Nuclear Structure Theory I

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Outline

- Major problems and challenges in nuclear structure theory
- Basic approaches to nuclear many-body problem
- “First order” approach: Nuclear Shell Model and Density Functional Theory

- Fermionic propagators in the strongly-correlated medium: spectroscopic factors and response functions

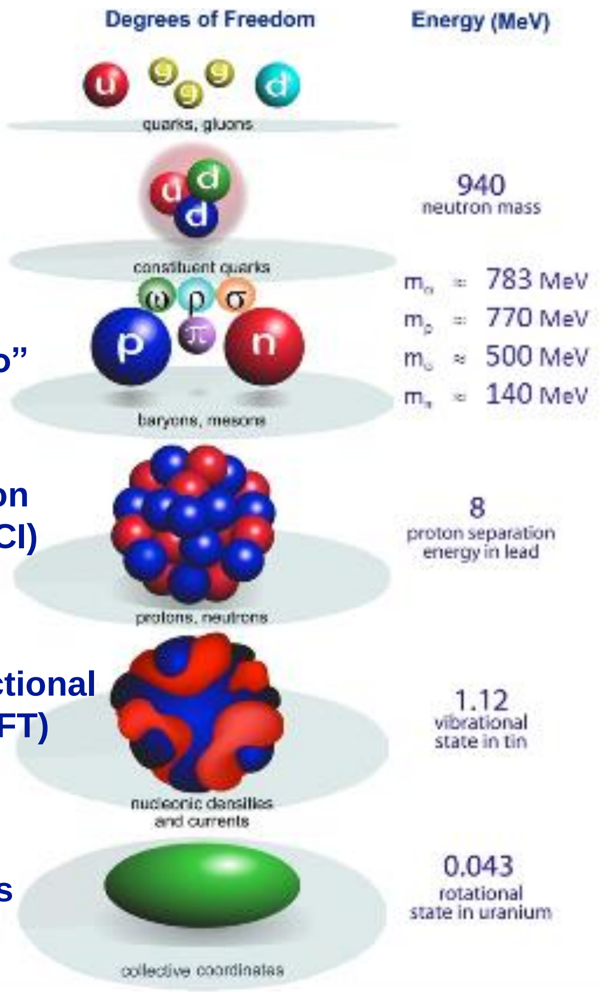
- Exotic nuclear phenomena:

  - Changing/disappearance of magic numbers
  - Physics of neutron skin
  - Isospin-transfer excitations and beta decay
  - The onset of pion condensation
  - Continuum and finite temperature effects

- Literature

Major problems in nuclear structure theory

- Nuclear scales: Hierarchy problem
- No connection between the scales in the traditional NS models



QCD

"ab initio"

Configuration Interaction (CI)

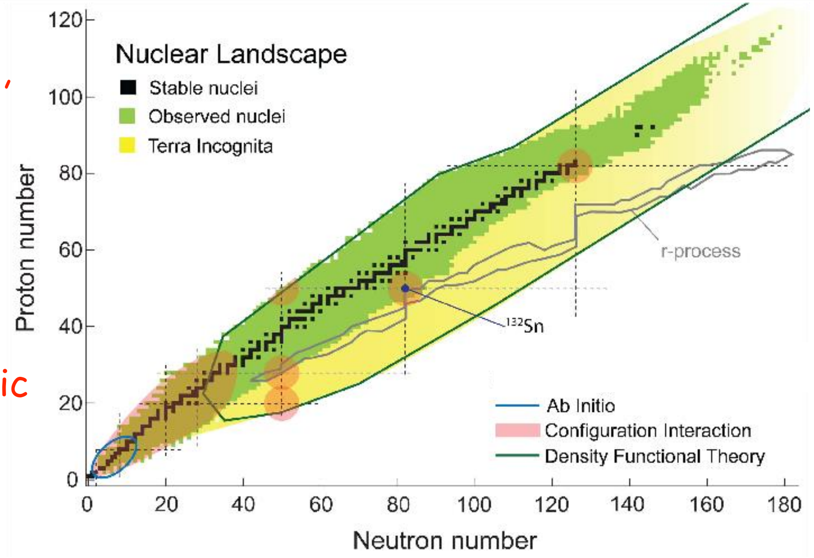
Density Functional Theory (DFT)

Collective coordinates (CC)

Expanding,

but still limited domains

of microscopic theories



Tremendous error propagation in the astrophysical modeling with phenomenological nuclear structure input:

M. Mumpower et al., Progr. Part. Nucl. Phys. 86, 86 (2016).

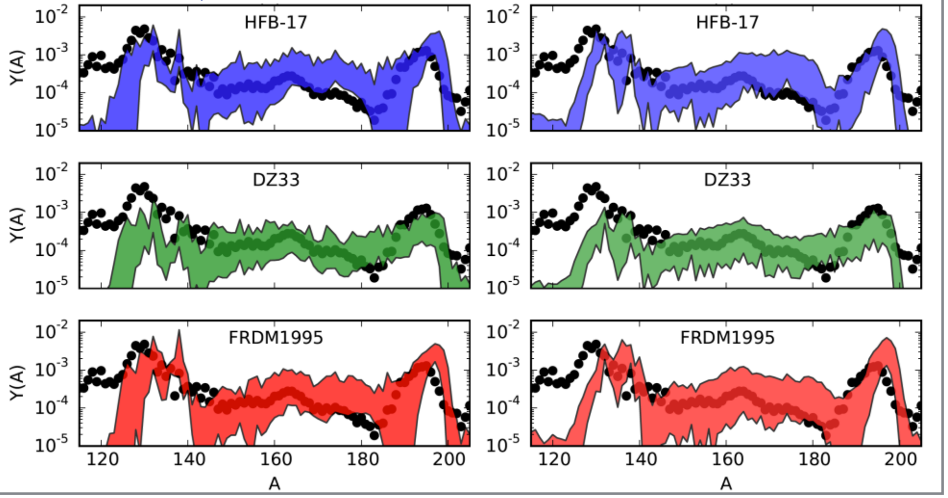
Beta-decay uncertainties

Neutron capture uncert.

DFT

CC

CC



Building blocks for nuclear structure theories

- Degrees of freedom

  at ~1-50 MeV excitation energies:
  single-particle & collective (vibrational, rotational)
  NO complete separation of the scales!
  -Coupling between single-particle and collective:
  -Coupling to continuum
  as nuclei are open quantum systems

- Symmetries -> Eqs. of motion

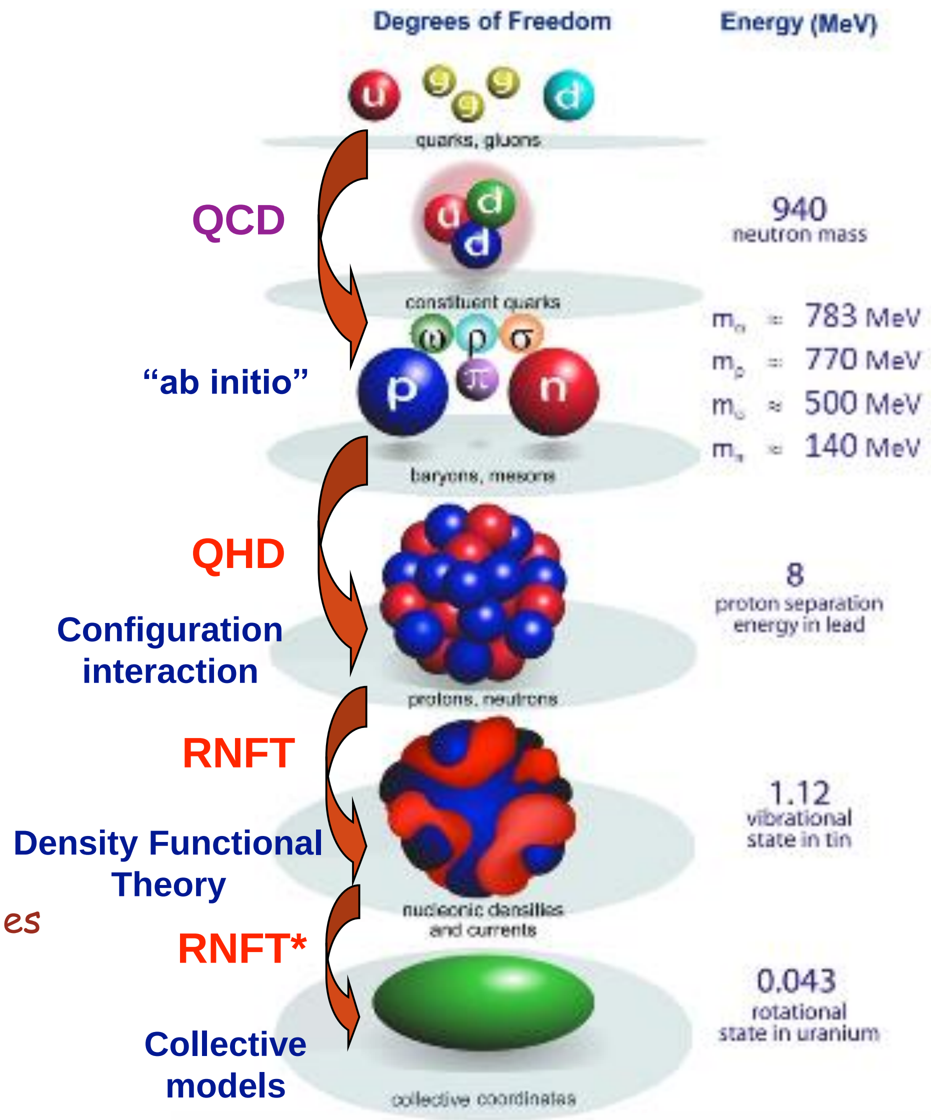
  Galilean inv. -> Schrödinger Equation
  Lorentz inv. -> Dirac, Klein-Gordon Equations

- Interaction V_{NN} : 3 basic concepts

  Ab initio: from vacuum V_{NN} -> in-medium V_{NN}
  Configuration interaction: matrix elements for in-medium V_{NN}
  Density functional: an ansatz for in-medium VNN

- (Relativistic) Nuclear Field Theory: connecting scales

Nuclear scales



QCD

“ab initio”

QHD

Configuration interaction

RNFT

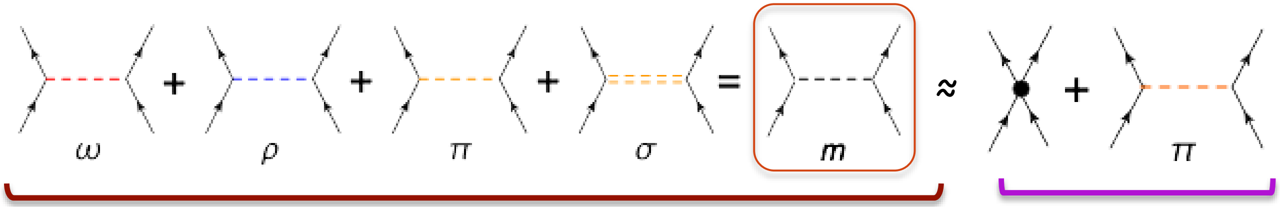
Density Functional Theory

RNFT*

Collective models

Nuclear forces: meson exchange

Pion (Yukawa, 1935), heavy mesons 1950-s



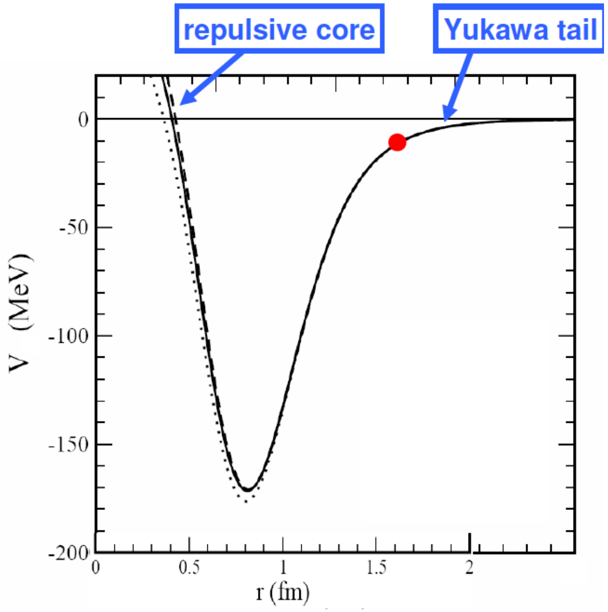
Chiral effective field theory (xEFT):

Quantum Hadrodynamics

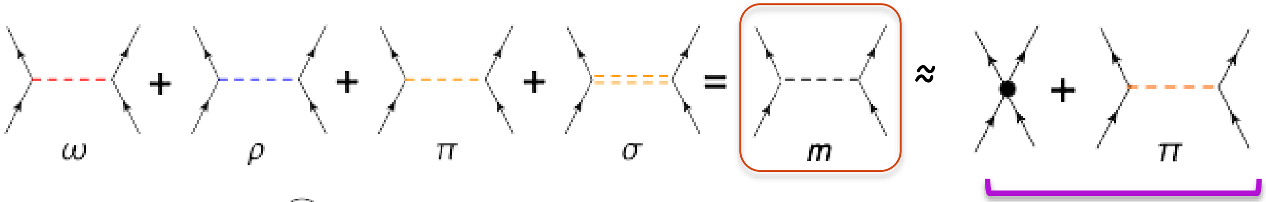
Nucleon-nucleon interaction:

Nuclear "forces"

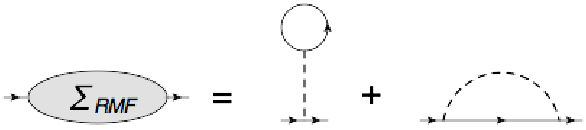
- The nucleons in the interior of the nuclear medium do not feel the same bare force V
- They feel an effective force G (calculated from V in "ab initio" methods).
- The Pauli principle prohibits the scattering into states, which are already occupied in the medium.
- Therefore this force G(ρ) depends on the density
- This force G is much weaker than bare force V.
- Nucleons move nearly free in the nuclear medium and feel only a strong attraction at the surface (shell model)



Theories based on the meson-exchange interaction

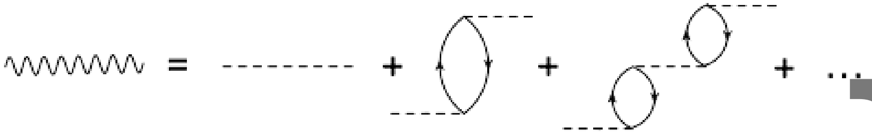


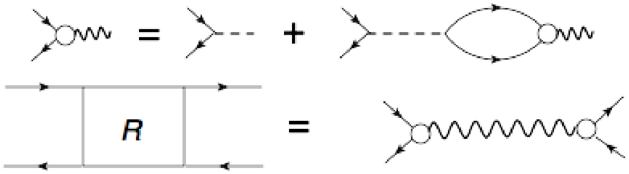
χEFT: order by order



Hartree-Fock (HF)

Relativistic Mean Field (P. Ring et al.) Covariant DFT
(8-10 parameters fixed) = Extended Walecka model





Random
Phase
Approximation

RPA

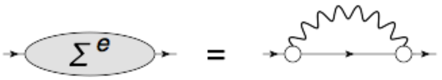
Emergent collective degrees of freedom: 'phonons'

New order parameter: phonon coupling vertex

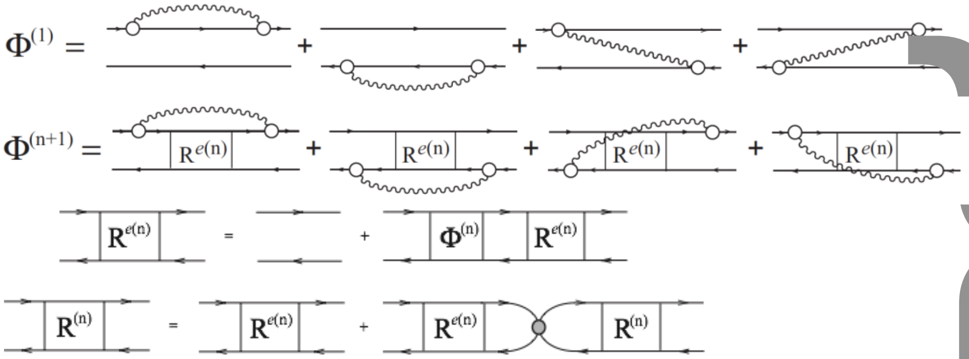
Finite size & angular momentum couplings

Hierarchy of contributions:

-> mean field
-> line corrections
-> vertex corrections



Quasiparticle-vibration coupling (QVC)



Nuclear Field Theory (NFT)

Relativistic NFT:
EL, P. Ring,
PRC 73,044328 (2006);
EL, P. Ring, V. Tselyaev,
PRC 78, 014312 (2008)

RNFT*

Nuclear Field Theory:
Copenhagen - Milano
(P.F. Bortignon, G. Bertsch
R.Broglia, G. Colo,
E. Vigezzi et al.): NFT
&
St.Petersburg-Juelich
J. Speth, V. Tselyaev,
S. Kamerdzhiev et al.:
Extension of
Landau-Migdal theory:
ETFFS

First approximation: Density Functional Theory (DFT) for a many-body quantum system

The manybody problem is mapped onto a one-body problem:

Density functional theory starts from the

Hohenberg-Kohn theorem:

„The exact ground state energy E[ρ] is a universal functional for the local density ρ(r)“

Many-body wave function: Slater determinant:

Kohn-Sham theory starts

with a density dependent self-energy:

$$h(\mathbf{r}) = \frac{\delta E[\rho]}{\delta \rho(\mathbf{r})}$$

and the single particle equation:

$$h(\mathbf{r})|\varphi_i\rangle = \varepsilon_i|\varphi_i\rangle$$

with the exact density:

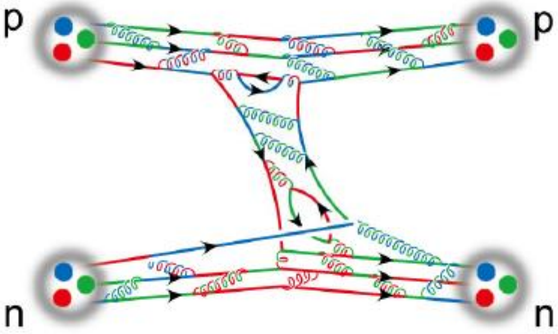
$$\rho(\mathbf{r}) = \sum_i^A |\varphi_i(\mathbf{r})|^2$$

$$\Psi = \frac{1}{\sqrt{N!}} \begin{vmatrix} \phi_1(\mathbf{r}_1) & \phi_1(\mathbf{r}_2) & \cdots & \phi_1(\mathbf{r}_N) \\ \phi_2(\mathbf{r}_1) & \phi_2(\mathbf{r}_2) & \cdots & \phi_2(\mathbf{r}_N) \\ \vdots & \vdots & \ddots & \vdots \\ \phi_N(\mathbf{r}_1) & \phi_N(\mathbf{r}_2) & \cdots & \phi_N(\mathbf{r}_N) \end{vmatrix}$$

Problems:

For Coulombic systems the density functional is derived ab initio: for nuclei it is much more complicated!

