Effects of meson-nucleon dynamics in a relativistic approach to medium-mass nuclei

Elena Litvinova

Western Michigan University

International Nuclear Physics Conference, Adelaide, Australia, September 11-16, 2016

Outline

- *Relativistic Nuclear Field Theory (RNFT) solutions to the nuclear many-body problem*

- *Recent developments: pion degrees of freedom*

- *Spin-isospin nuclear response:*
  - *Gamow-Teller resonance (GTR)*
  - *Spin-Dipole resonance and higher multipoles: the onset of pion condensation in medium-mass nuclei*

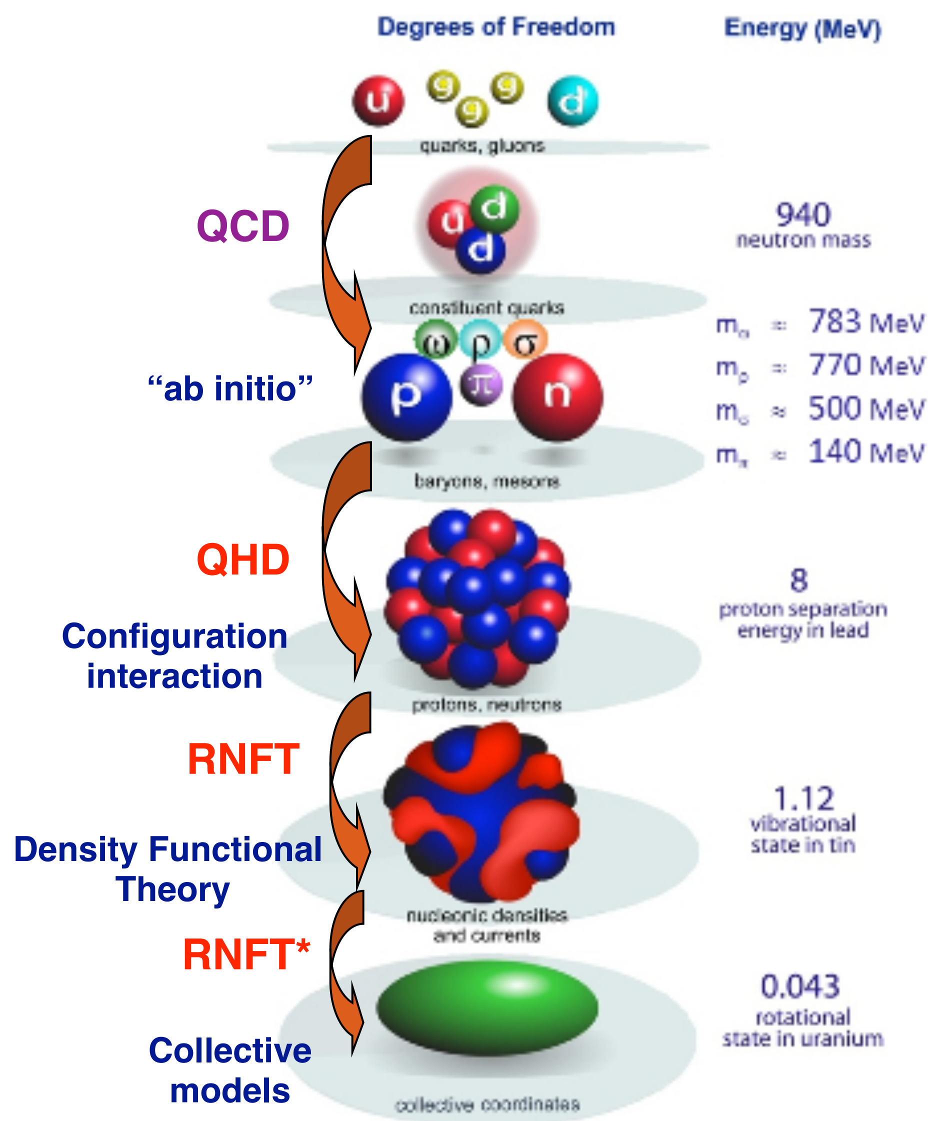
- *Pion-exchange contributions to the nucleonic self-energy:*
  - *Shell structure of tin isotopes*

