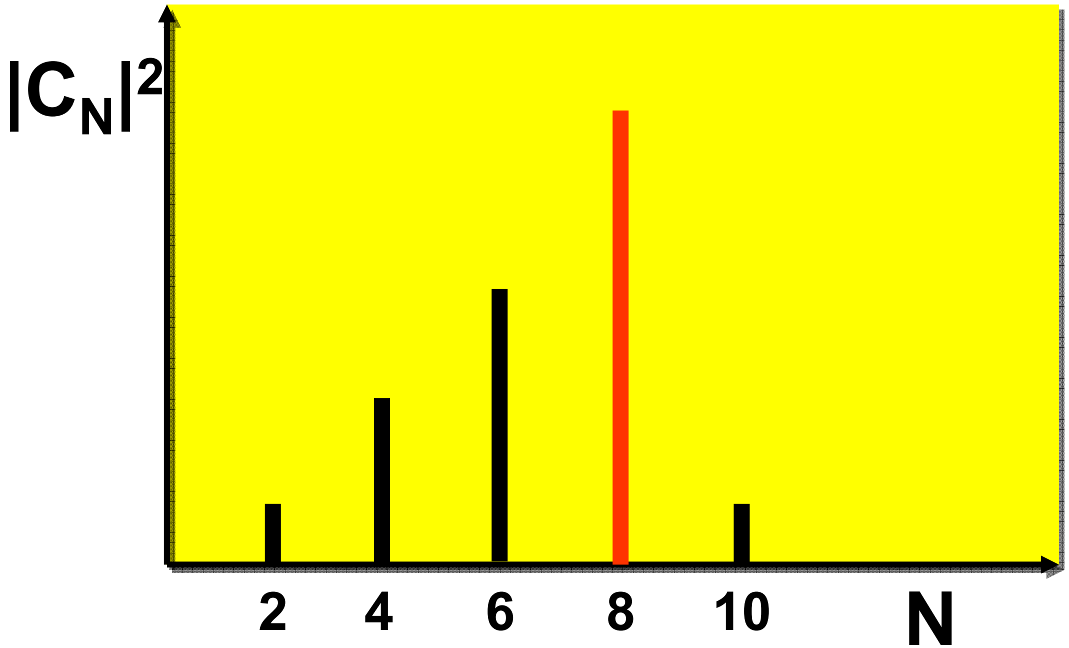
- Conservation of symmetries by projection before variation
- Motion with large amplitude by Generator Coordinates
- Coupling to collective vibrations
  - shifts of single particle energies
  - decay width of giant resonances

Halo wave function in the canonical basis:

$$|\Phi\rangle = \sum_N c_N |N\rangle$$

$$|\Phi\rangle = c_2|^5Li\rangle + c_4|^7Li\rangle + c_6|^9Li\rangle + c_8|^{11}Li\rangle + \ldots$$

$$\hat{P}^N|\Phi\rangle = c_8|^{11}Li\rangle$$



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):