DFT in nuclei can not provide a precise description, but rather only the first approximation to the nuclear many-body problem



Relativistic Hartree (Fock): mean field approximation (=DFT)

Total energy :

$$E_{RMF}[\hat{\rho},\phi] = Tr[(\boldsymbol{\alpha}\mathbf{p}+\beta m)\hat{\rho}] + \sum_m \left\{ Tr[(\beta\Gamma_m\phi_m)\hat{\rho}] \mp \int \left[\frac{1}{2}(\boldsymbol{\nabla}\phi_m)^2 + U(\phi_m)\right] d^3r \right\}$$

$$\begin{cases} \mathcal{H}_{RHB}|\psi_k^{\eta}\rangle = \eta E_k|\psi_k^{\eta}\rangle, \qquad \eta = \pm 1 \\ -\Delta\phi_m(\boldsymbol{r}) + U'(\phi_m(\boldsymbol{r})) = \mp\sum_k V_k^{\mathsf{T}}(\boldsymbol{r})\beta\Gamma_m V_k^*(\boldsymbol{r}) \end{cases}$$

Nucleons

Mesons

Relativistic Hartree (Fock)-Bogoliubov (HFB) Hamiltonian

$$\hat{\mathcal{H}}_{RHB} = \frac{\delta E_{RHB}}{\delta\mathcal{R}} = \begin{pmatrix} h^{\mathcal{D}} - m - \lambda & \Delta \\ -\Delta^* & -h^{\mathcal{D}*} + m + \lambda \end{pmatrix}$$

Dirac Hamiltonian

$$h^{\mathcal{D}} = \boldsymbol{\alpha}\mathbf{p} + \beta(m + \underline{\sum_m \Gamma_m\phi_m(\mathbf{r})})$$

$$\tilde{\Sigma}(\mathbf{r})$$

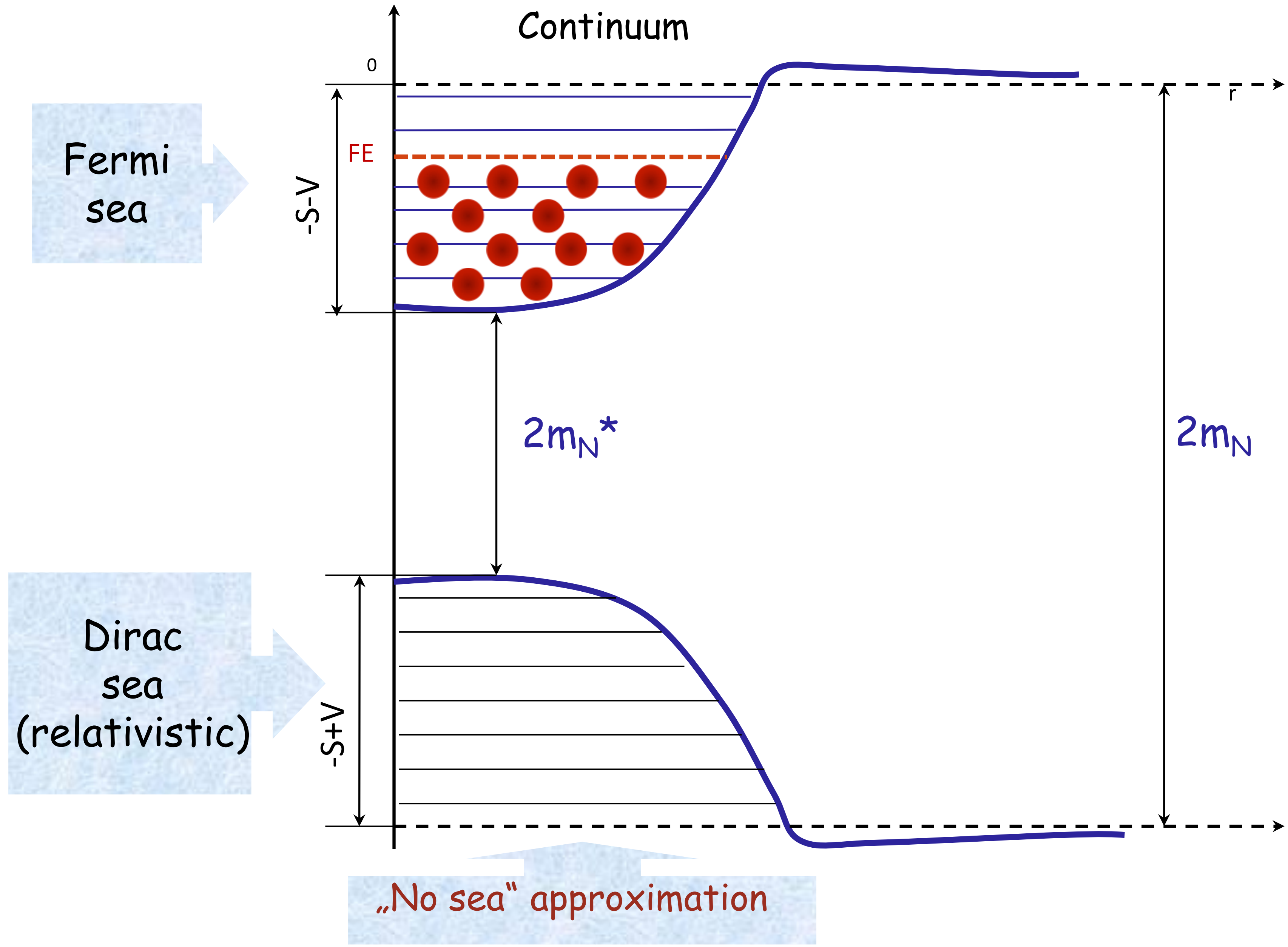
RMF self-energy

$$|\psi_k^+(\boldsymbol{r})\rangle = \begin{pmatrix} U_k(\boldsymbol{r}) \\ V_k(\boldsymbol{r}) \end{pmatrix}$$

Eigenstates

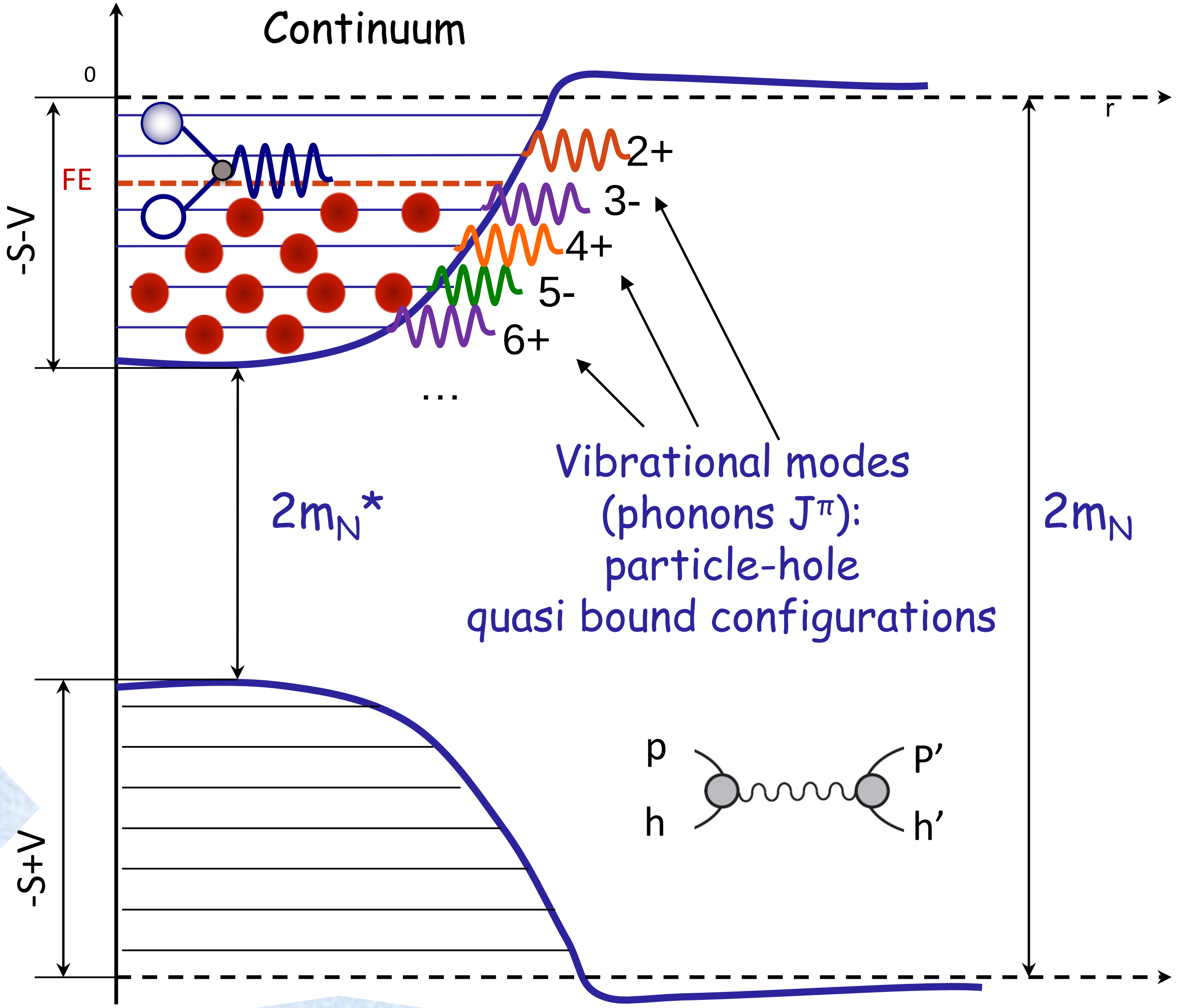
$$|\psi_k^-(\boldsymbol{r})\rangle = \begin{pmatrix} V_k^*(\boldsymbol{r}) \\ U_k^*(\boldsymbol{r}) \end{pmatrix}$$

Uncorrelated ground state as the zero-th approximation: (Relativistic) Mean FieldApproximation



Beyond Mean Field: coherent oscillations

Fermi sea



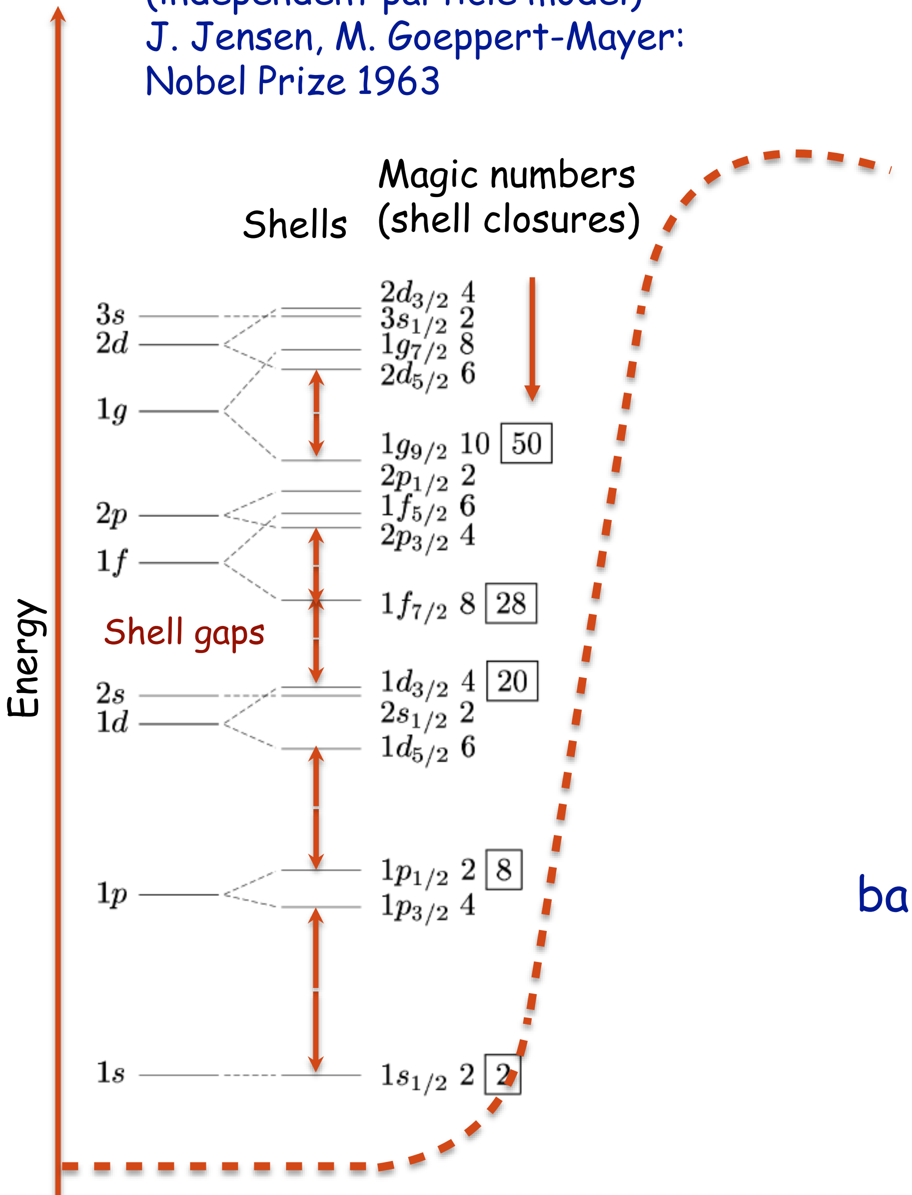
Vibrational modes (phonons J^{π}): particle-hole quasi bound configurations

Dirac sea (relativistic)

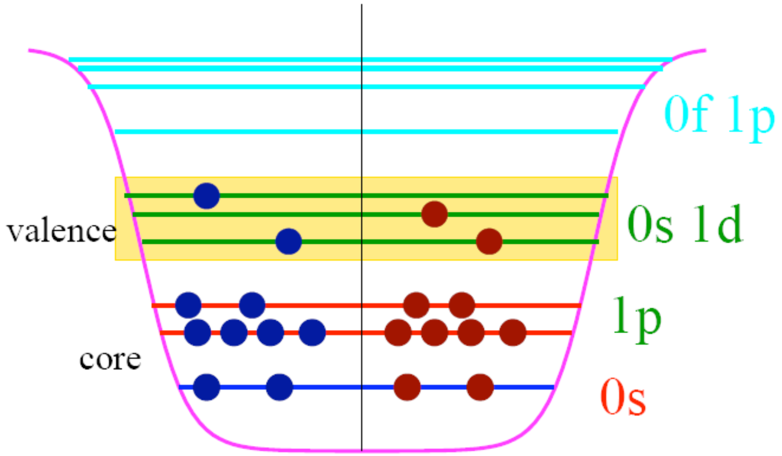
„No sea“ approximation

Shell Model

"Naive" Shell-model
(independent particle model)
J. Jensen, M. Goeppert-Mayer:
Nobel Prize 1963



Configuration Interaction shell-model:
core + valence space => interaction
=> diagonalization
(B.A. Brown, F. Nowacki, A. Poves et al.)



No-core shell-model:
bare NN potential => effective interaction
(G-matrix theory, SRG etc.)
=> exact diagonalization
(B. Barrett, E. Ormand, P. Navratil)

Single-quasiparticle Green's function

One-body Green's function in (N+1)-body system

$$G(x,x') = -i\langle\Phi_0^N|\hat{T}\hat{a}(x)\hat{a}^\dagger(x')|\Phi_0^N\rangle$$

$$x = \{\xi, t\}$$

Lehmann expansion (Fourier transform):

$$G(\xi,\xi';\varepsilon) = \sum_n \frac{(\Psi(\xi))_{0n}(\Psi^\dagger(\xi'))_{n0}}{\varepsilon - (E_n^{(N+1)} - E_0^{(N)}) + i\delta} + \\ + \sum_m \frac{(\Psi^\dagger(\xi'))_{0m}(\Psi(\xi))_{m0}}{\varepsilon + (E_m^{(N-1)} - E_0^{(N)}) - i\delta},$$

Excited state (N+1)

$$\begin{aligned} (\Psi^\dagger(\xi))_{n0} &= \langle\Phi_n^{(N+1)}|\Psi^\dagger(\xi)|\Phi_0^{(N)}\rangle, \\ (\Psi(\xi))_{n0} &= \langle\Phi_n^{(N-1)}|\Psi(\xi)|\Phi_0^{(N)}\rangle, \end{aligned}$$

Ground state (N)

"Free quasiparticle" propagator
in the mean field:

$$\tilde{G}_k^\eta(\varepsilon) = \frac{1}{\varepsilon - \eta E_k + i\eta\delta}$$

Basis states (spherical):

$$k = |n_k, j_k, l_k, m_k\rangle$$

Spectroscopic
factors
(occupancies)

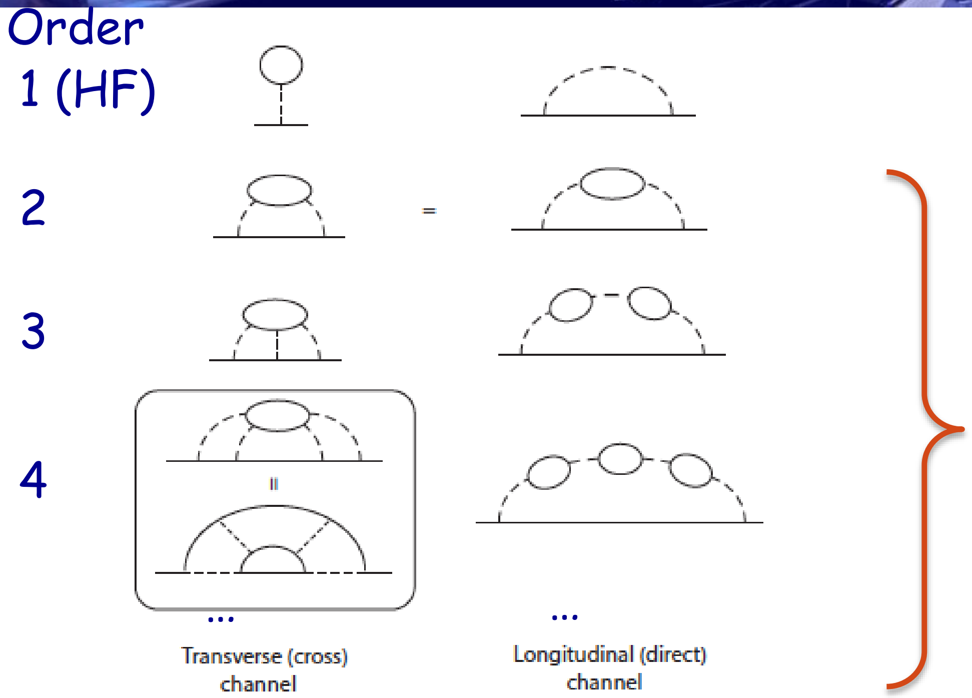
Interacting
(fragmented):