- *Conclusions and perspectives*

Relativistic Nuclear Field Theory (RNFT):

- *RNFT as a solution: microscopic, universal, connecting scales from Quantum Hadrodynamics to emergent collective phenomena*
- *Lagrangian for mesons and nucleons constrained by QCD symmetries and sum rules*
- *Lorentz covariance: ~5-10% accuracy at the excitation energy of interest (grows with energy)*
- *Spin-orbit and tensor "forces" are naturally included*
- *Fewer parameters; hidden correlations minimized (4-10 universal parameters)*
- *Natural extension to the inclusion of the delta isobar, to higher excitation energy ~200-300 MeV and to hypernuclei*
- *Non-perturbative self-consistent response theory with high-order NN correlations*

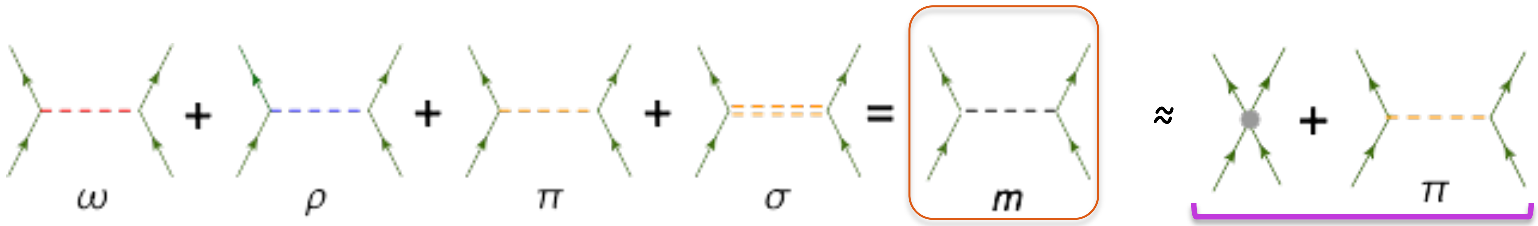
Nuclear scales



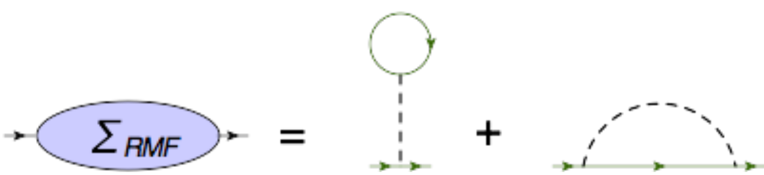
Systematic expansion in the RNFT: single-nucleon self-energy

Quantum Hadrodynamics

(QHD)



χEFT

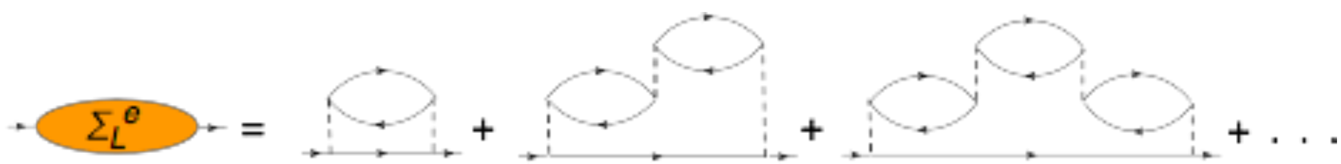


Explicit

Explicit
or implicit
(Fierz transformation)

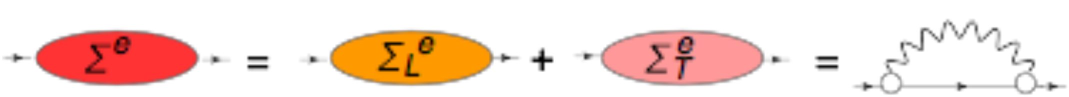
Hartree-
Fock
(HF)