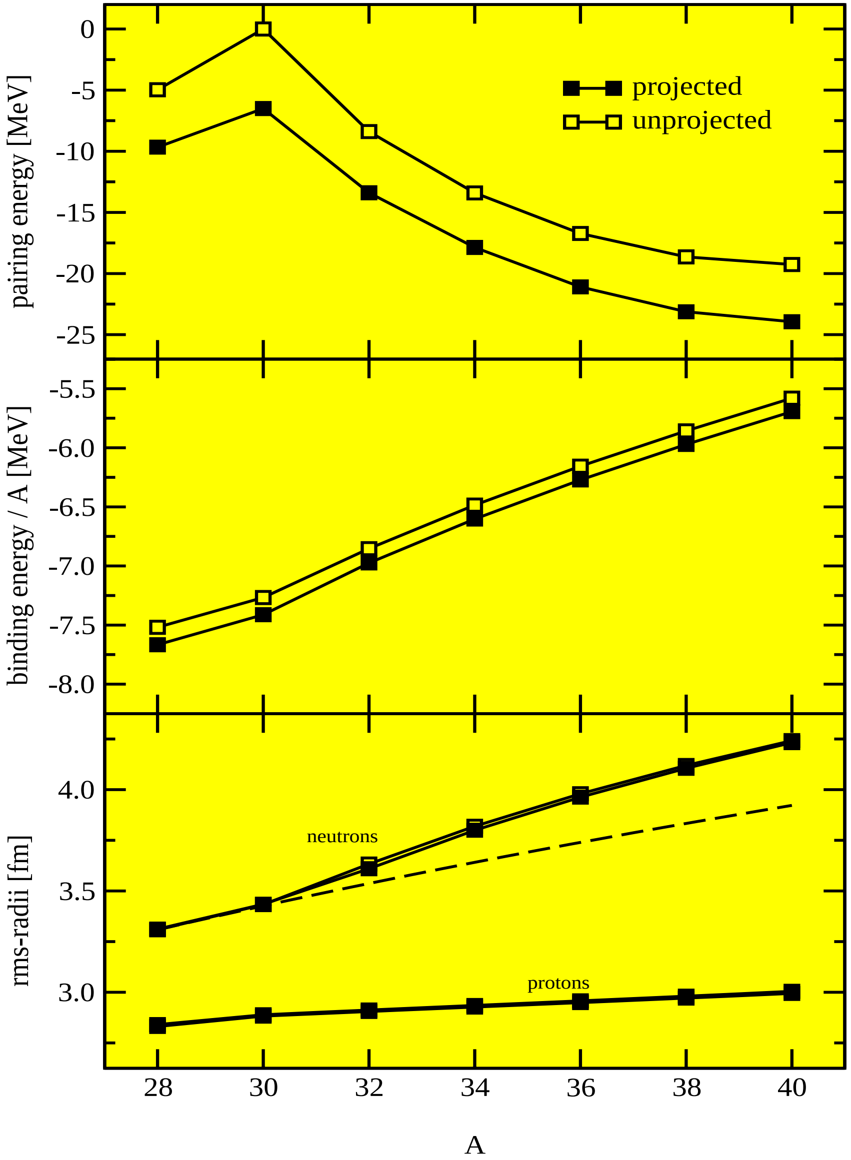
$$\begin{pmatrix} \hat{h}^N & \hat{\Delta}^N \\ -\Delta^{N*} & -\hat{h}^{N*} \end{pmatrix} \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} = \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} E_k$$

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

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

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

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

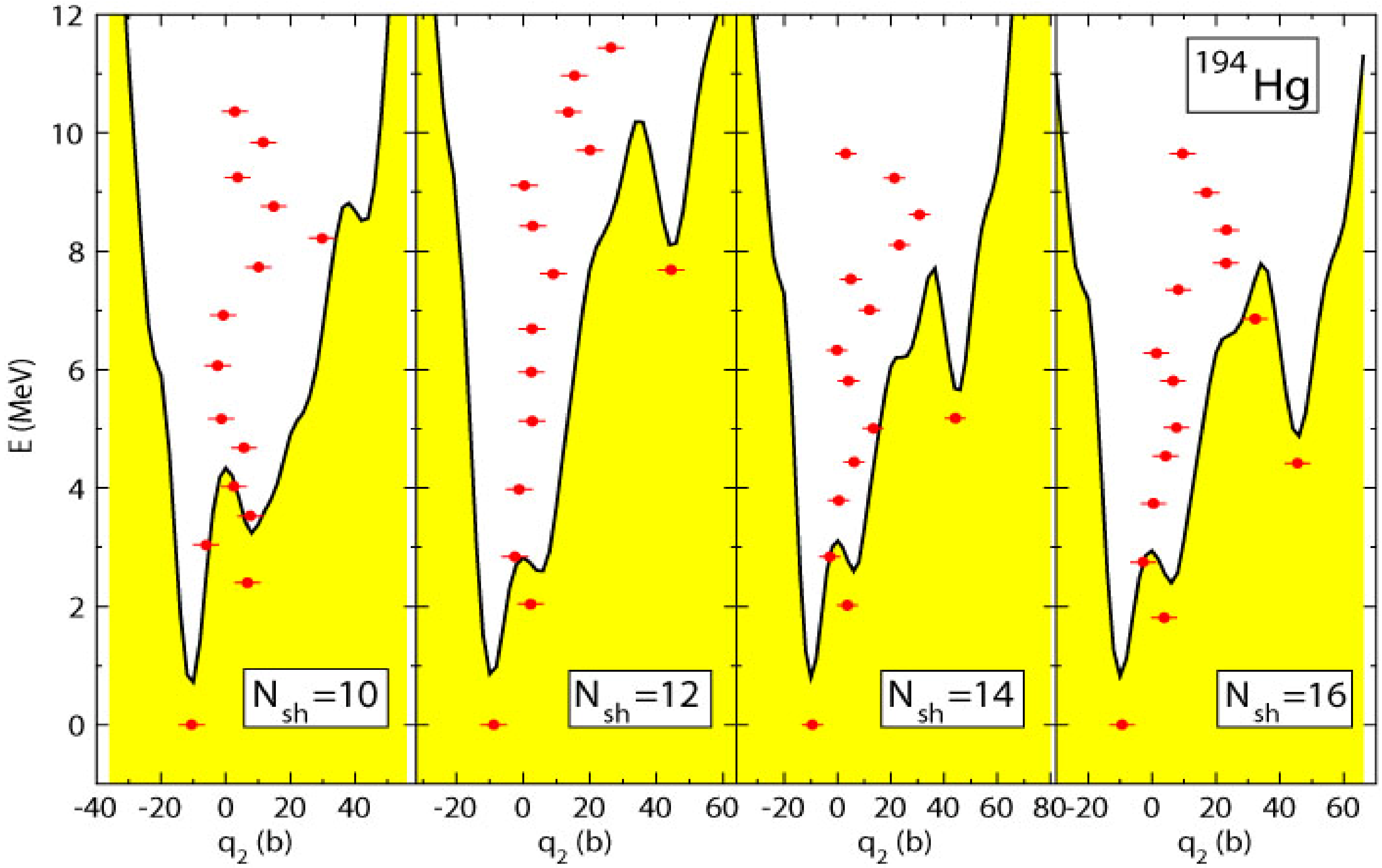
Hill-Wheeler equation:

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

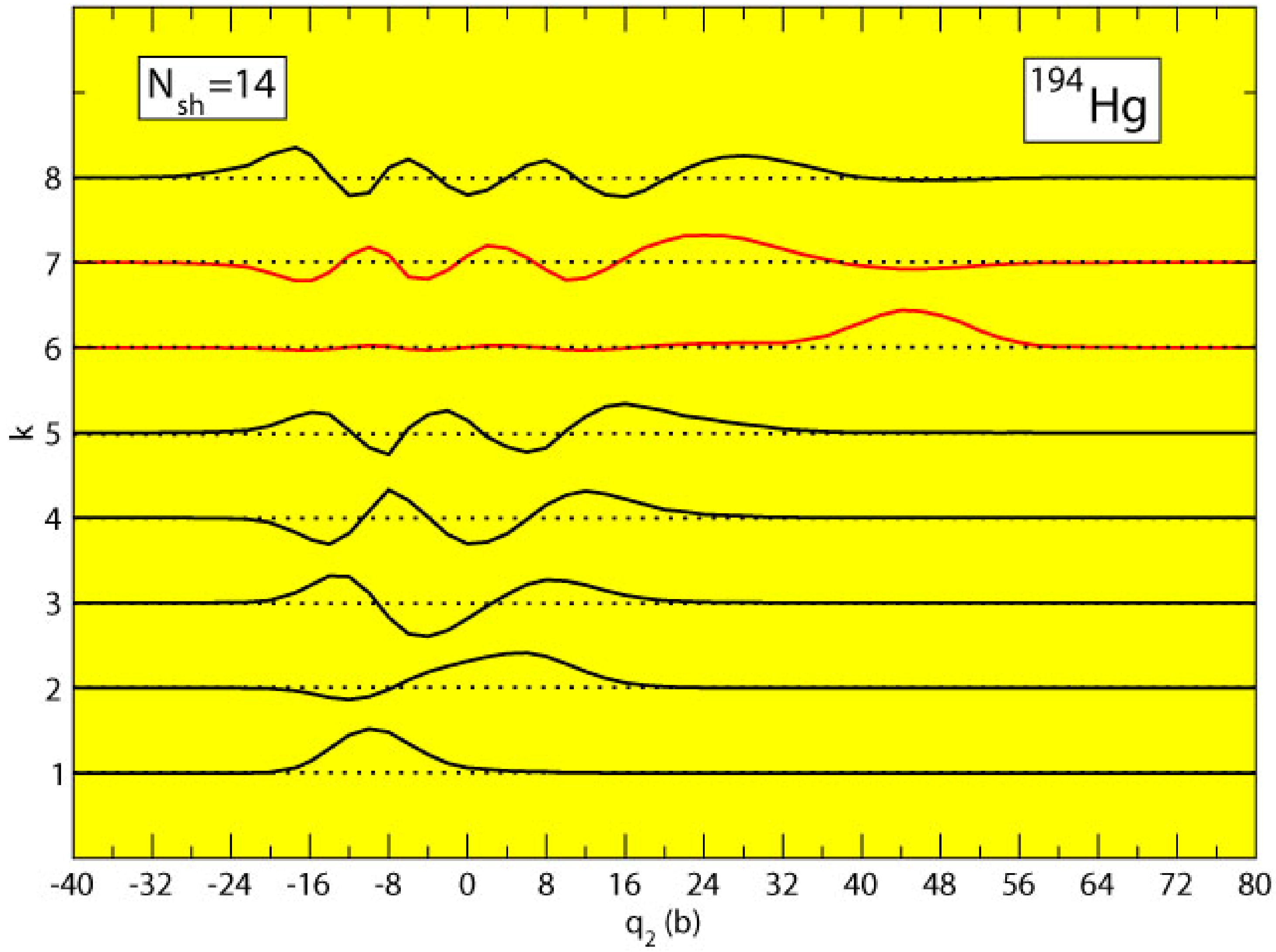
with projection:

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

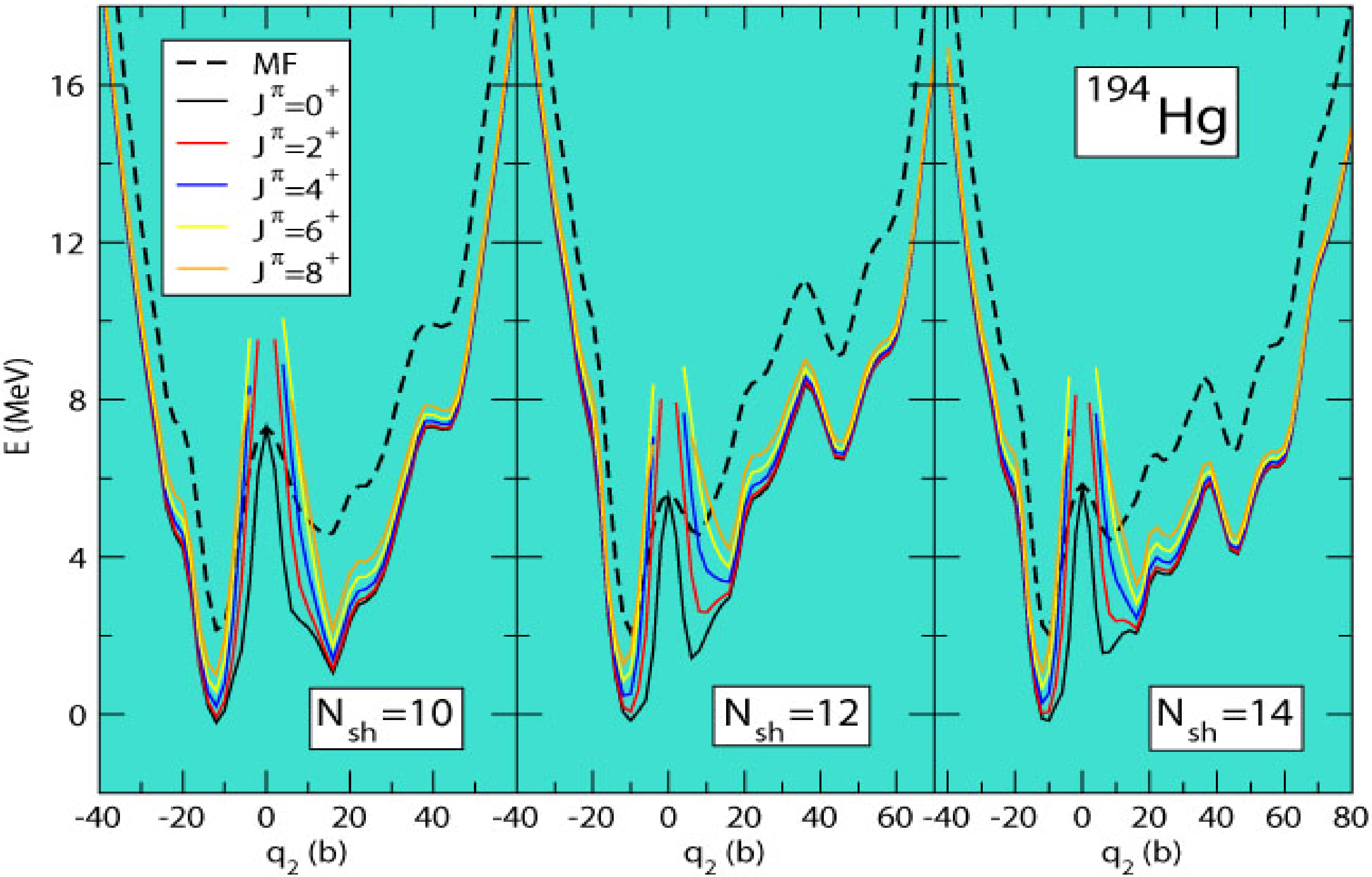
GCM without projection:



GCM-wave functions of the lowest states



Ang. momentum projected energy surfaces:

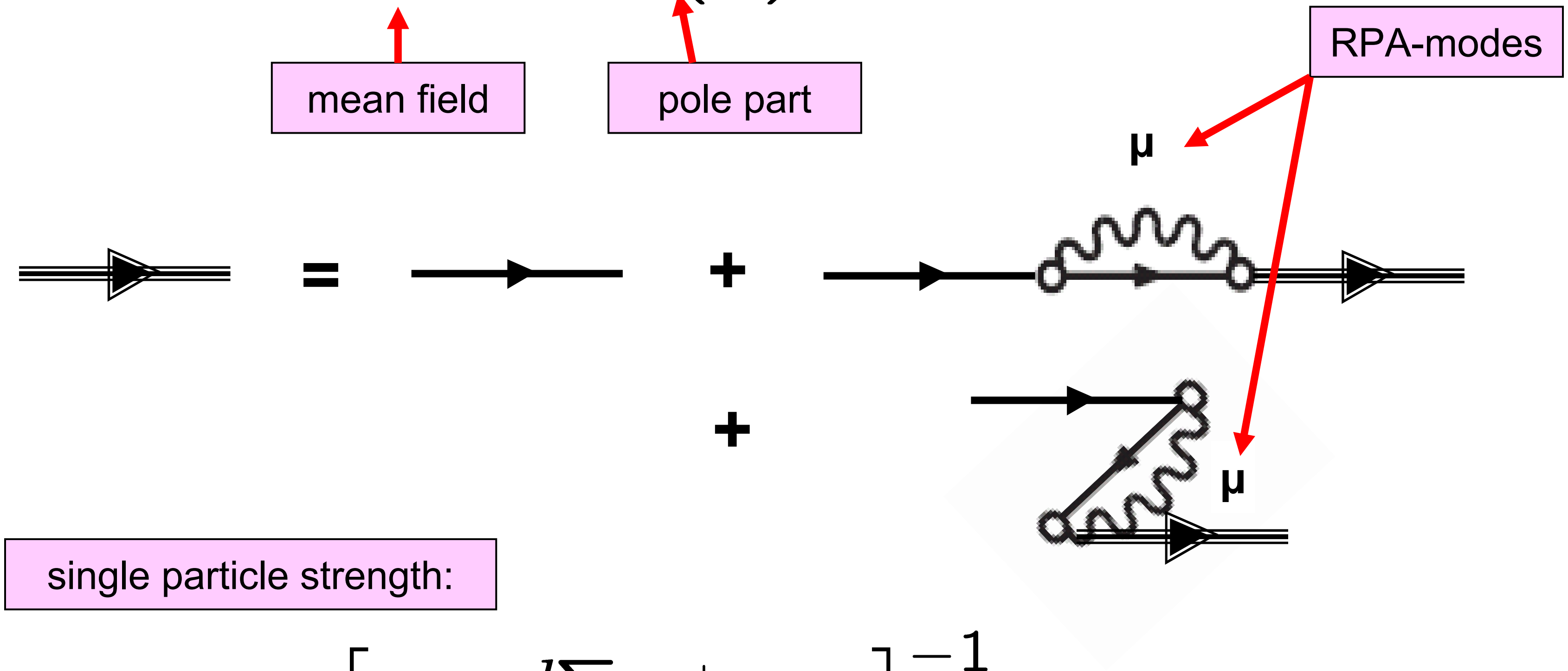


Vibrational Couplings: energy dependent self-energy:

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

mean field

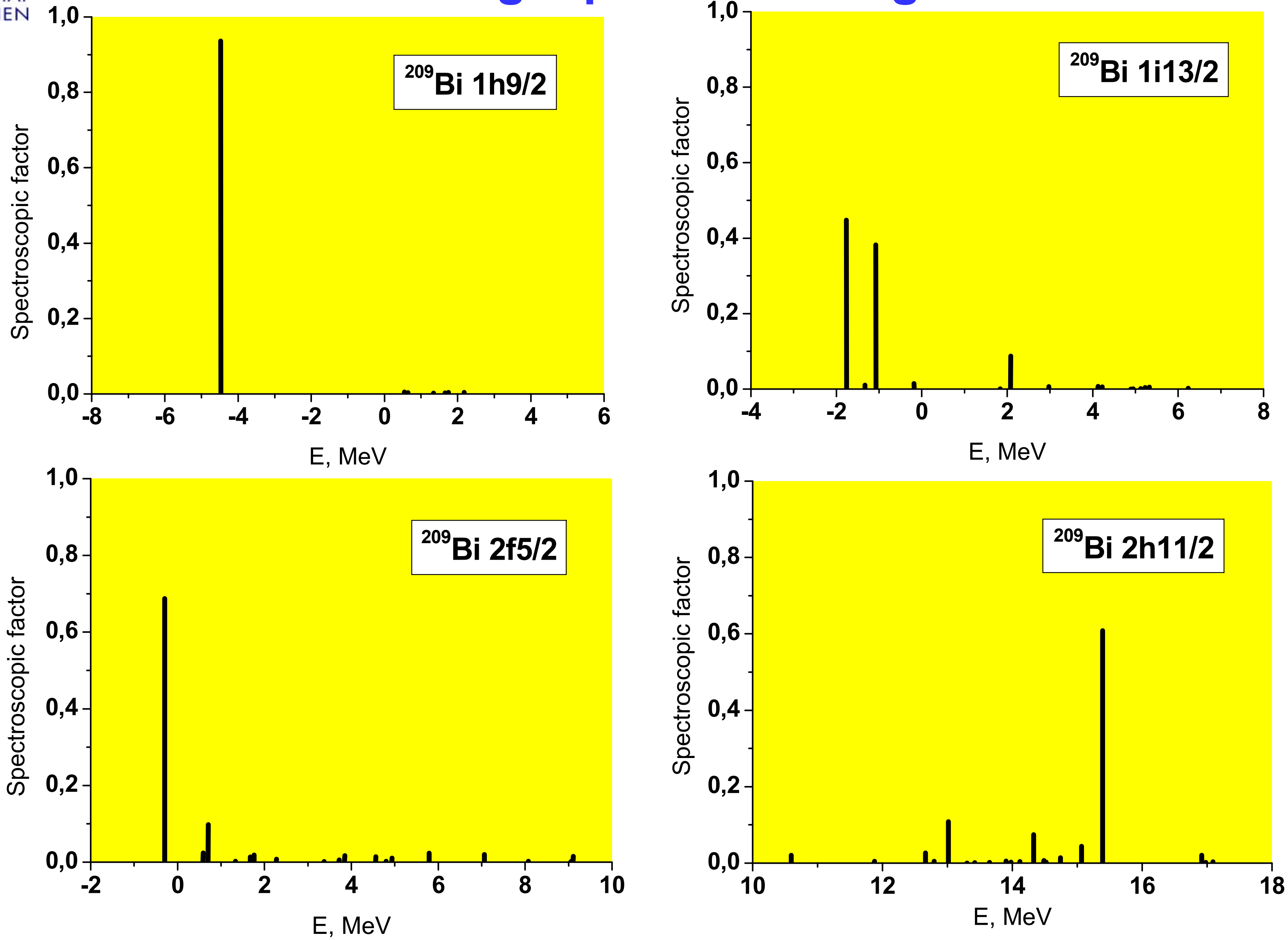