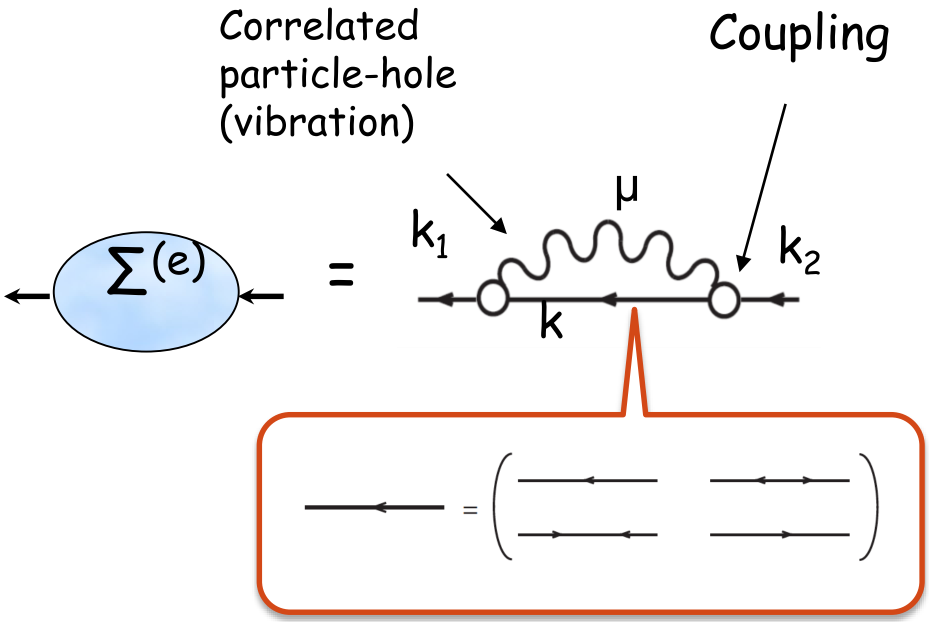
$$G_k^\eta(\varepsilon) = \sum_{\nu,\eta'} \frac{\tilde{S}_k^{\eta'(\nu)}}{\varepsilon - \eta\eta' E_k^{(\nu)}}$$

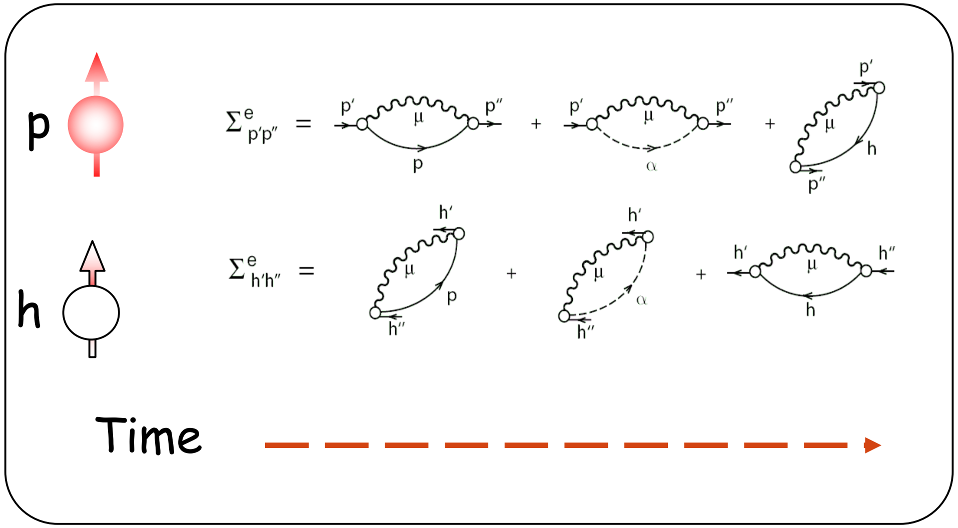
Quasiparticle
Energies

$$\eta = \pm 1$$

Systematic expansion in meson-exchange interaction: one-fermion self-energy







Superfluidity: Gor'kov's GF
Doubled quasiparticle space:

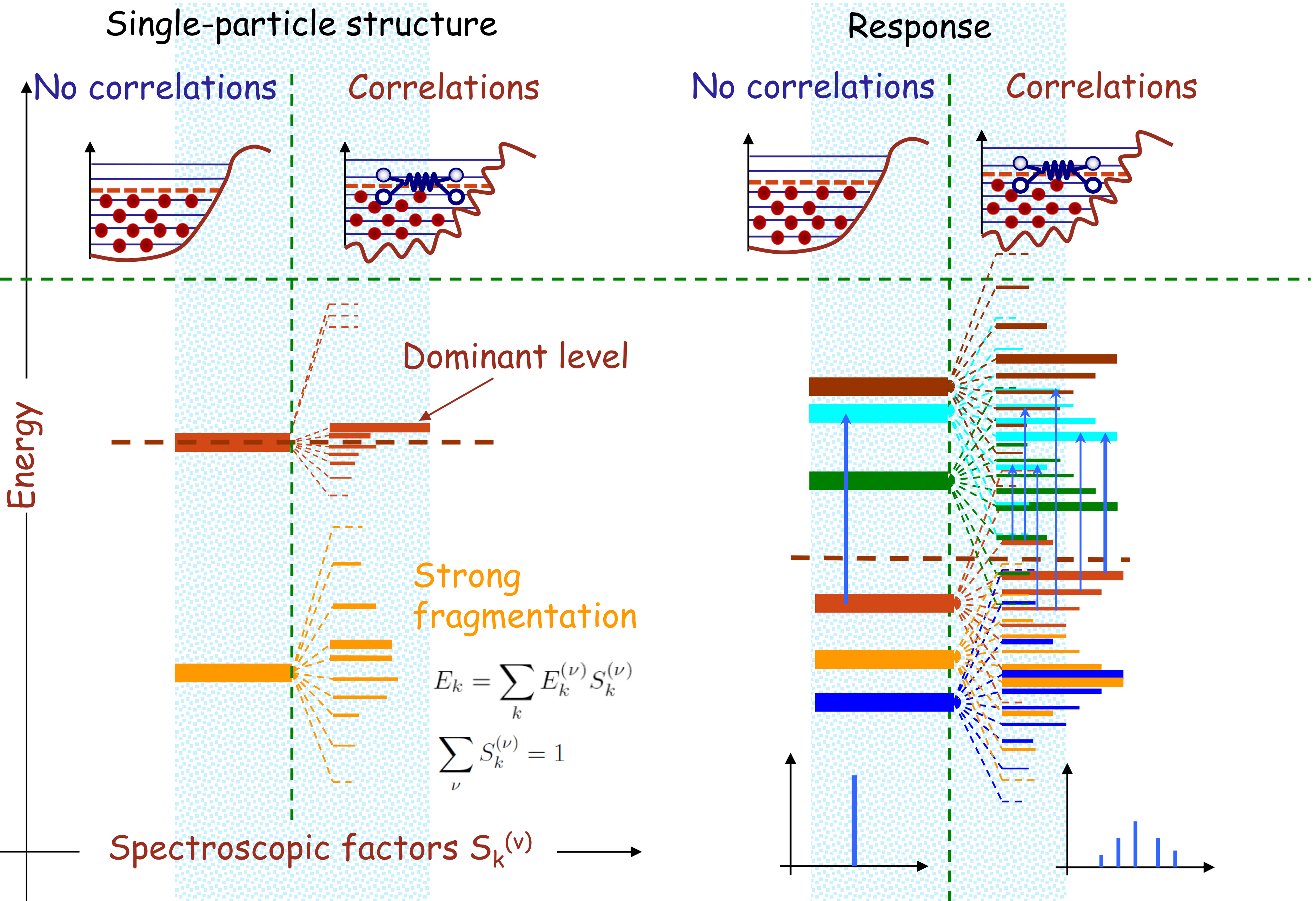
$$\Sigma^{(e)\eta_1\eta_2}_{k_1k_2}(\varepsilon) = \sum_{\eta=\pm1}\sum_{k,\mu} \frac{\gamma^{\eta;\eta_1\eta}_{\mu;k_1k}\ \gamma^{\eta;\eta_2\eta*}_{\mu;k_2k}}{\varepsilon - \eta(E_k + \Omega_\mu - i\delta)}$$

$$\big(\varepsilon - \mathcal{H}_{RHB} - \Sigma^{(e)}(\varepsilon)\big)G(\varepsilon) = 1$$

$\eta = \pm1$

Dyson Equation

Fragmentation of states in odd and even systems (schematic)

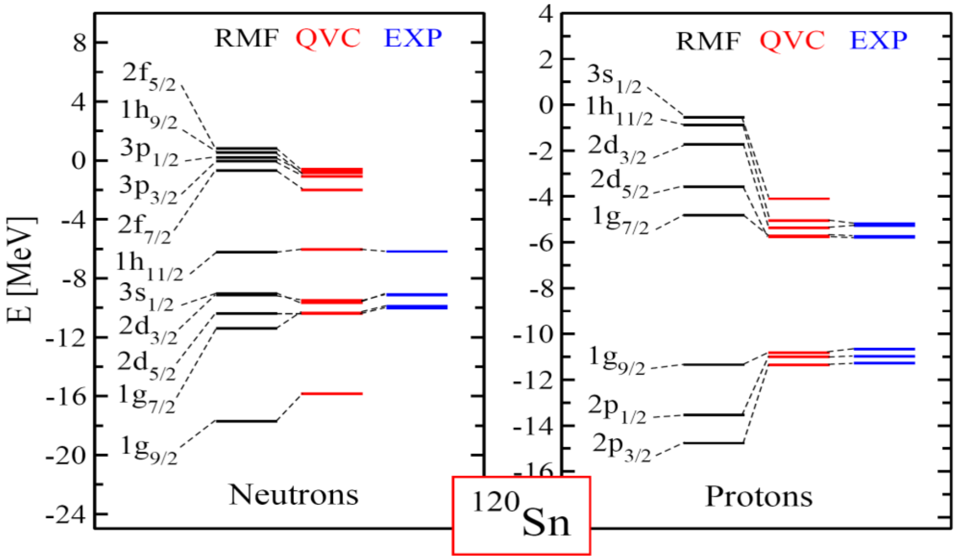


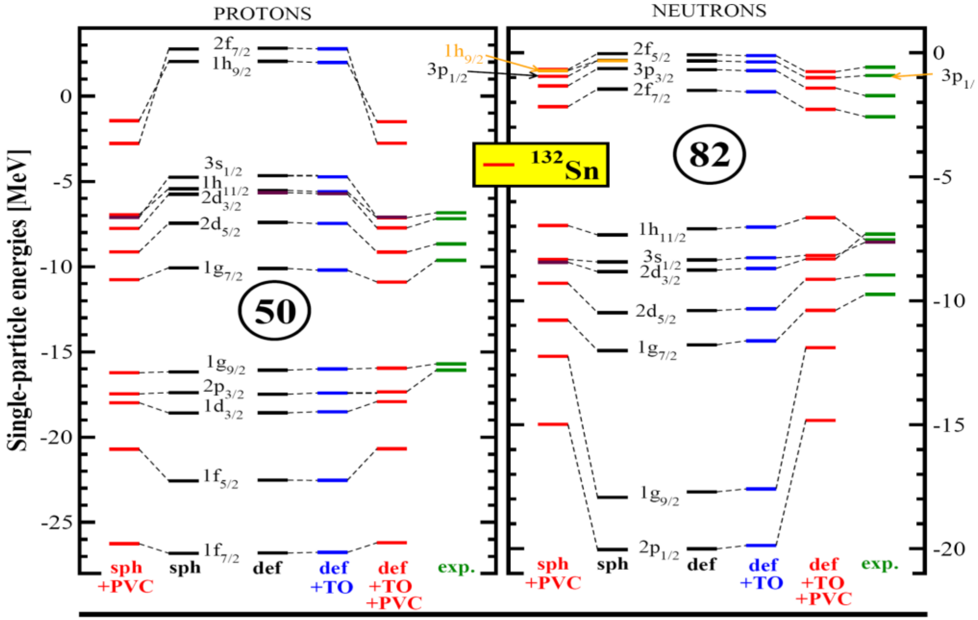
$$E_k = \sum_k E_k^{(\nu)} S_k^{(\nu)}$$

$$\sum_\nu S_k^{(\nu)} = 1$$

Quasiparticle-vibration coupling: Pairing correlations of the superfluid type + coupling to phonons

E.L., PRC 85, 021303(R) (2012)





Spectroscopic factors in ^{120}Sn:

(nlj) ν	S^{th}	S^{exp}
$2d_{5/2}$	0.32	0.43
$1g_{7/2}$	0.40	0.60
$2d_{3/2}$	0.53	0.45
$3s_{1/2}$	0.43	0.32
$1h_{11/2}$	0.58	0.49
$2f_{7/2}$	0.31	0.35
$3p_{3/2}$	0.58	0.54

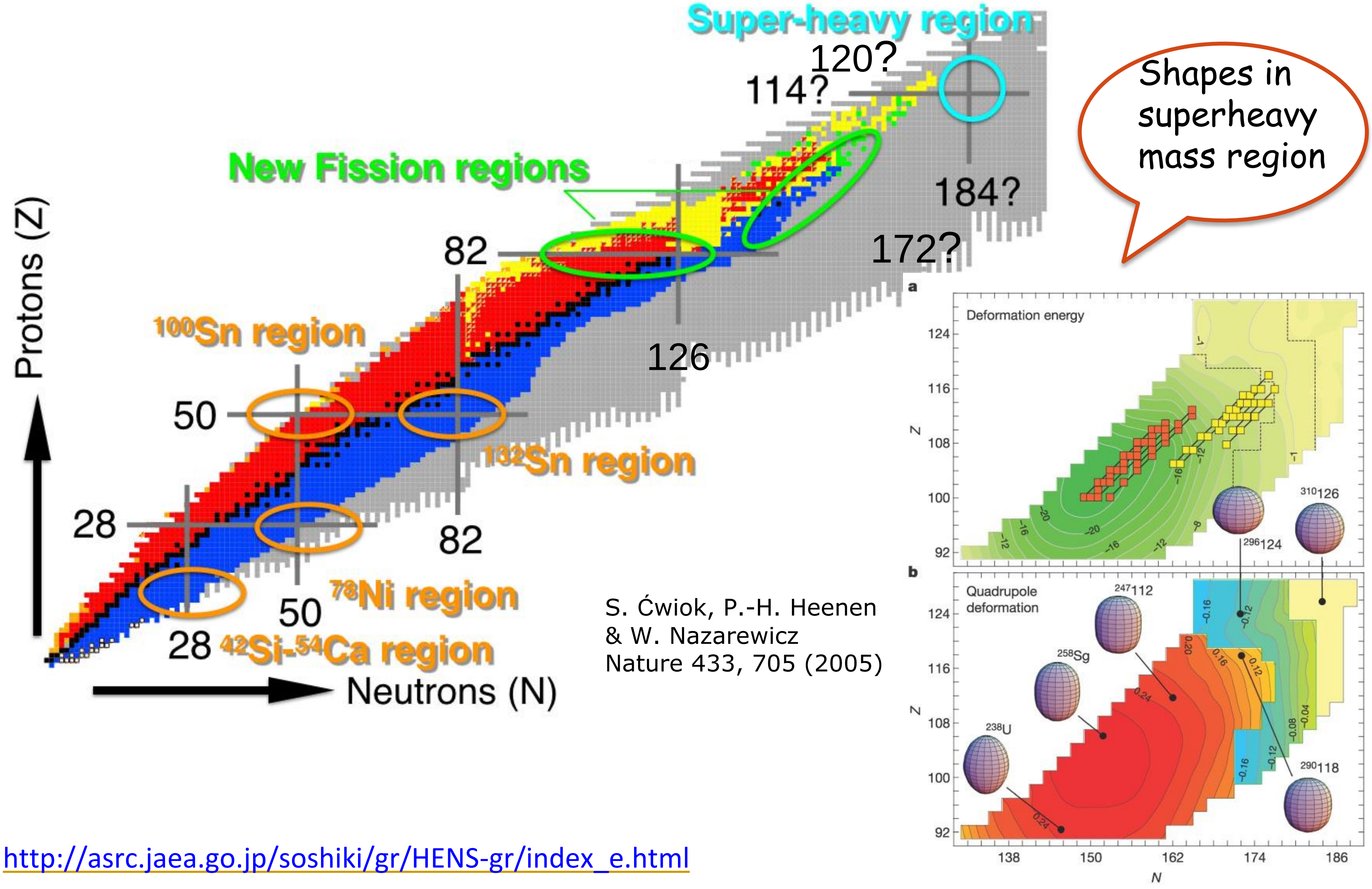
Spectroscopic factors in ^{132}Sn:

(nlj) ν	S^{th} *	S^{exp} **
$2f_{7/2}$	0.89	0.86±0.16
$3p_{3/2}$	0.91	0.92±0.18
$1h_{9/2}$	0.88	
$3p_{1/2}$	0.91	1.1±0.3
$2f_{5/2}$	0.89	1.1±0.2

*E. L., A.V. Afanasjev, PRC 84, 014305 (2011)