- Adjusting masses and couplings at HF level (CDFT)
- Brueckner-HF (from bare interaction)



Explicit

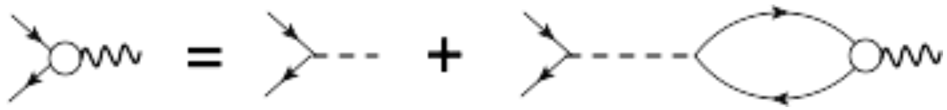
Explicit
or implicit



Quasiparticle-vibration
coupling (QVC)

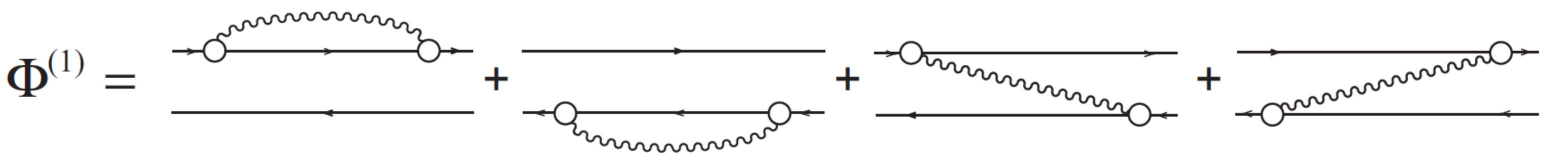
Systematic expansion in the RNFT: nuclear response function

Vibration (phonon) vertex:

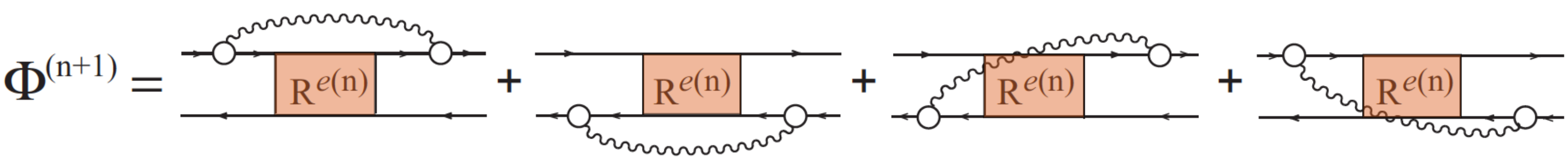


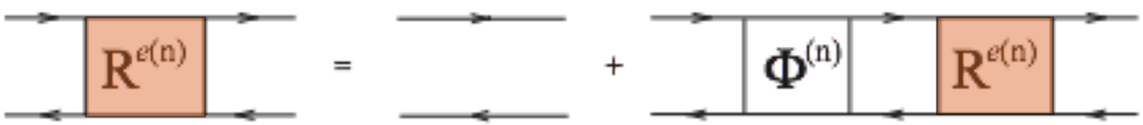
Relativistic (Quasiparticle) Random Phase Approximation (QRPA)

2q+phonon coupling amplitude:



2q+Nphonon coupling amplitude:





Correlated propagator

Response function

E.L. PRC 91, 034332 (2015)

Isospin transfer response function: proton-neutron relativistic quasiparticle time blocking approximation (pn-RQTBA)

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

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

Static: R(Q)RPA

$$V_\rho(1,2) = g_\rho^2 \vec{\tau}_1\vec{\tau}_2(\beta\gamma^\mu)_1(\beta\gamma_\mu)_2 D_\rho(\mathbf{r}_1,\mathbf{r}_2)$$

$$V_\pi(1,2) = -\Big(\frac{f_\pi}{m_\pi}\Big)^2 \vec{\tau}_1\vec{\tau}_2(\mathbf{\Sigma}_1\nabla_1)(\mathbf{\Sigma}_2\nabla_2)D_\pi(\mathbf{r}_1,\mathbf{r}_2)$$