pole part

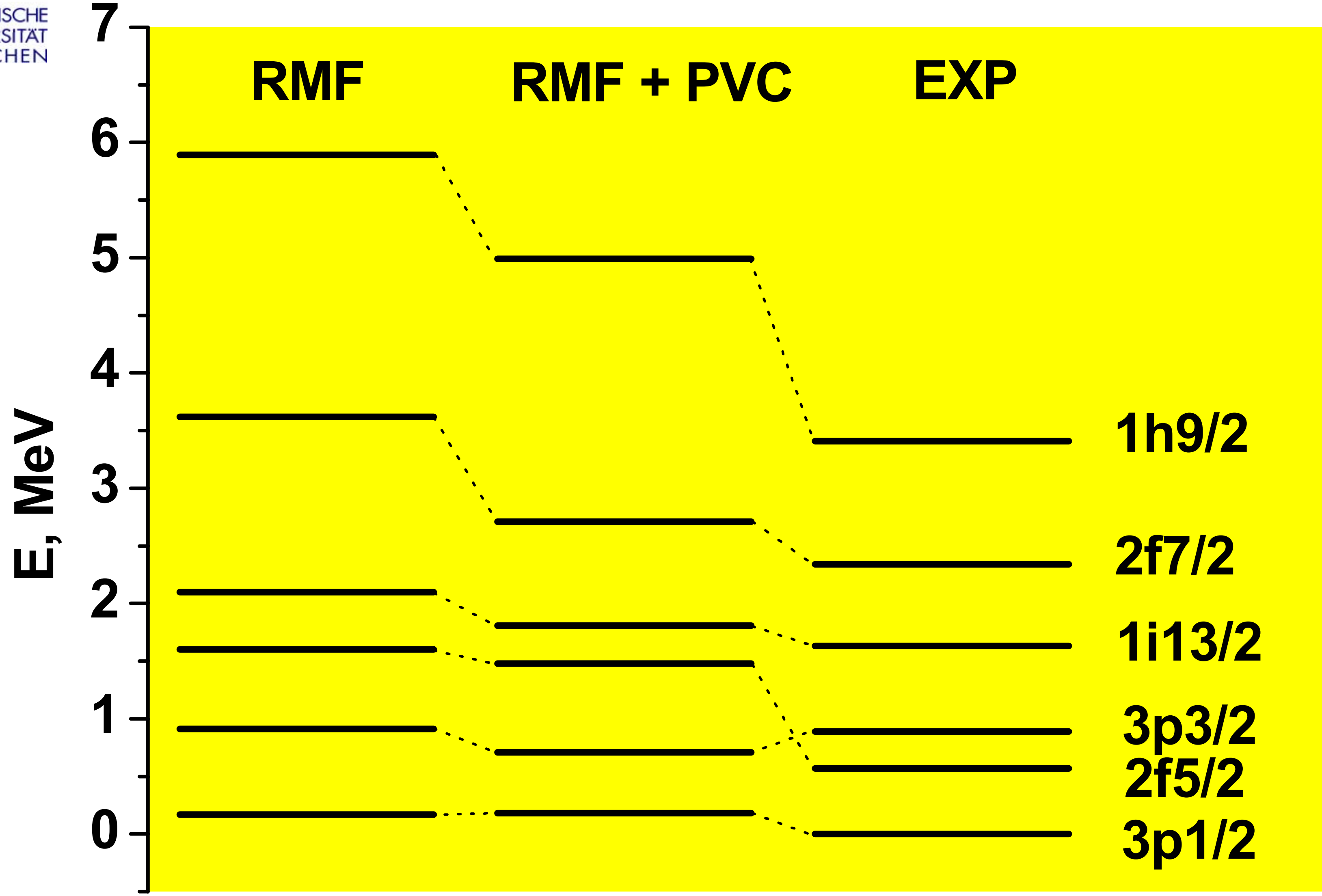


single particle strength:

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

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

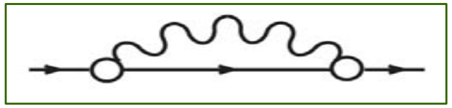




Level scheme for ^{207}Pb

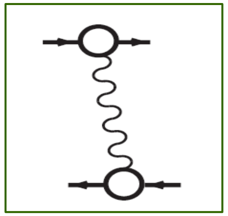
Contributions of complex cofigurations

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

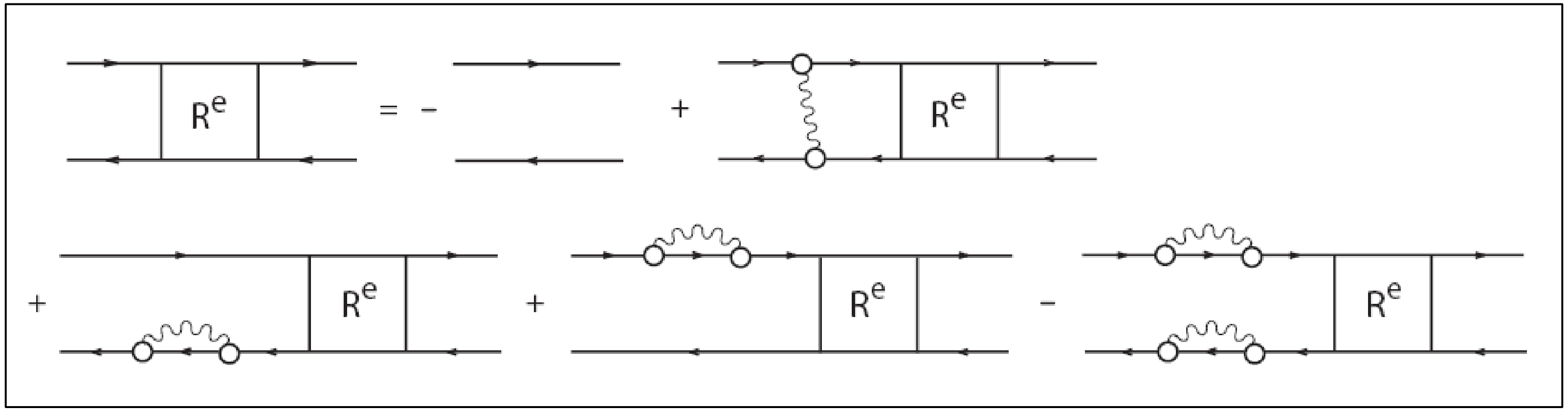


Self energy

g – phonon amplitudes (QRPA)



ph interaction amplitude

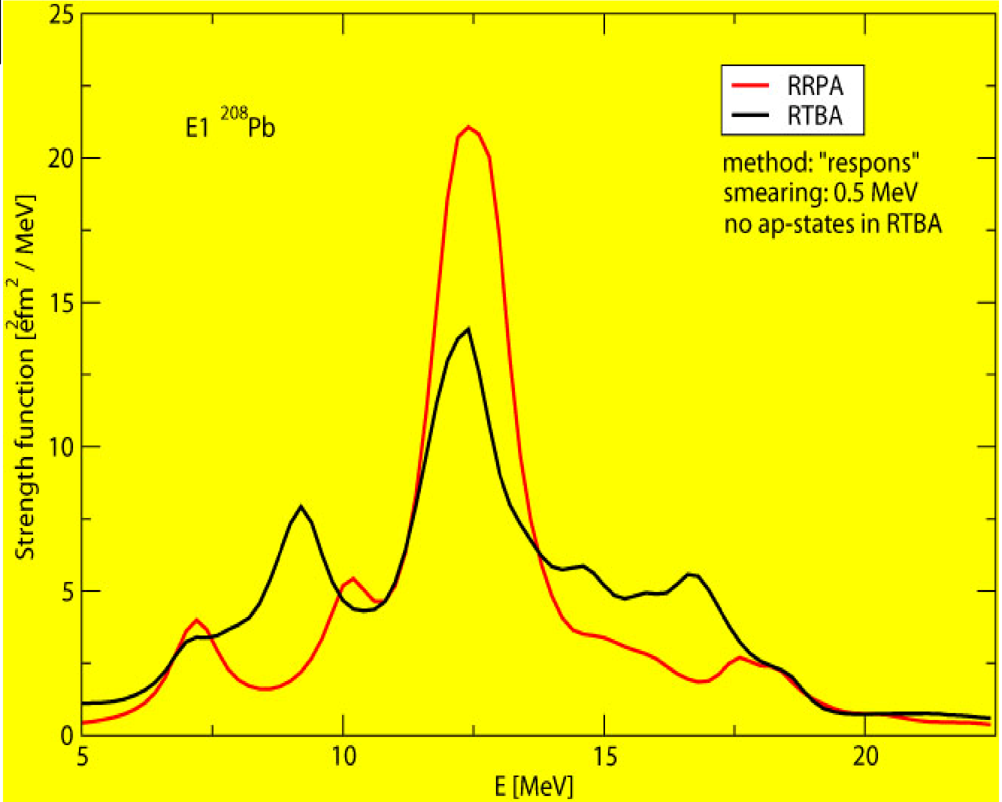


Decay-width of the Giant Resonances

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

E1 photoabsorption cross section

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



Conclusions

There is a relatistic formulation of pairing

Pairing is a totally non-relativistic phenomenon
excellent separation of scales!

RHB-model uses Gogny force in the pairing channel

Applications in finite nuclei
- rotational spectra (cranked RHB-theory)
- halo phenomena (continuum 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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