**K.L. Jones et al., Nature 465, 454 (2010)

Magic numbers in superheavy mass region

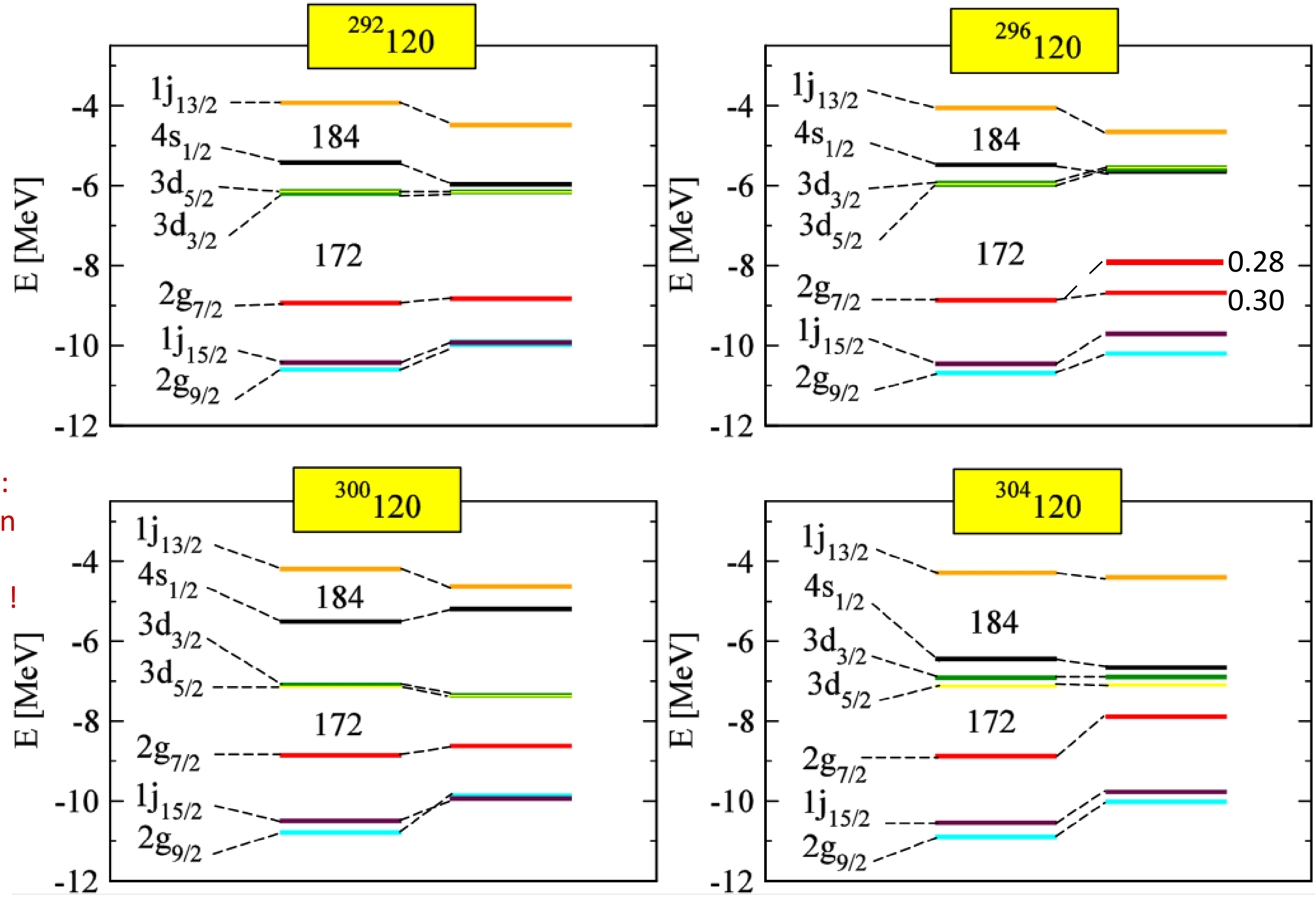


Shapes in superheavy mass region

S. Ćwiok, P.-H. Heenen & W. Nazarewicz
Nature 433, 705 (2005)

http://asrc.jaea.go.jp/soshiki/gr/HENS-gr/index_e.html

Dominant neutron states in superheavy Z = 120 isotopes



Comparable Spectroscopic strengths

shell gap ???

PC+QVC: Formation of the shell gap !

RMF+BCS

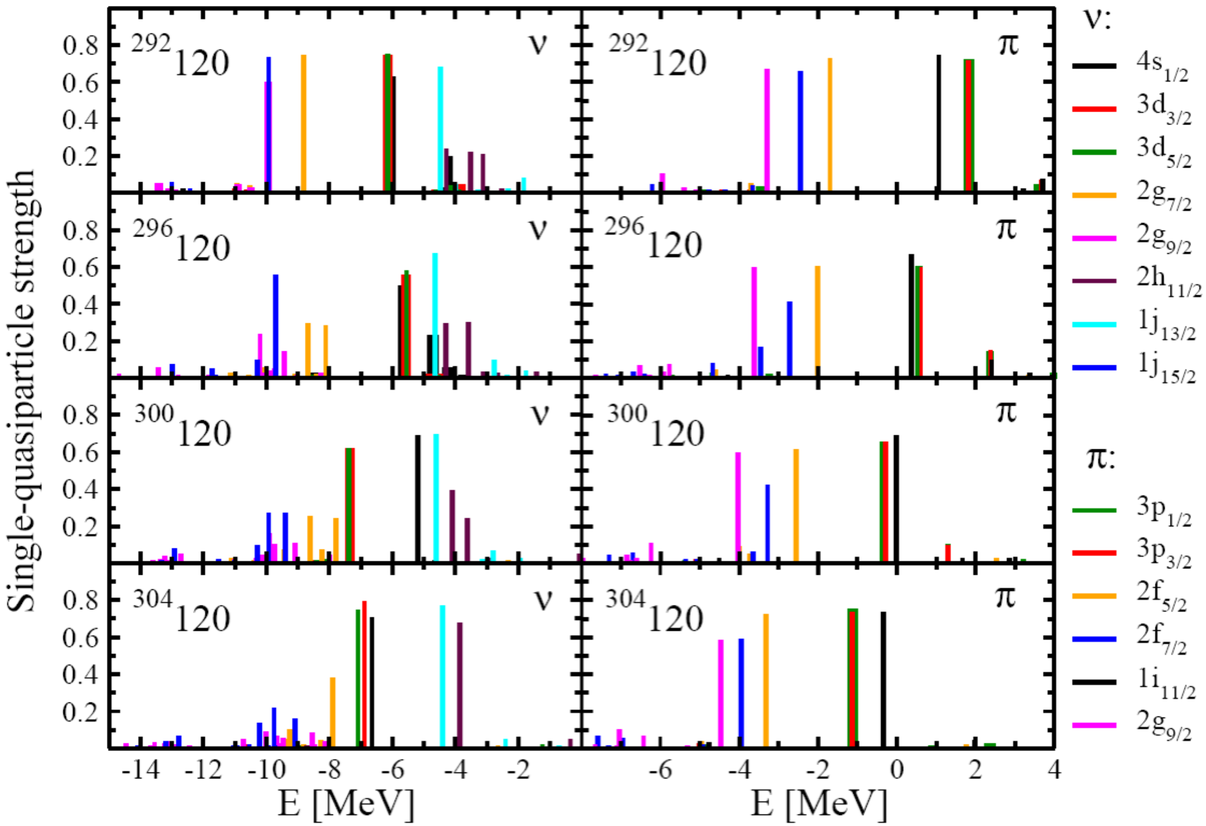
...+QVC

RMF+BCS

...+QVC

Shell evolution in superheavy Z = 120 isotopes: Quasiparticle-vibration coupling (QVC) in a relativistic framework

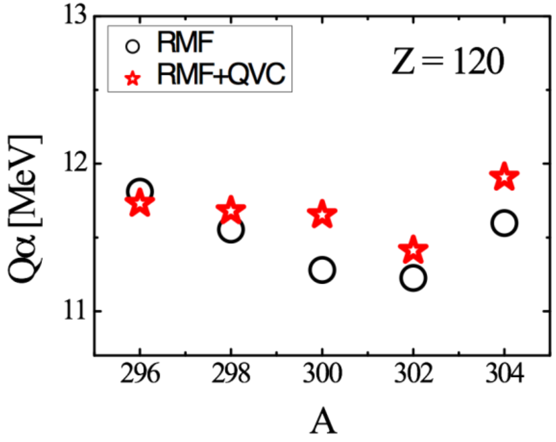
1. Relativistic Mean Field: spherical minima
2. π: collapse of pairing, clear shell gap
3. ν: survival of pairing coexisting with the shell gap
4. Very soft nuclei: large amount of low-lying collective vibrational modes (~100 phonons below 15 MeV)



Vibration corrections to binding energy (RQRPA)

$$E_{VC} = -\sum_{\mu} \Omega_{\mu} \sum_{k_1 k_2} |Y^{\mu}_{k_1 k_2}|^2$$

Vibration corrections to 〈 -decay Q-values



Vibrational corrections:

1. Impact on the shell gaps
2. Smearing out the shell effects

Shell stabilization & vibration stabilization/destabilization (?)

E.L., PRC 85, 021303(R) (2012)

From 3D harmonic oscillator to a realistic phenomenological potential

3D Harmonic Oscillator:

$$V_{\mathrm{HO}}(r) = \frac{1}{2} m\omega^2 r^2$$

$$\varepsilon_\alpha = \hbar\omega \left(\underbrace{2n_\alpha + l_\alpha}_{N_a} + \frac{3}{2} \right)$$

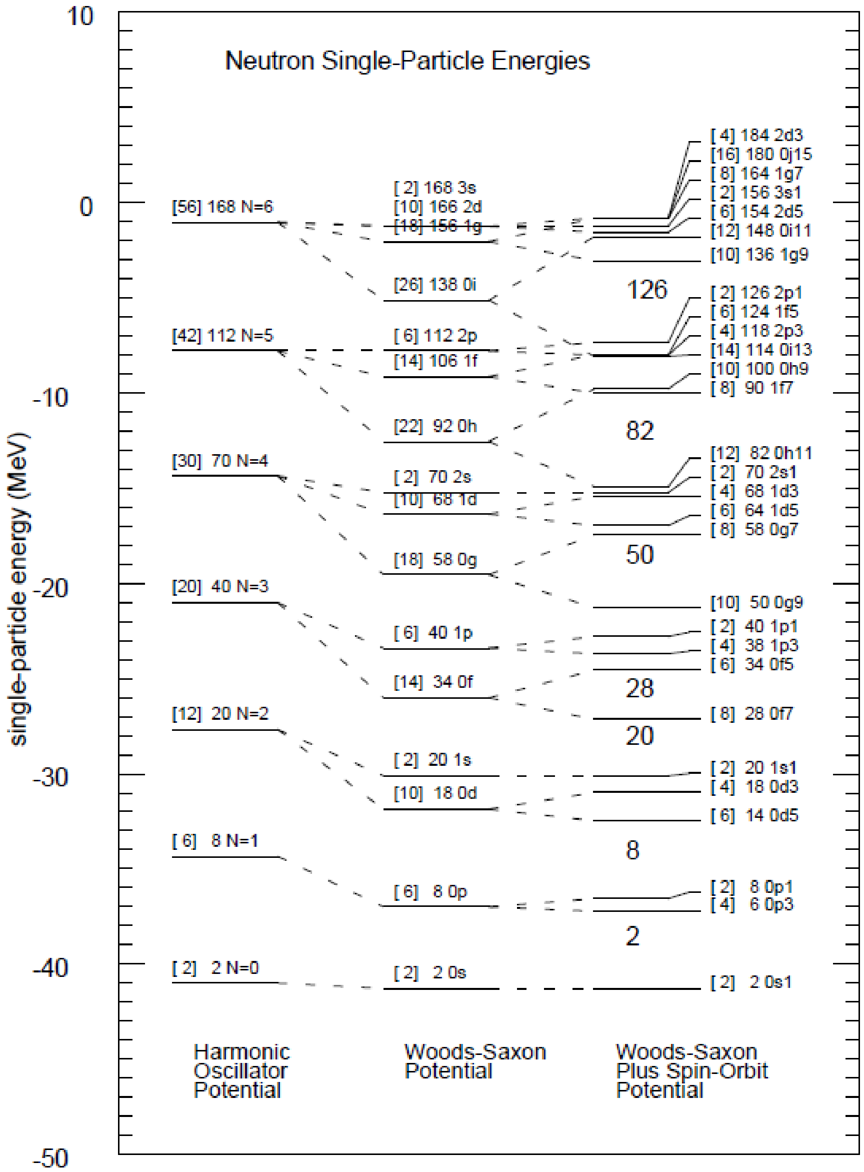
Degeneracy

Woods-Saxon (WS) potential:

$$V_{\mathrm{WS}}(r) = -\frac{V_0}{1 + \exp{(r - R)/a}}$$

WS + spin-orbit interaction:

$$V_{\mathrm{WS+ls}}(r) = -\frac{V_0}{1 + \exp{(r - R)/a}} + V_{ls}(r)\boldsymbol{ls}$$



http://nucleartalent.github.io/Course2ManyBodyMethods/doc/pub/intro/html/intro.html

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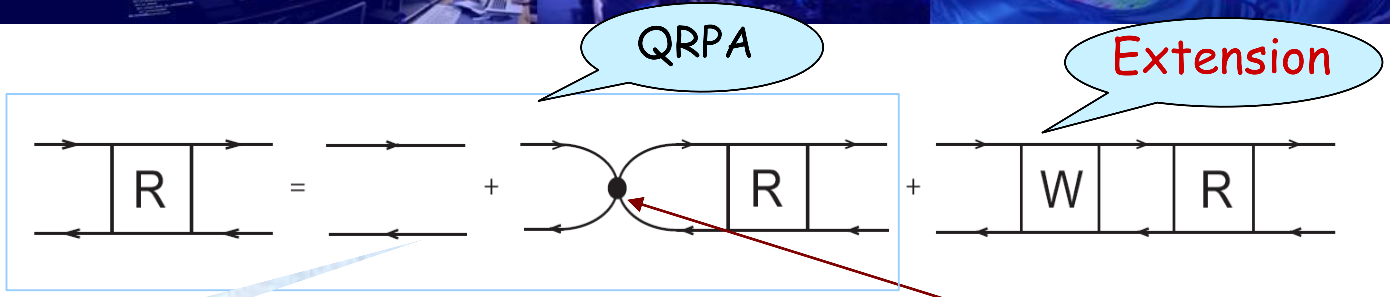
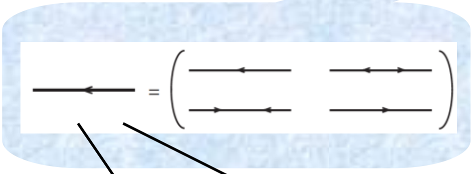
Excited states: nuclear response function

Bethe-Salpeter Equation (BSE):



E.L., V. Tselyaev,
PRC 75, 054318 (2007)



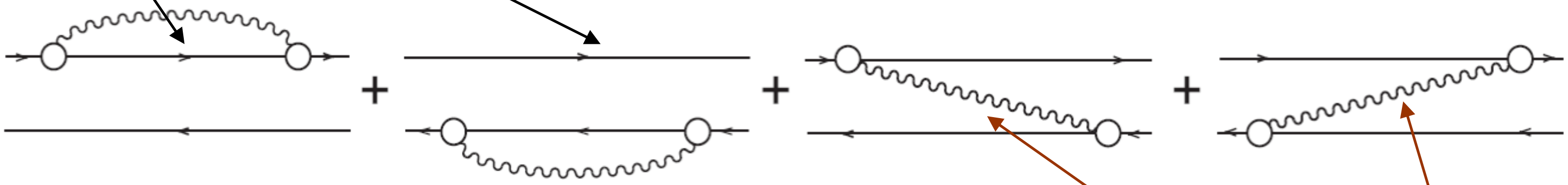
$$R(\omega) = A(\omega) + A(\omega)\,[V + W(\omega)]\,R(\omega)$$

$$V = \frac{\delta\Sigma^{RMF}}{\delta\rho}$$

$$W(\omega) = \Phi(\omega) - \Phi(0)$$

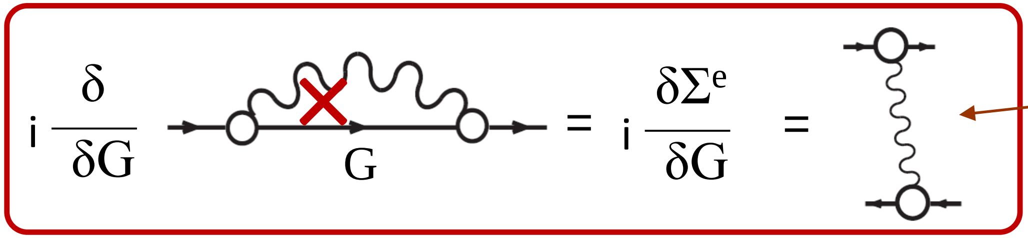
Self-consistency

$\Phi =$



$$U^e = i\,\frac{\delta\Sigma^e}{\delta G}$$

Consistency on 2p2h-level

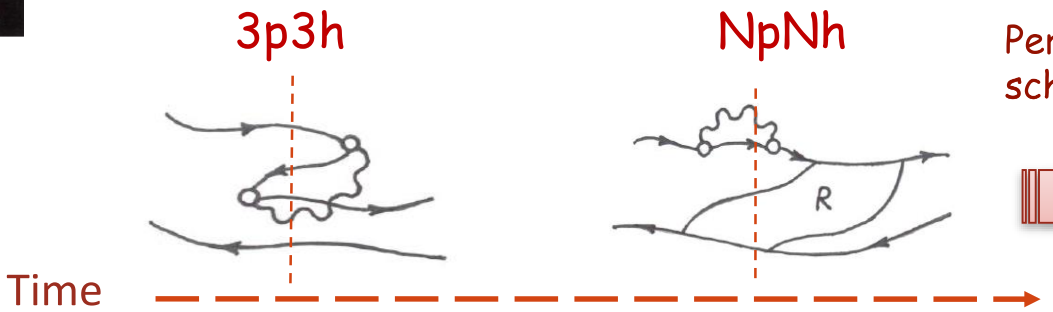


$i\frac{\delta}{\delta G}$ $=$ $i\frac{\delta\Sigma^e}{\delta G}$ $=$

Time blocking approximation

Problem:

'Melting' diagrams

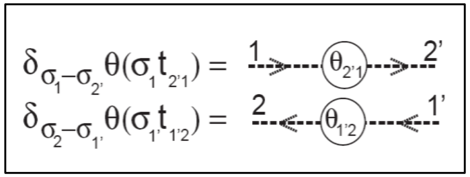


Perturbative schemes:

Unphysical result:
negative
cross sections

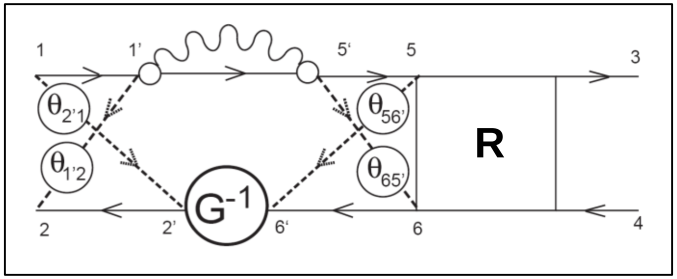
Solution:

Time-projection operator:



$$\delta_{\sigma_1-\sigma_{2'}}\theta(\sigma_1 t_{2'1}) =$$

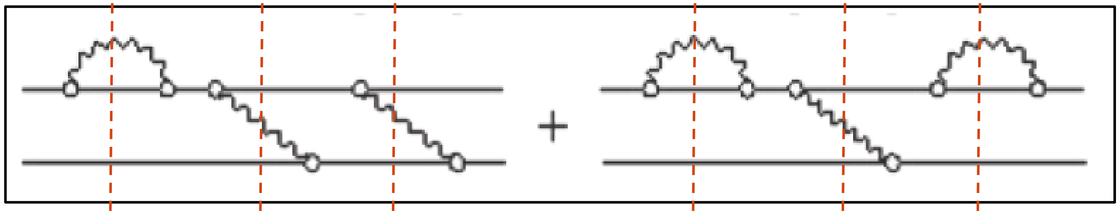
$$\delta_{\sigma_2-\sigma_{1'}}\theta(\sigma_{1'} t_{1'2}) =$$



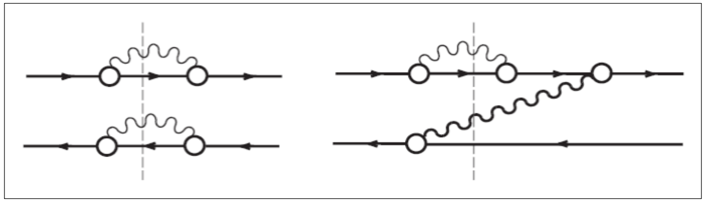
Partially fixed

V.I. Tselyaev, Yad. Fiz. 50,1252 (1989)

Allowed terms: 1p1h, 2p2h



Blocked terms: 3p3h, 4p4h,…



Time

- Separation of the integrations in the BSE kernel
- R has a simple-pole structure (spectral representation)
- »» Strength function is positive definite!