$$V_{\delta\pi}(1,2) = g'\Big(\frac{f_\pi}{m_\pi}\Big)^2 \vec{\tau}_1\vec{\tau}_2\mathbf{\Sigma}_1\mathbf{\Sigma}_2\delta(\mathbf{r}_1-\mathbf{r}_2)$$

free-space coupling:

fixed strength

Dynamic (retardation), 2-nd order:

quasiparticle-vibration coupling

in time blocking approximation

$$\Phi^\eta_{k_1k_4,k_2k_3}(\omega) =$$

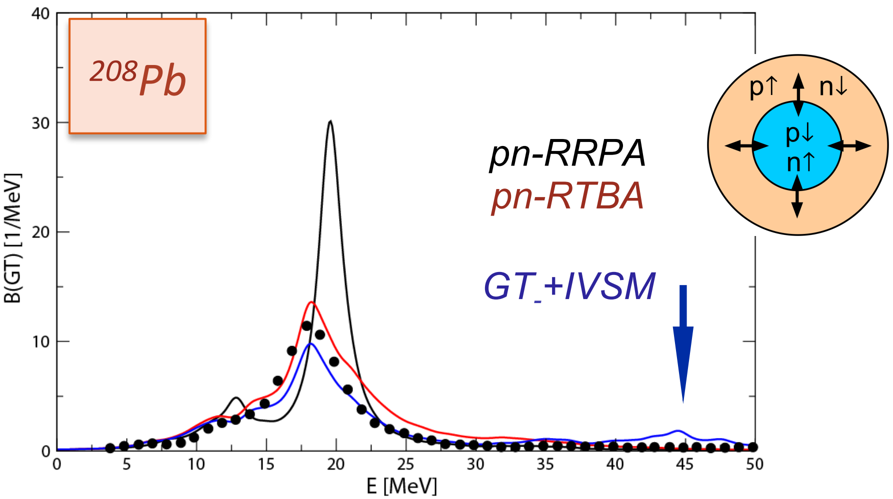
$$= \sum_{\mu\xi}\delta_{\eta\xi}\Big[\delta_{k_1k_3}\sum_{k_6}\frac{\gamma^{\eta;-\xi}_{\mu;k_6k_2}\gamma^{\eta;-\xi*}_{\mu;k_6k_4}}{\eta\omega - E_{k_1} - E_{k_6} - \Omega_\mu} + \delta_{k_2k_4}\sum_{k_5}\frac{\gamma^{\eta;\xi}_{\mu;k_1k_5}\gamma^{\eta;\xi*}_{\mu;k_3k_5}}{\eta\omega - E_{k_5} - E_{k_2} - \Omega_\mu}$$

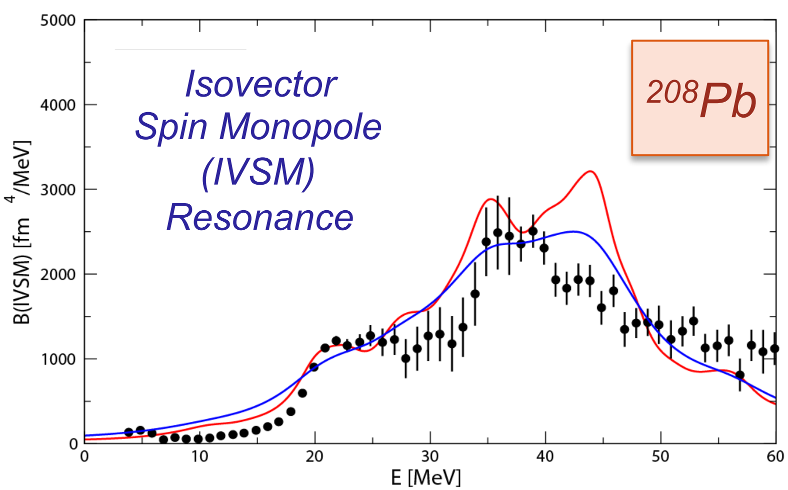
$$-\Big(\frac{\gamma^{\eta;\xi}_{\mu;k_1k_3}\gamma^{\eta;-\xi*}_{\mu;k_2k_4}}{\eta\omega - E_{k_3} - E_{k_2} - \Omega_\mu} + \frac{\gamma^{\eta;\xi*}_{\mu;k_3k_1}\gamma^{\eta;-\xi}_{\mu;k_4k_2}}{\eta\omega - E_{k_1} - E_{k_4} - \Omega_\mu}\Big)\Big]$$