Included on the next step

Response function in the neutral channel: relativistic quasiparticle time blocking approximation (RQTBA)

Response
$$R(\omega) = \tilde{R}^0(\omega) + \tilde{R}^0(\omega)W(\omega)R(\omega)$$

Interaction
$$W(\omega) = \underbrace{V_\sigma + V_\omega + V_\rho + V_e}_{} + \underbrace{\Phi(\omega)}_{} - \underbrace{\Phi(0)}_{}$$

Subtraction to avoid double counting

Static: RQRPA
$$\left\{\begin{aligned} v_\sigma(1,2) &= -g_\sigma^2\gamma_1^0 D_\sigma(1,2)\gamma_2^0 \\ v_\omega(1,2) &= +g_\omega^2(\gamma^0\gamma_\mu)_1 D_\omega^{\mu\nu}(1,2)(\gamma^0\gamma_\nu)_2 \\ v_\rho^V(1,2) &= +g_\rho^2(\gamma^0\gamma_\mu\vec{\tau})_1\vec{\tau}_1\cdot\vec{\tau}_2 D_\rho^{\mu\nu}(1,2)(\gamma^0\gamma_\nu\vec{\tau})_2 \end{aligned}\right.$$

Dynamic (retardation):

Quasiarticle-vibration coupling

in time blocking approximation

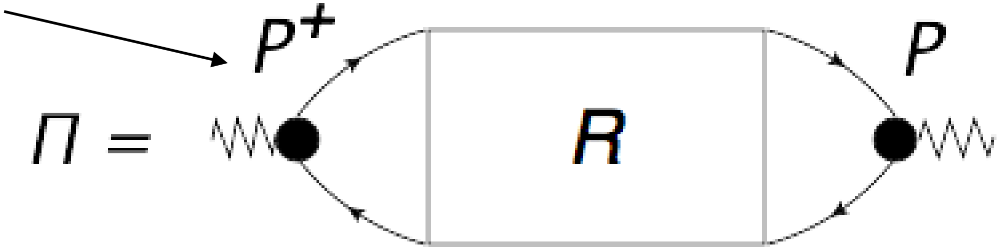
$$\boxed{\begin{aligned} &\Phi^{\eta}_{k_1k_4,k_2k_3}(\omega) = \\ &= \sum_{\mu\xi}\delta_{\eta\xi}\Big[\delta_{k_1k_3}\sum_{k_6}\frac{\gamma^{\eta;-\xi}_{\mu;k_6k_2}\gamma^{\eta;-\xi*}_{\mu;k_6k_4}}{\eta\omega - E_{k_1} - E_{k_6} - \Omega_\mu} + \delta_{k_2k_4}\sum_{k_5}\frac{\gamma^{\eta;\xi}_{\mu;k_1k_5}\gamma^{\eta;\xi*}_{\mu;k_3k_5}}{\eta\omega - E_{k_5} - E_{k_2} - \Omega_\mu} \\ &\qquad - \Big(\frac{\gamma^{\eta;\xi}_{\mu;k_1k_3}\gamma^{\eta;-\xi*}_{\mu;k_2k_4}}{\eta\omega - E_{k_3} - E_{k_2} - \Omega_\mu} + \frac{\gamma^{\eta;\xi*}_{\mu;k_3k_1}\gamma^{\eta;-\xi}_{\mu;k_4k_2}}{\eta\omega - E_{k_1} - E_{k_4} - \Omega_\mu}\Big)\Big] \end{aligned}}$$

Response to an external field: strength function

Nuclear Polarizability:

$$\Pi_{PP}(\omega) = P^{\dagger}R(\omega)P := \sum_{k_1k_2k_3k_4} P^{*}_{k_1k_2}R_{k_1k_4,k_2k_3}(\omega)P_{k_3k_4}$$

External field



Strength function:

$$S(E) = -\frac{1}{\pi}\lim_{\Delta\to+0} Im\ \Pi_{PP}(E+i\Delta)$$

Transition density:

$$\rho^{\nu}_{k_1k_2} = \langle 0|\psi^{\dagger}_{k_2}\psi_{k_1}|\nu\rangle$$

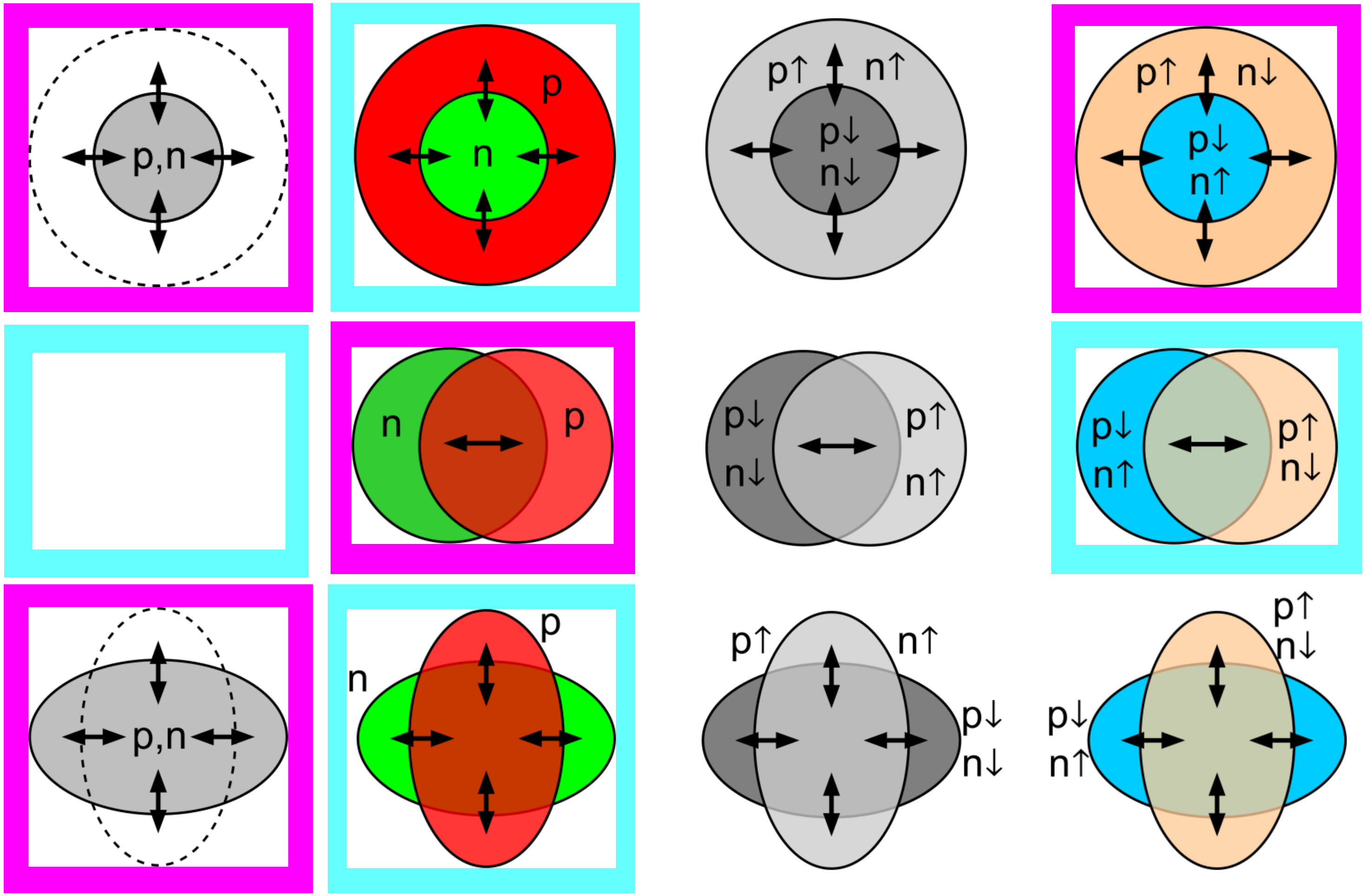
Response function:

$$R^{\nu}_{k_1k_4,k_2k_3}(\omega) \approx \frac{\rho^{\nu}_{k_1k_2}\rho^{\nu *}_{k_3k_4}}{\omega - \Omega^{\nu}}$$

$$\omega \longrightarrow \Omega^{\nu}$$

Nuclear excitation modes

Gamow-Teller



Monopole
⊗L = 0

Dipole
⊗L = 1

Quadrupole
⊗L = 2

⊗T = 0
⊗S = 0

⊗T = 1
⊗S = 0

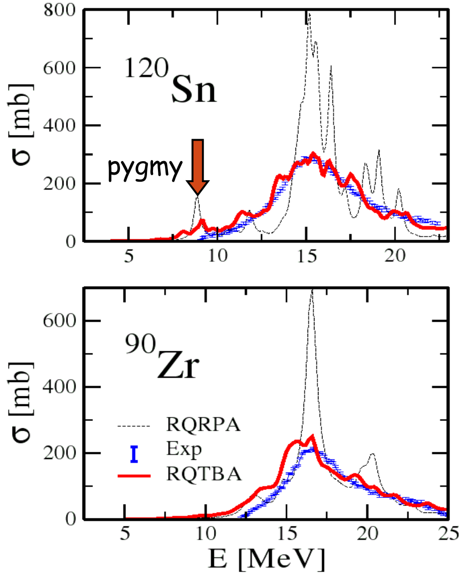
⊗T = 0
⊗S = 1

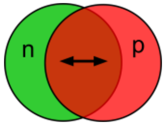
⊗T = 1
⊗S = 1

* M. N. Harakeh and A. van der Woude: Giant Resonances

Dipole response in medium-mass and heavy nuclei within Relativistic Quasiparticle Time Blocking Approximation (RQTBA)

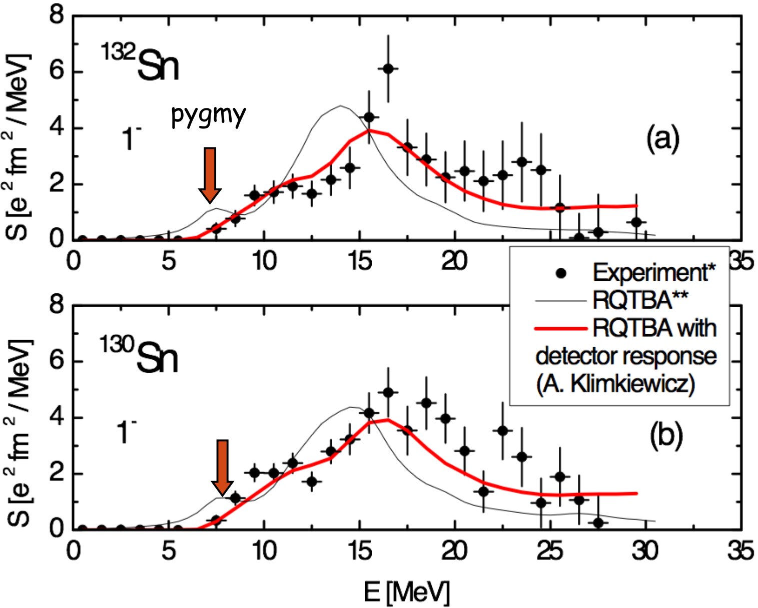
Test case: E1 (IVGDR) stable nuclei



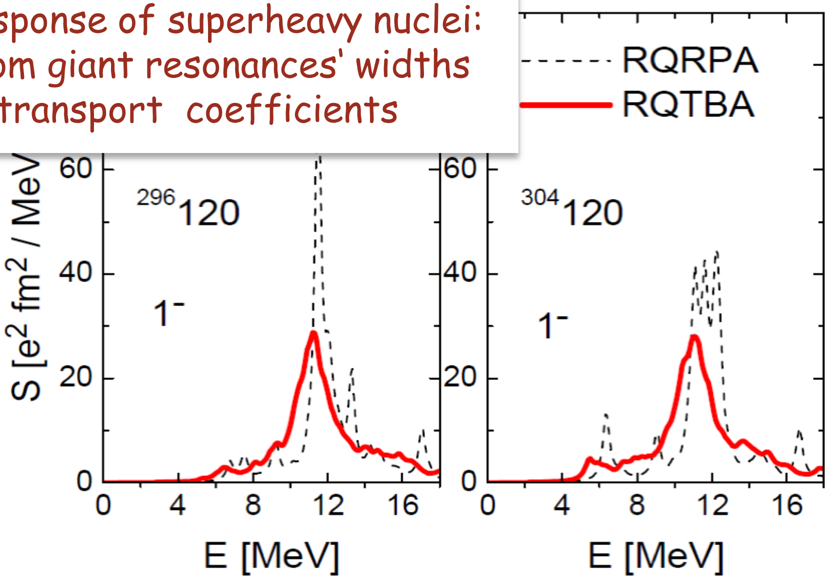


Giant & pygmy dipole resonances

Neutron-rich Sn



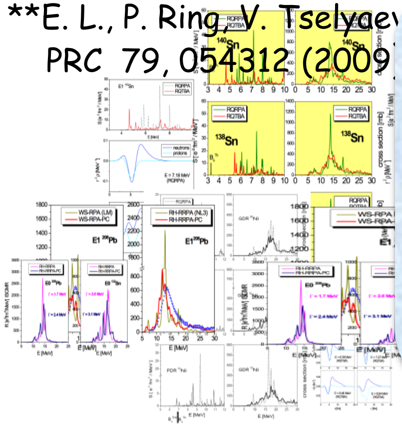
Response of superheavy nuclei:
From giant resonances' widths
to transport coefficients



E. L., P. Ring, and V. Tselyaev,
Phys. Rev. C 78, 014312 (2008)

* P. Adrich, A. Klimkiewicz, M. Fallot et al.,
PRL 95, 132501 (2005)

**E. L., P. Ring, V. Tselyaev,
PRC 79, 054312 (2009)



Input for
r-process nucleosynthesis:
E. L., H.P. Loens, K. Langanke, et al. Nucl. Phys. A 823, 26 (2009).

Microscopic structure of pygmy dipole resonance is extremely important for stellar (n,γ) reaction rates

Exotic modes of excitation: pygmy dipole resonance in neutron-rich nuclei

- exotic nuclei (nuclei with unusual N/Z ratios: neutron-rich or proton-rich) are characterized by weak binding of outermost nucleons, diffuse neutron densities, formation of the neutron skin and halo

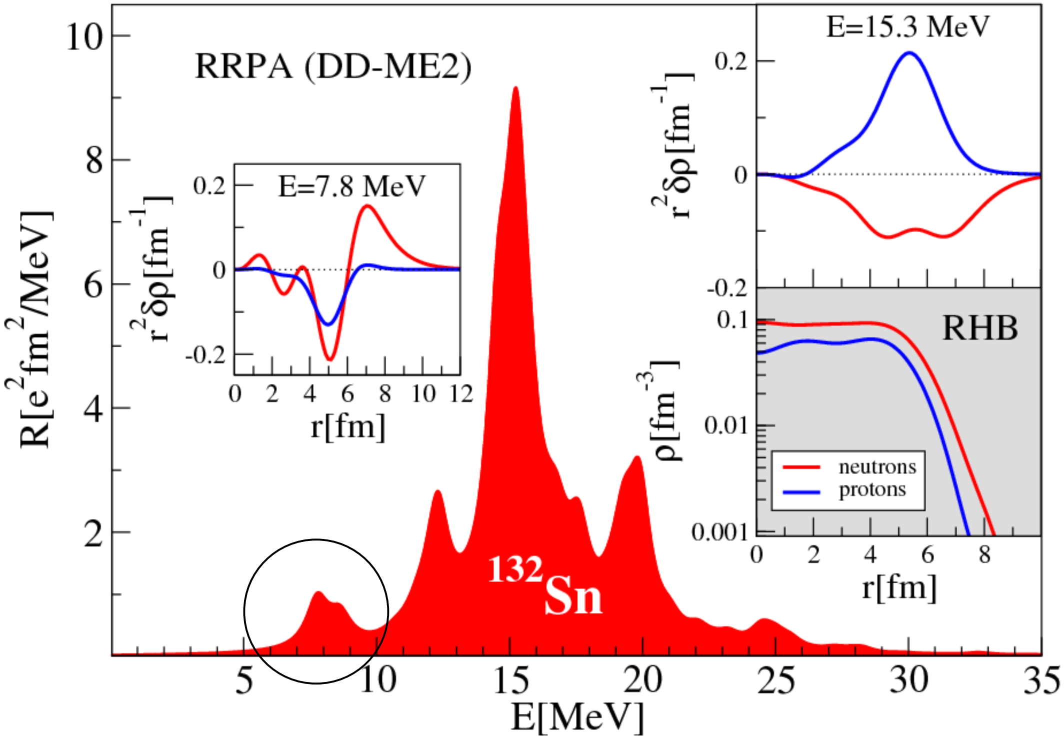
- effect on multipole response → new exotic modes of excitation

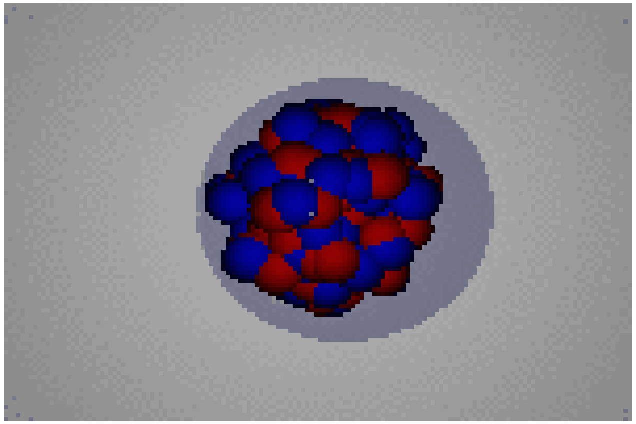
Pygmy dipole resonance (PDR):
N. Paar et al.

Nucleonic density:

$$\rho(r,t) = \rho_0(r) + \delta\rho(r,t)$$

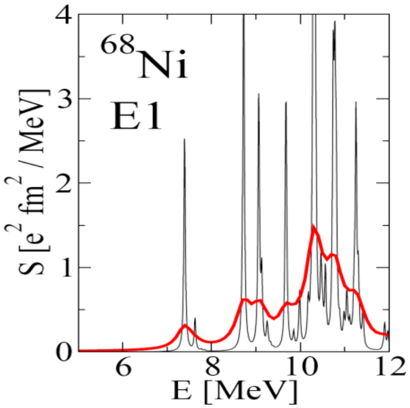
Neutron skin oscillations





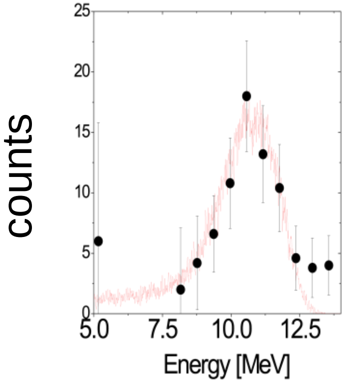
RQTBA dipole transition densities in ^{68}Ni at 10.3 MeV

Theory:

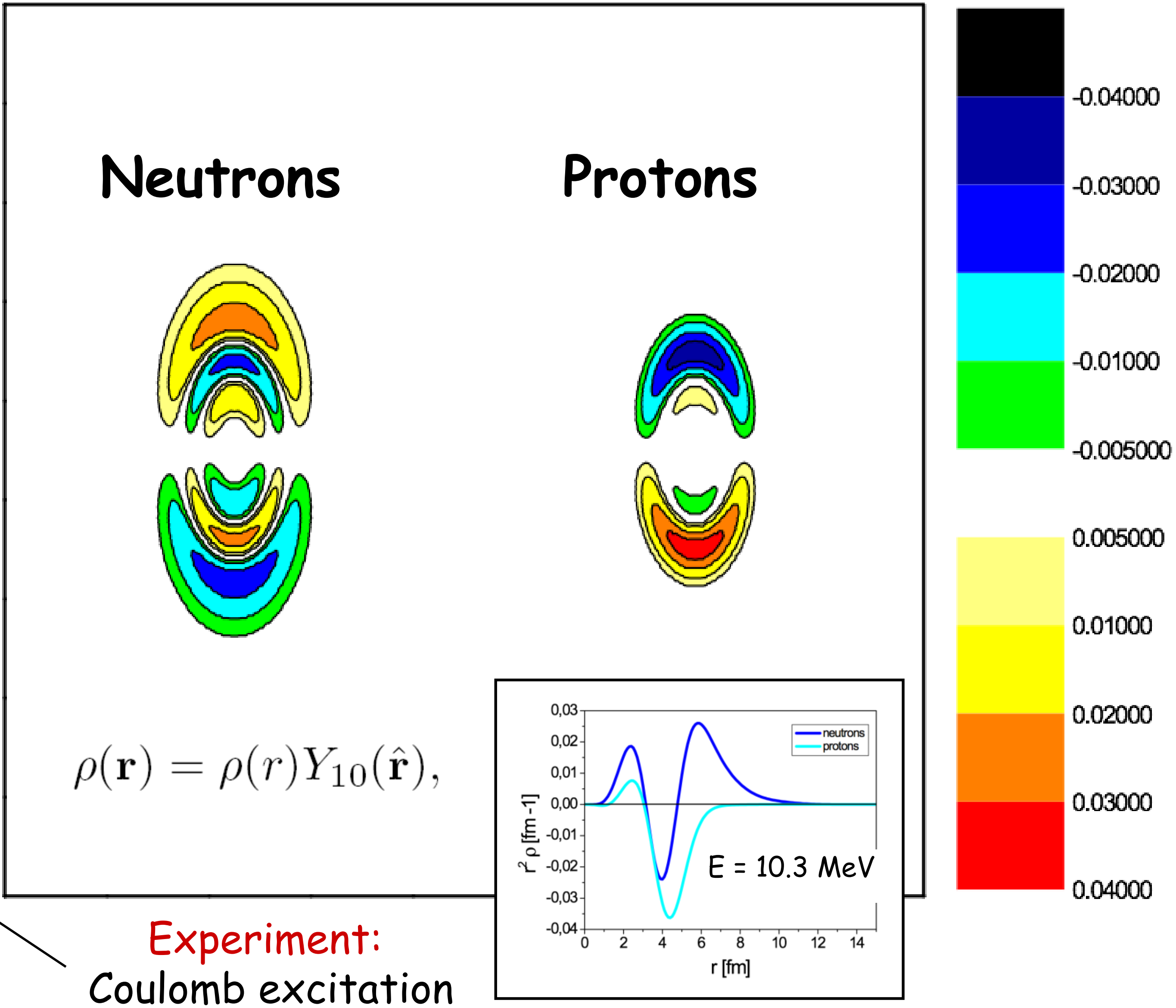


E.L., P.Ring, V.Tselyaev,
PRL 105, 02252 (2010)

Experiment:



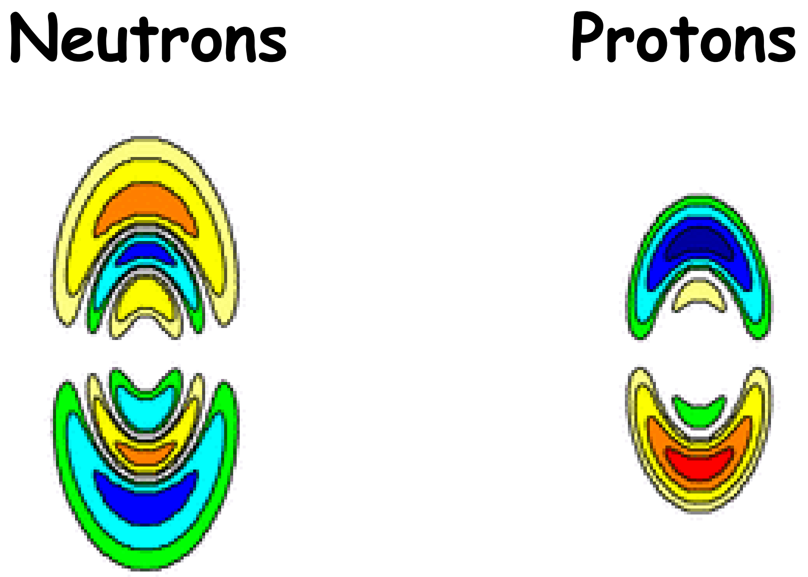
O.Wieland et al.,
PRL 102, 092502 (2009)

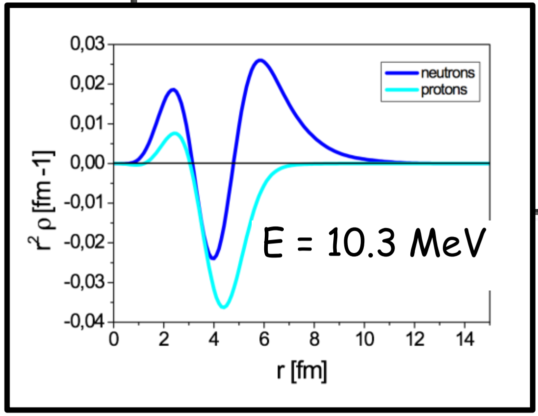


$$\rho(\mathbf{r}) = \rho(r) Y_{10}(\hat{\mathbf{r}}),$$

Experiment:
Coulomb excitation
of ^{68}Ni at 600 AMeV

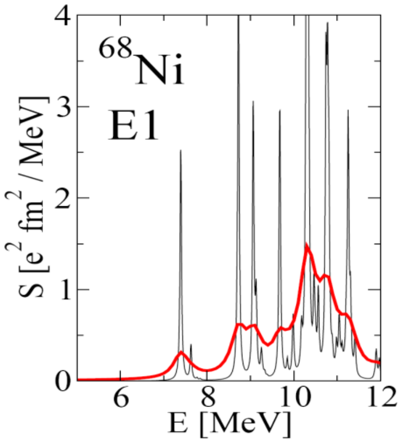
RQTBA dipole transition densities in ^{68}Ni at 10.3 MeV





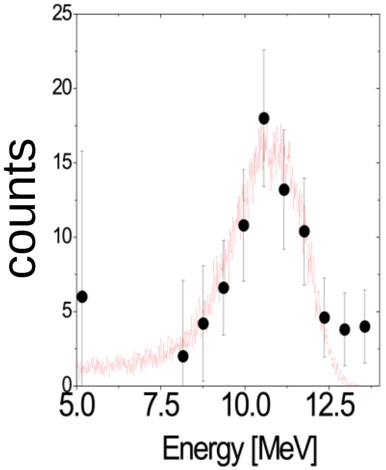
$$\rho(\mathbf{r},t) = \rho(r)Y_{10}(\hat{\mathbf{r}})e^{i\omega t}$$

Theory: RQTBA-2



E.L., P.Ring, V.Tselyaev,
PRL 105, 02252 (2010)

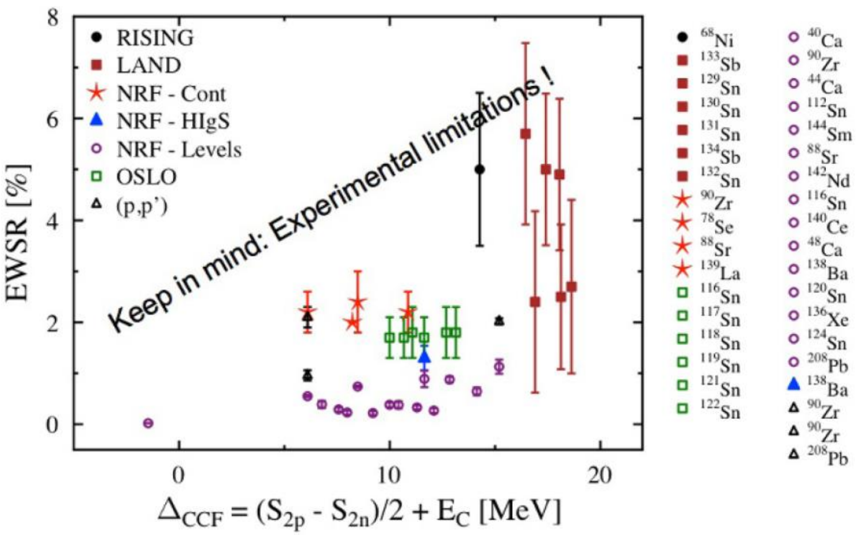
Experiment:

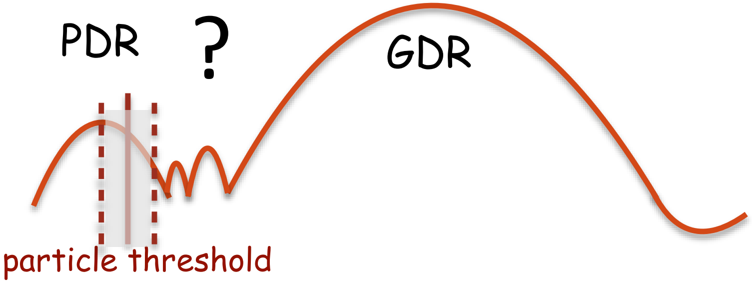


O.Wieland et al.,
PRL 102, 092502 (2009)

Experimental vs theoretical systematics of the pygmy dipole resonance

Experimental systematics:
various measurements



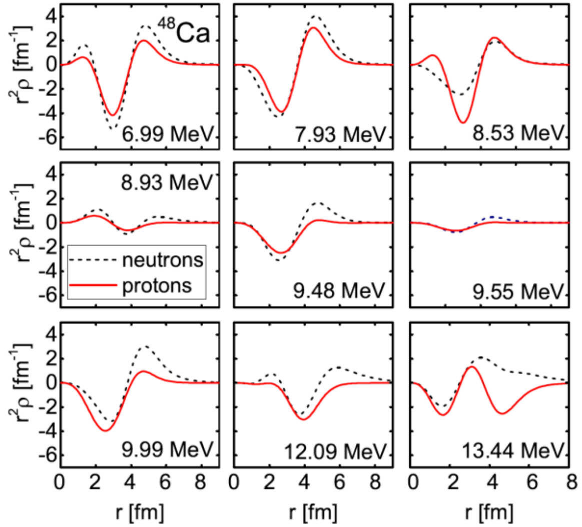


D. Savran, T. Aumann, A. Zilges,
Prog. Part. Nucl. Phys. 70, 210 (2013) } EM vs hadron probes

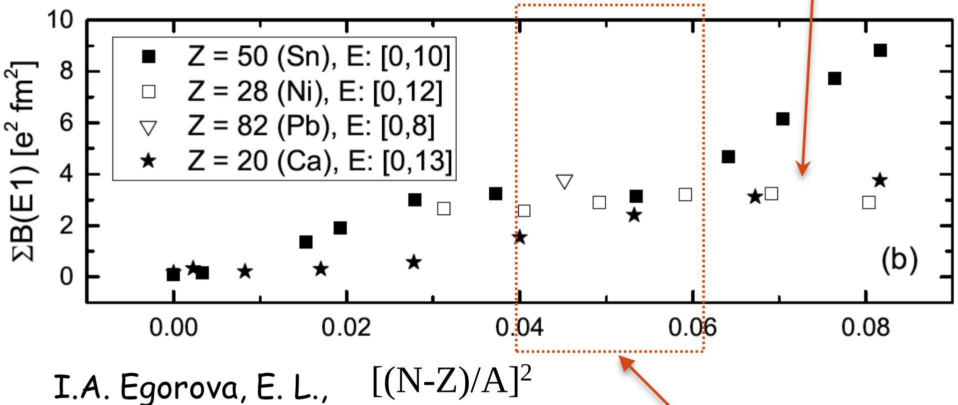
A. Tamii et al., PRL 107, 062502 (2011)
A. Krumbholtz, PLB 744, 7 (2015) } polarized (p,p')

Theoretical systematics:

- Consistent calculations within the same framework
- Accurate separation of PDR from GDR by transition density analysis:



"Plateau" shell effects



I.A. Egorova, E. L.,
arXiv:1605.08482,
to appear in PRC (2016)

"Pure" neutron matter!