Spin-isospin excitations in proton-neutron relativistic time blocking approximation (pn-RTBA)

Gamow-Teller resonance

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





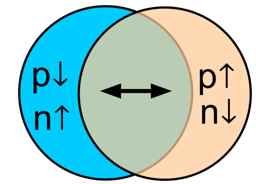
E.L., B.A. Brown, D.-L. Fang, T. Marketin, R.G.T. Zegers, PLB 730, 307 (2014)

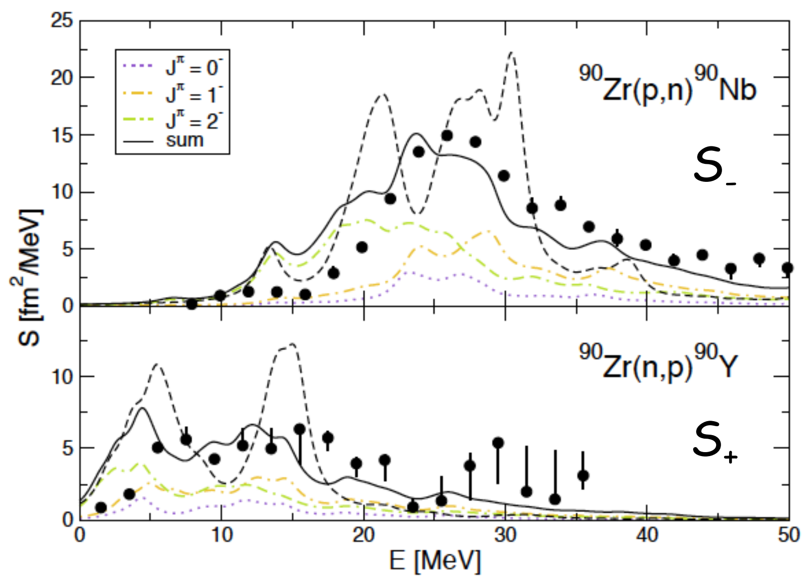
Spin-dipole resonance

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

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

- - - - -	pn-RRPA
———	pn-RTBA



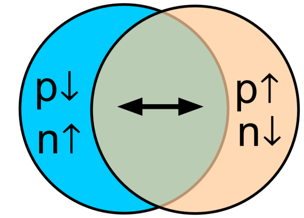


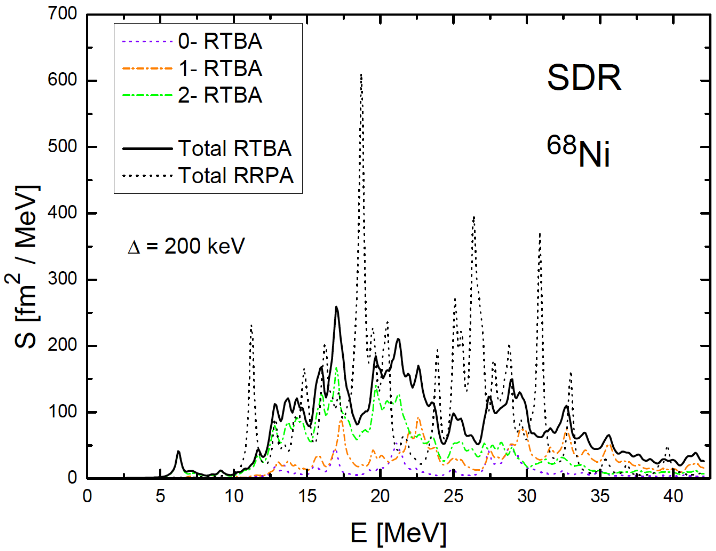
T. Marketin, E.L., D. Vretenar, P. Ring, PLB 706, 477 (2012).

Spin-isospin response in open-shell nuclei: see talk of Caroline Robin tomorrow afternoon at Nuclear Structure A

Spin-dipole resonance in neutron-rich nuclei

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



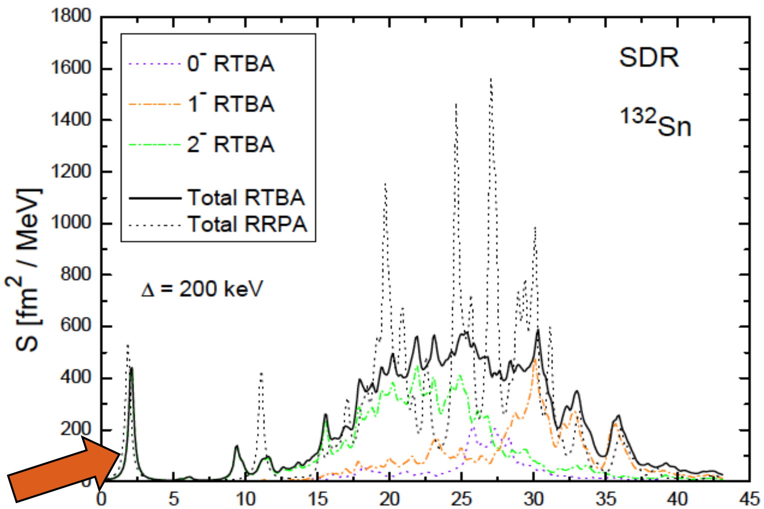


ΔL = 1
ΔT = 1
ΔS = 1
λ = 0,1,2

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)

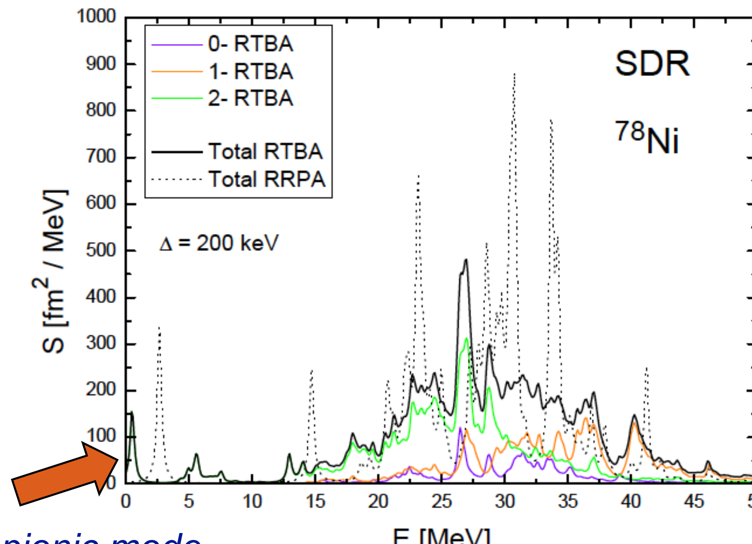
Existence of low-lying unnatural parity states indicates that nuclei are close to the pion condensation point. However, it is not clear which observables are sensitive to this phenomenon.



2- 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.