Isospin transfer response function: proton-neutron RQTBA (pn-RQTBA)

Response

$$R(\omega) = \tilde{R}^0(\omega) + \tilde{R}^0(\omega)\overline{W}(\omega)R(\omega)$$

Interaction

$$\overline{W}(\omega) = \underbrace{\underbrace{V_\rho + V_\pi + V_{\delta\pi}} + \underbrace{\Phi(\omega)} - \underbrace{\Phi(0)}}$$

Subtraction to avoid double counting

Static: RRPA

$$\begin{cases} V_\rho(1,2) = g_\rho^2 \vec{\tau}_1\vec{\tau}_2(\beta\gamma^\mu)_1(\beta\gamma_\mu)_2 D_\rho(\mathbf{r}_1,\mathbf{r}_2) \\ V_\pi(1,2) = -\Big(\dfrac{f_\pi}{m_\pi}\Big)^2 \vec{\tau}_1\vec{\tau}_2(\mathbf{\Sigma}_1\nabla_1)(\mathbf{\Sigma}_2\nabla_2)D_\pi(\mathbf{r}_1,\mathbf{r}_2), \end{cases}$$

very small

free-space coupling:

Dynamic (retardation):

quasiparticle-vibration coupling

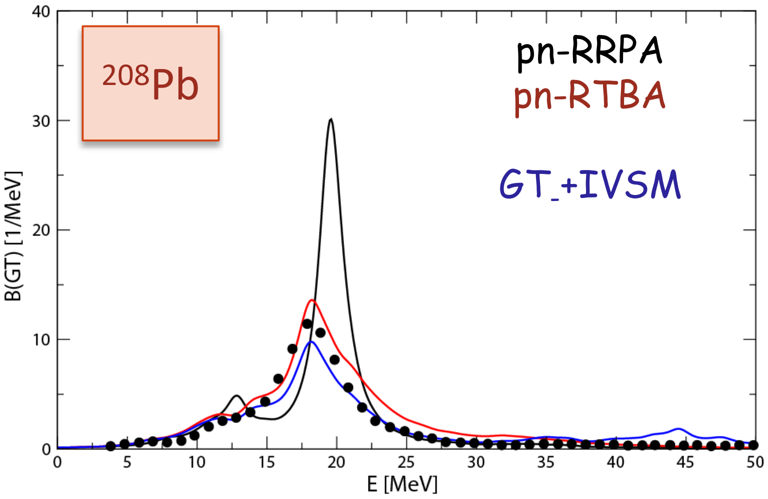
in time blocking approximation

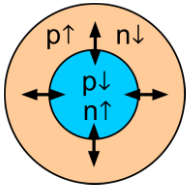
$$\boxed{\begin{aligned} &\Phi^{\eta}_{k_1k_4,k_2k_3}(\omega) = \\ &= \sum_{\mu\xi}\delta_{\eta\xi}\Big[\delta_{k_1k_3}\sum_{k_6}\frac{\gamma^{\eta;-\xi}_{\mu;k_6k_2}\gamma^{\eta;-\xi*}_{\mu;k_6k_4}}{\eta\omega - E_{k_1} - E_{k_6} - \Omega_\mu} + \delta_{k_2k_4}\sum_{k_5}\frac{\gamma^{\eta;\xi}_{\mu;k_1k_5}\gamma^{\eta;\xi*}_{\mu;k_3k_5}}{\eta\omega - E_{k_5} - E_{k_2} - \Omega_\mu} \\ &\qquad - \Big(\frac{\gamma^{\eta;\xi}_{\mu;k_1k_3}\gamma^{\eta;-\xi*}_{\mu;k_2k_4}}{\eta\omega - E_{k_3} - E_{k_2} - \Omega_\mu} + \frac{\gamma^{\eta;\xi*}_{\mu;k_3k_1}\gamma^{\eta;-\xi}_{\mu;k_4k_2}}{\eta\omega - E_{k_1} - E_{k_4} - \Omega_\mu}\Big)\Big] \end{aligned}}$$

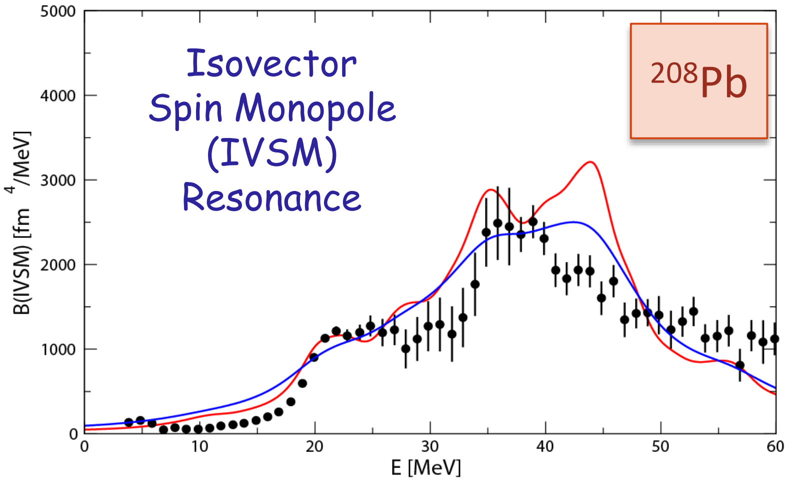
Gamow-Teller resonance from closed-shell to open-shell: superfluid pairing and phonon coupling

Closed shell, stable

$$P = \sum_i \sigma^{(i)} \tau_{\pm}^{(i)}$$

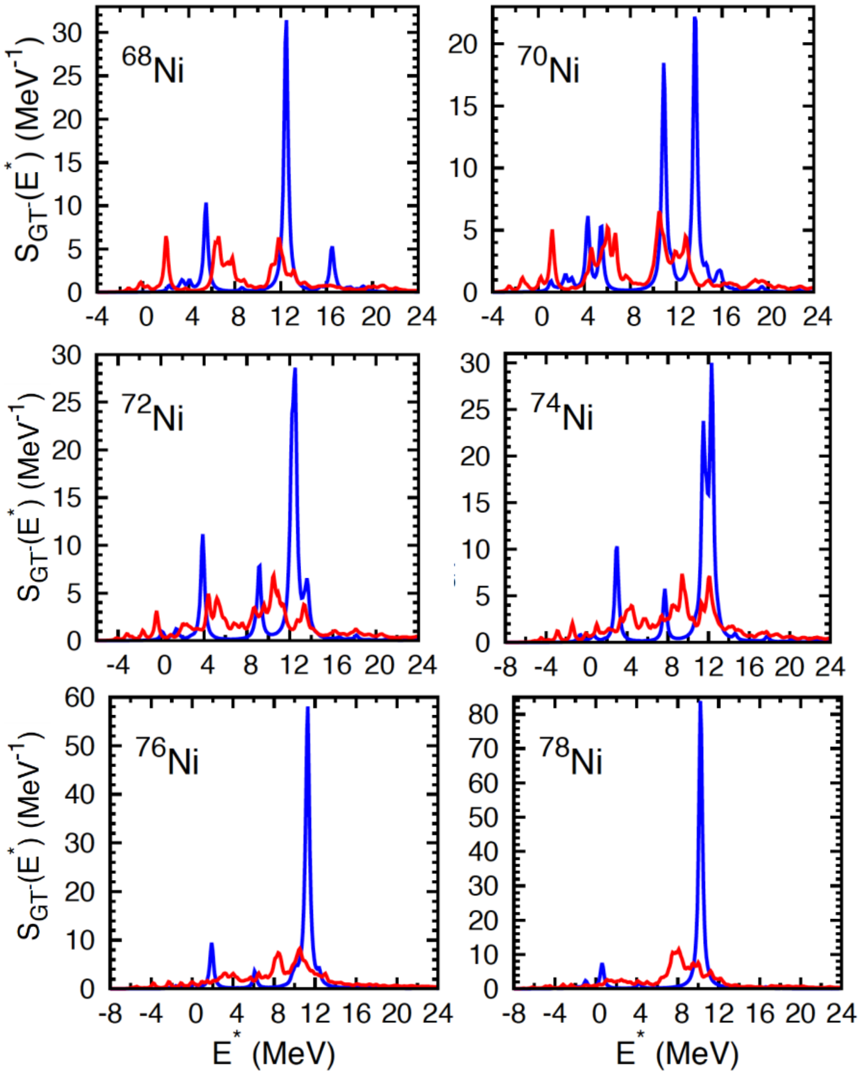






E.L., B.A. Brown, D.-L. Fang, T. Marketin, R.G.T. Zegers, PLB 730, 307 (2014)

Open shell, neutron rich



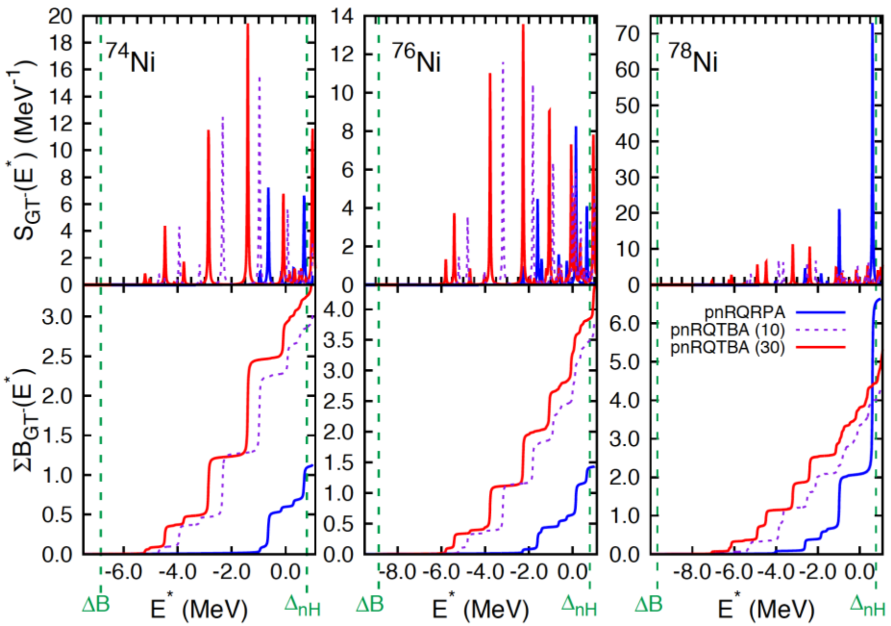
pn-RQRPA

pn-RQTBA

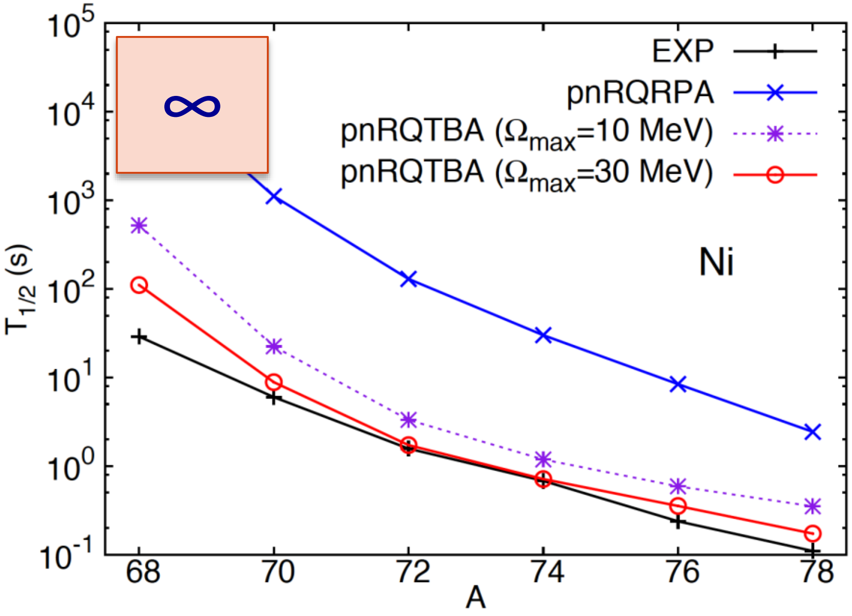
C. Robin, E.L., arXiv:1605.00683, to appear in Eur. Phys. J. A (2016)

Beta decay half-lives in Ni isotopic chain

Low-energy GT strength



Beta decay half-lives:



$$\frac{1}{T_{1/2}} = \sum_m \lambda_{if}^m = D^{-1} g_A^2 \sum_m \int dE_e \left| \sum_{pn} < 1_\lambda^+ || \boldsymbol{\sigma} \tau_- || 0^+ > \right|^2 \frac{dn_m}{dE_e}$$

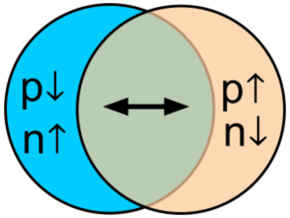
- For the 1st time a quantitative self-consistent description of $T_{1/2}$ without artificial quenching or other parameters is achieved
- Both phases of r-process can be computed within the same framework of high predictive power
- Description of the rp-process (on the proton-rich side) is available

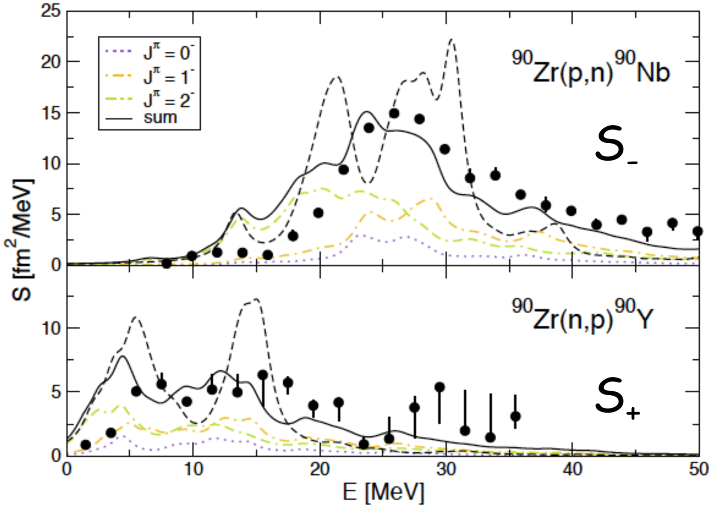
C. Robin, E.L., arXiv:1605.00683, to appear in Eur. Phys. J. A (2016)

Spin-dipole resonance: beta-decay, electron capture

T. Marketin, E.L., D. Vretenar, P. Ring,
PLB 706, 477 (2012).

$$P_{\pm}^{\lambda} = \sum_{i} r(i)\,[\boldsymbol{\sigma}(i) \otimes Y_1(i)]_{\lambda}\, t_{\pm}(i)$$





------- RRPA

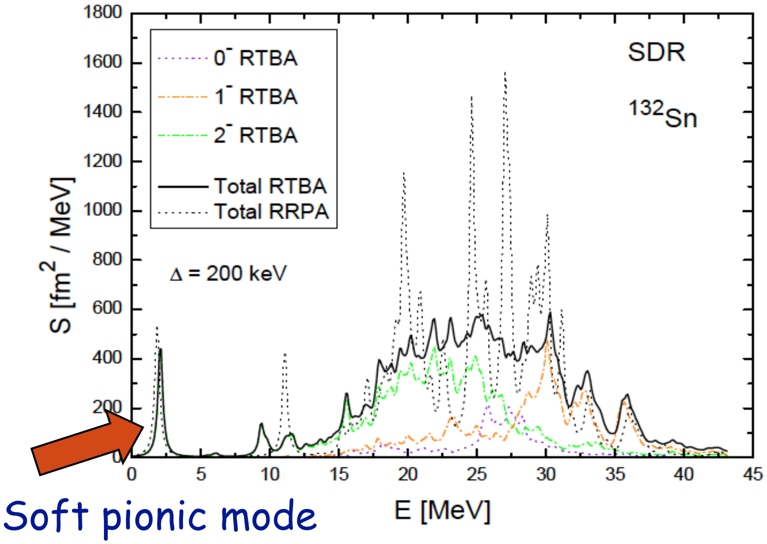
—— RTBA

$\Delta L = 1$
$\Delta T = 1$
$\Delta S = 1$
$\lambda = 0,1,2$

Earlier studies;

W.H. Dickhoff et al., PRC 23, 1154 (1981)
J. Meyer-Ter-Vehn, Phys. Rep. 74, 323 (1981)
A.B. Migdal et al., Phys. Rep. 192, 179 (1990)

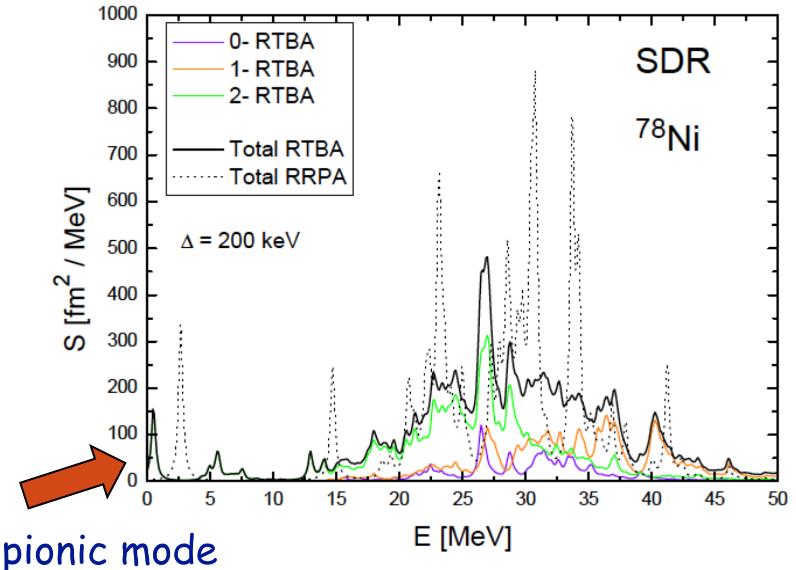
Existence of low-lying unnatural parity states indicates that nuclei are close to the pion condensation point. However, it is not clear which observables are sensitive to this phenomenon.



Soft pionic mode

Only nuclear matter and doubly-magic nuclei were studied…

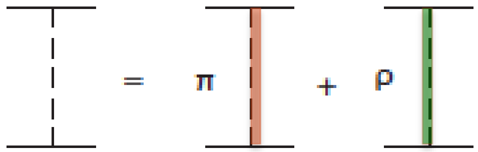
Now: In some exotic nuclei 2- states are found at very low energy. Similar situation with 0-, 4-, 6-,… states.