2- Soft pionic mode

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

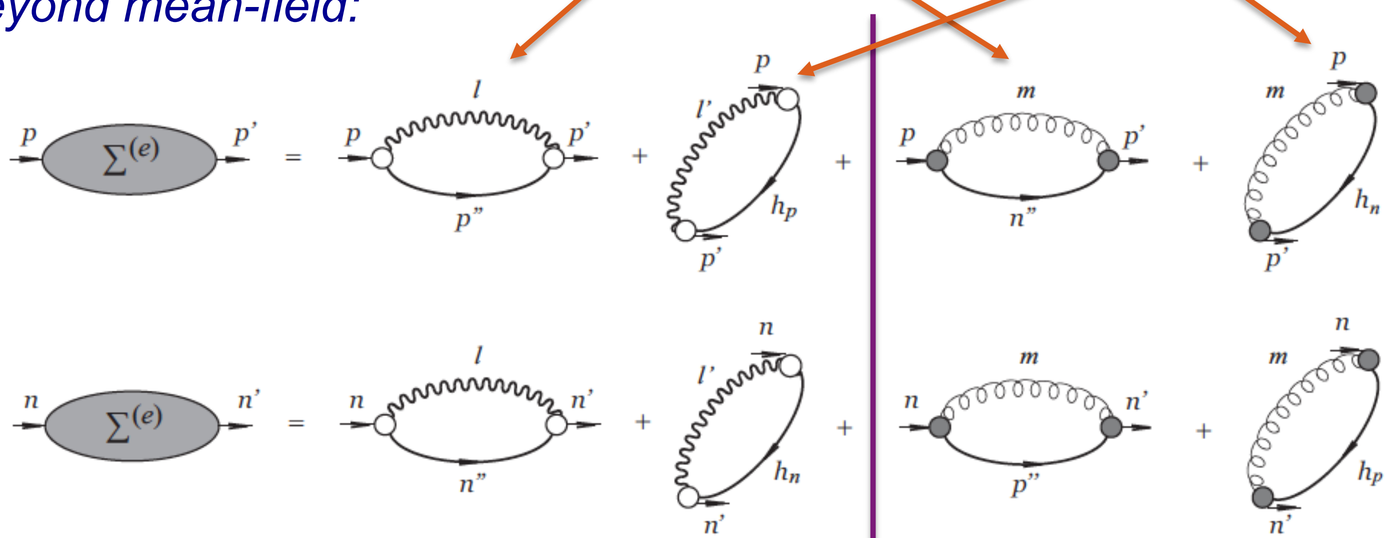
$(N,Z) \rightleftarrows (N+1,Z-1)$

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

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

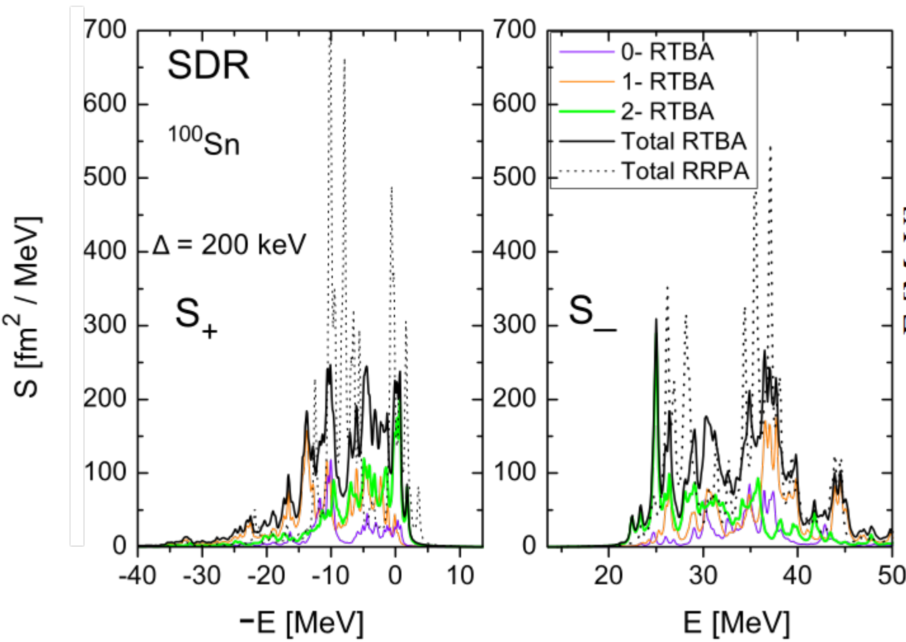
Matrix element in Nambu space

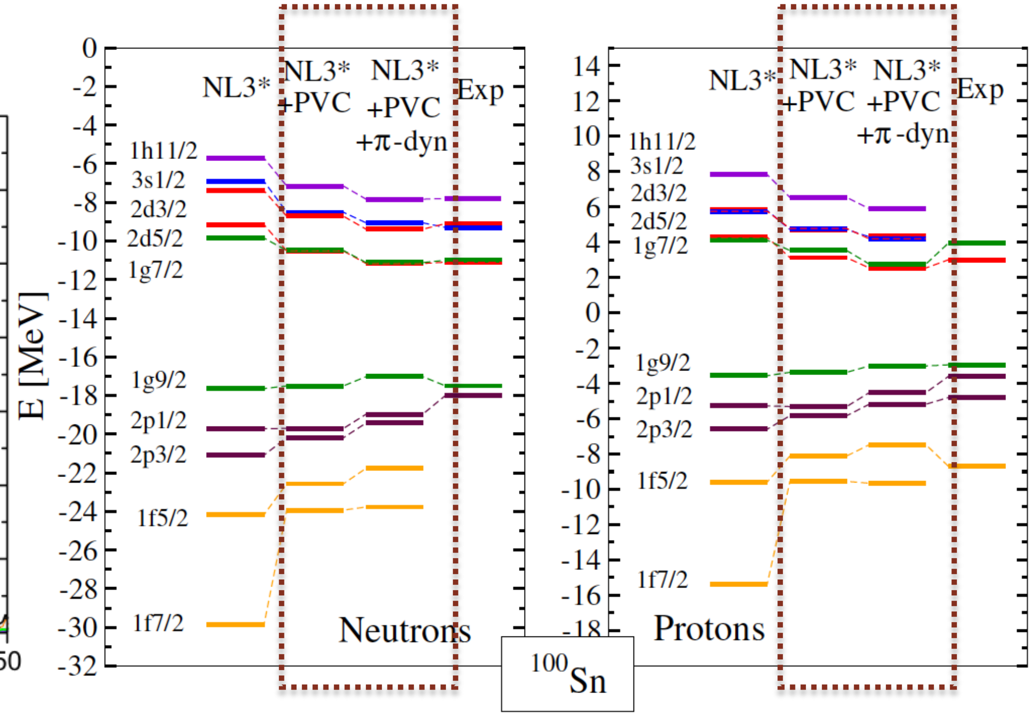
Single-particle states in 100-Sn: effects of pion dynamics

Truncation scheme: phonons below 20 MeV
Phonon basis: ΔT=0 phonons: 2+, 3-, 4+, 5-, 6+
ΔT=1 phonons: 0±, 1±, 2±, 3±, 4±, 5±, 6±
converged

Single-particle states:

0^-, 1^-, 2^- states in ^{100}Sn





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

Next step: isovector ground state correlations (backward going diagrams), in progress. Influence on GTR: see talk of Caroline Robin tomorrow afternoon

Outlook

- *Relativistic NFT offers a powerful framework for the treatment of meson-nucleon correlations beyond the Hartree-Fock approximation.*

- *Non-perturbative self-consistent response theory based on QHD and including high-order correlations is available for a large class of nuclear excited states.*

- *Effects of isospin dynamics are introduced into RNFT. Pion exchange is included non-perturbatively in both shell structure and response calculations.*

- *Perspectives: dynamical proton-neutron pairing (deuteron transfer channel), higher-order ground-state correlations; deformations etc.*

Acknowledgements:

Caroline Robin (Western Michigan U)
Peter Ring (Technische Universität München)
Victor Tselyaev (St. Petersburg State U)
Tomislav Marketin (U Zagreb)
Anatoli Afanasjev (Mississippi State U)
Remco Zegers (NSCL @ Michigan State U)
Irina Egorova (Western Michigan U)
Herlik Wibowo (Western Michigan U)

Support: US-NSF Grants PHY-1204486 and PHY-1404343