Soft pionic mode

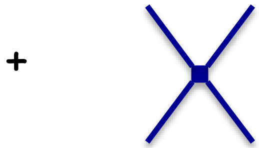
Isovector part of the interaction: diagrammatic expansion

IV interaction: pion ρ-meson



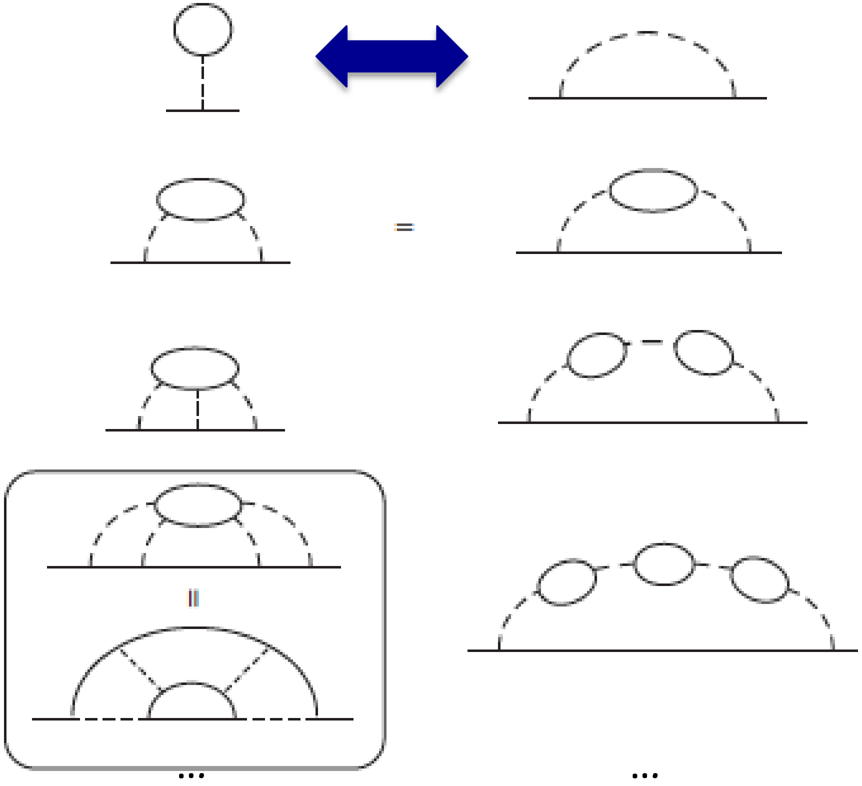
Free-space pseudovector coupling

RMF-Renormalized



Landau-Migdal contact term (g′-term)

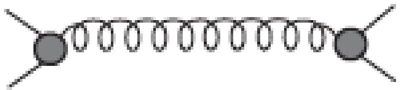
Fixed strength



Transverse (cross) channel

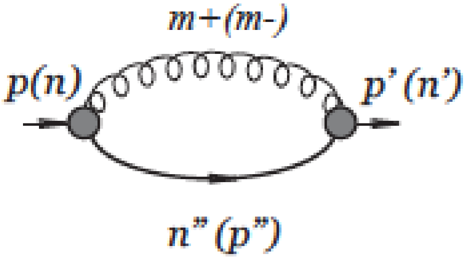
Longitudinal (direct) channel

Infinite sum:



Isovector phonon

Self-energy contribution

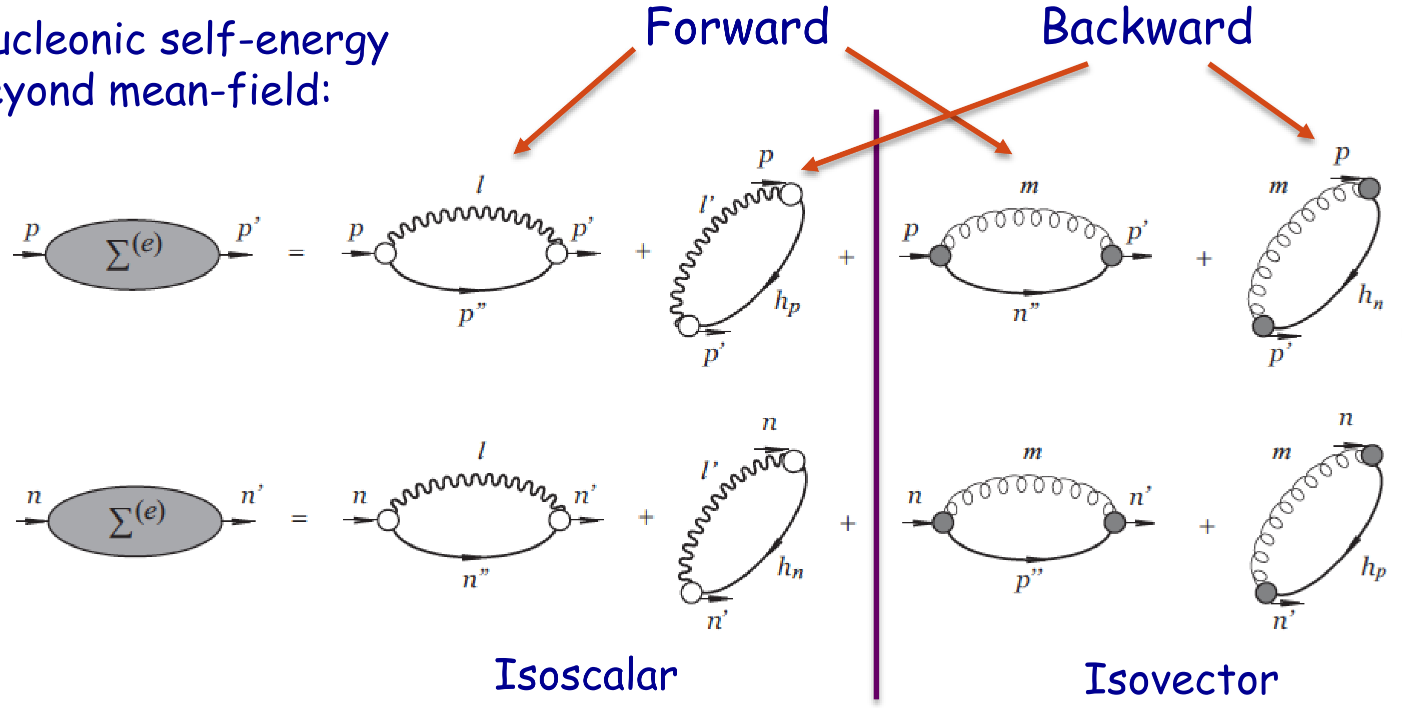


Low-lying states in ΔT=1 channel and nucleonic self-energy

$$(N,Z) \rightleftarrows (N+1,Z-1)$$

In spectra of neighboring odd-odd nuclei we see low-lying (collective) states with natural and unnatural parities: 0+, 0-, 1+, 1-, 2+, 2-, 3+, 3-,… Their contribution to the nucleonic self-energy is expected to affect single-particle states:

Nucleonic self-energy beyond mean-field:


Forward

Backward

Isoscalar

Isovector

Underlying Mechanism for pn-pairing or T=0 pairing

$$\Sigma^{(e)\eta_1\eta_2}_{k_1k_2}(\varepsilon) = \sum_{\eta=\pm1}\sum_{k,\mu}\frac{\gamma^{\eta;\eta_1\eta}_{\mu;k_1k}\;\gamma^{\eta;\eta_2\eta*}_{\mu;k_2k}}{\varepsilon-\eta(E_k+\Omega_\mu-i\delta)}$$

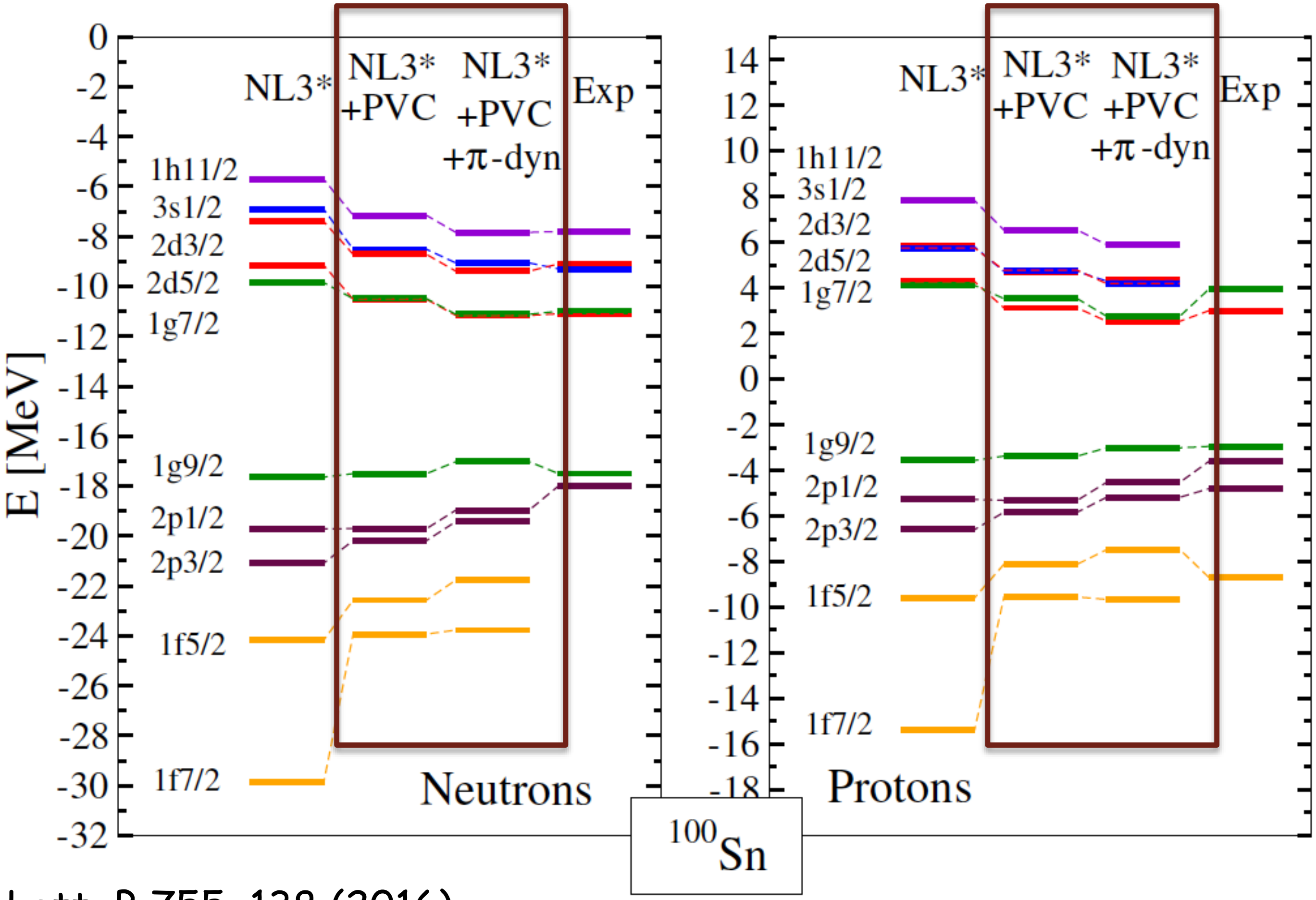
Matrix element in Nambu space

Single-particle states in 100-Sn: effects of pion dynamics

Truncation scheme: phonons below 20 MeV

Phonon basis: T=0 phonons: 2+, 3-, 4+, 5-, T=1 phonons: 0, ±1±, 2±, 3±, 4±, 5±, 6±

Converged



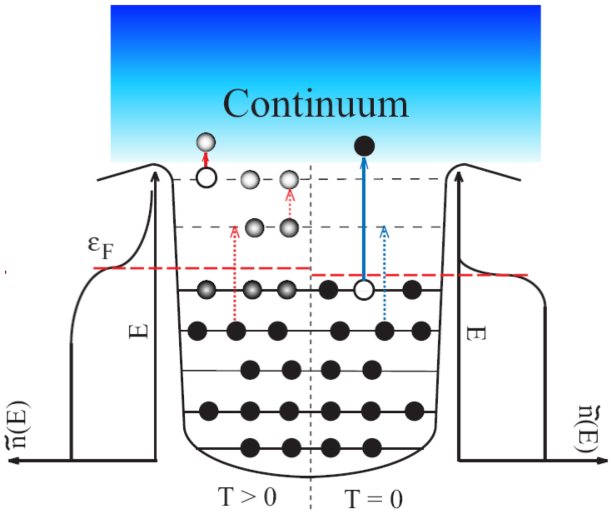
E.L., Phys. Lett. B 755, 138 (2016)

Next step: pionic ground state correlations (backward going diagrams), in progress

Nuclear dipole response at finite temperature

$$\tilde{n}_i(E_i,T) = (1 - v_i^2(T))n_i(E_i,T)$$

$$\tilde{n}_i(E_i,T) = v_i^2(T)(1 - n_i(E_i,T))$$



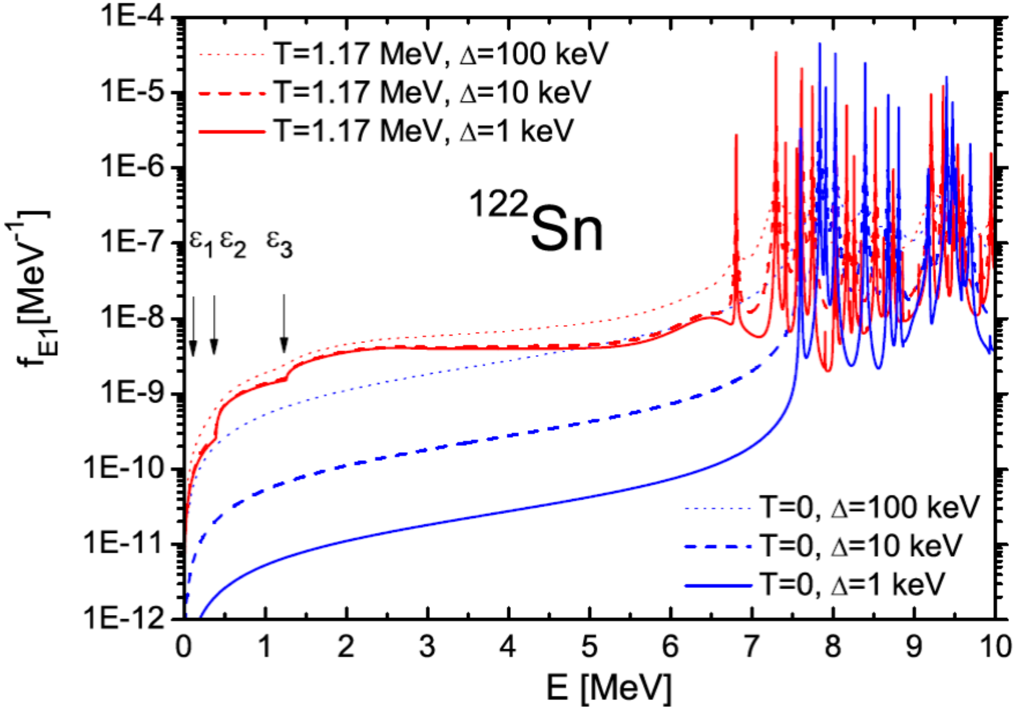
$$v_i^2$$

1. Saturation of the strength with Δ at Δ = 10 keV for T>0

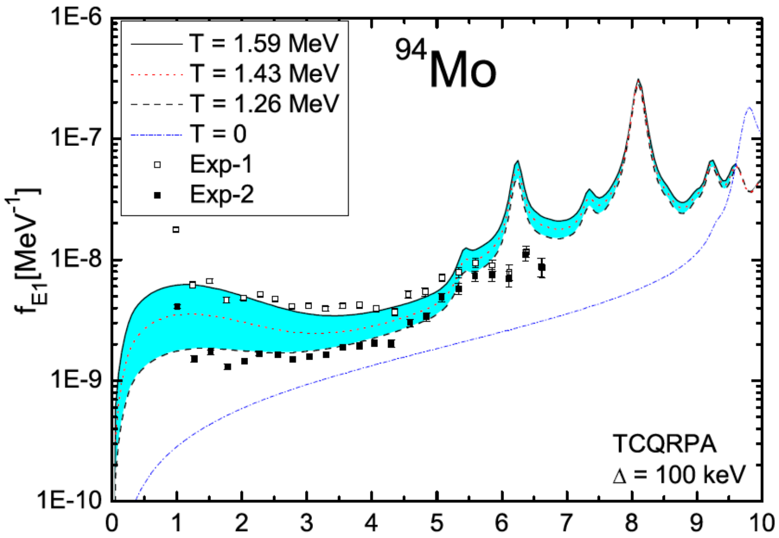
2. The low-energy strength is not a tail of the GDR and not a part of PDR

3. The nature of the strength at E_γ-> 0 is continuum transitions from the thermally unblocked states

4. Spurious translation mode should be eliminated exactly



Low-energy limit of the RSF in even-even Mo isotopes



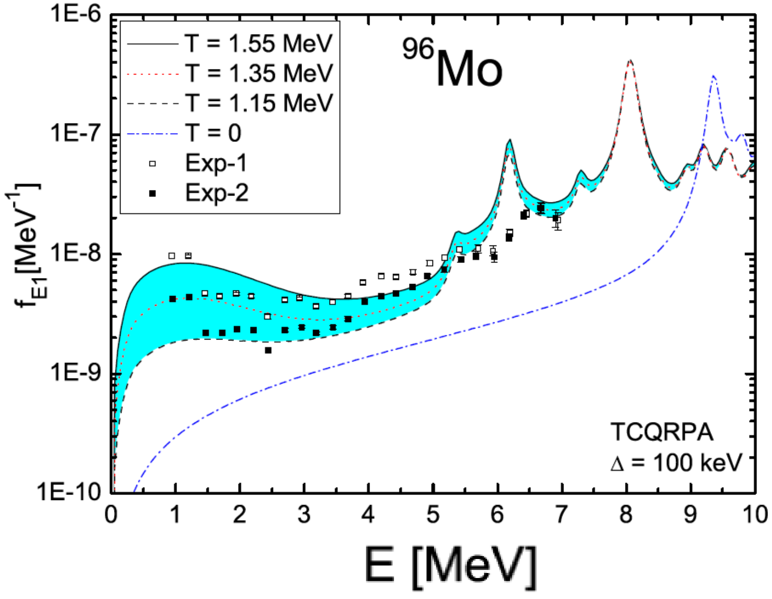
$$T = \sqrt{(E^* - \delta)/a}$$

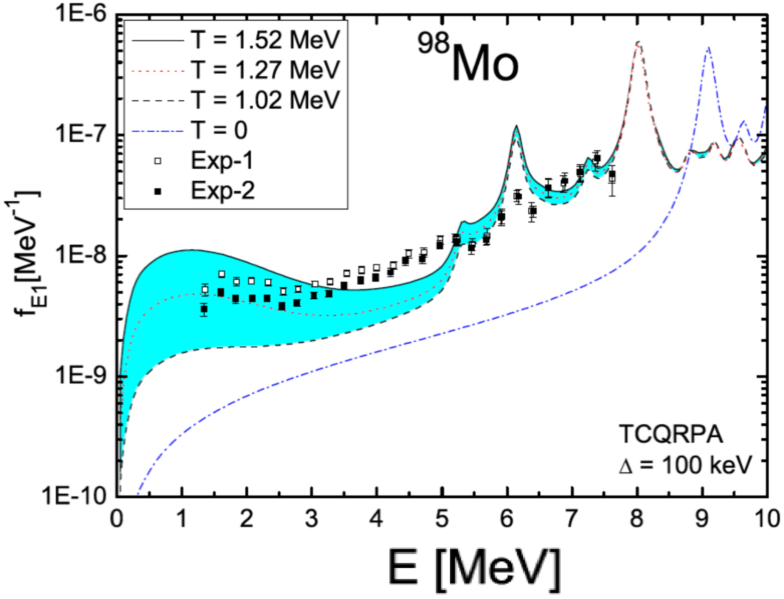
$a = a_{EGSF}$ => T_{min} (RIPL-3)

$a = \pi^2(g_\nu + g_\pi)/6$ ®T_{max}

(microscopic)

Exp-1: NLD norm-1,
M. Guttormsen et al., PRC 71, 044307 (2005)
Exp-2: NLD norm-2,
S. Goriely et al., PRC 78, 064307 (2008)





Theory: E. L., N. Belov,
PRC 88, 031302(R)(2013)

Data: A.C. Larsen, S. Goriely, PRC 014318 (2010)

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Lecture notes and slides:

- TALENT Courses 2013-2016: http://www.nucleartalent.org
- A. Volya, Exotic Beam Summer School 2015: http://aruna.physics.fsu.edu/ebss_lectures/EBSS2015_Schedule.html
- J.D. Holt, A. Poves, R. Roth, 2015 TRIUMF Summer Institute: http://tsi.triumf.ca/2015/program.html
- P. Ring: http://indico2.riken.jp/indico/getFile.py/access?contribId=8&sessionId=4&resId=0&materialId=slides&confId=1450