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Quasiparticle-phonon coupling in relativistic framework: shell structure of Z=120 isotopes

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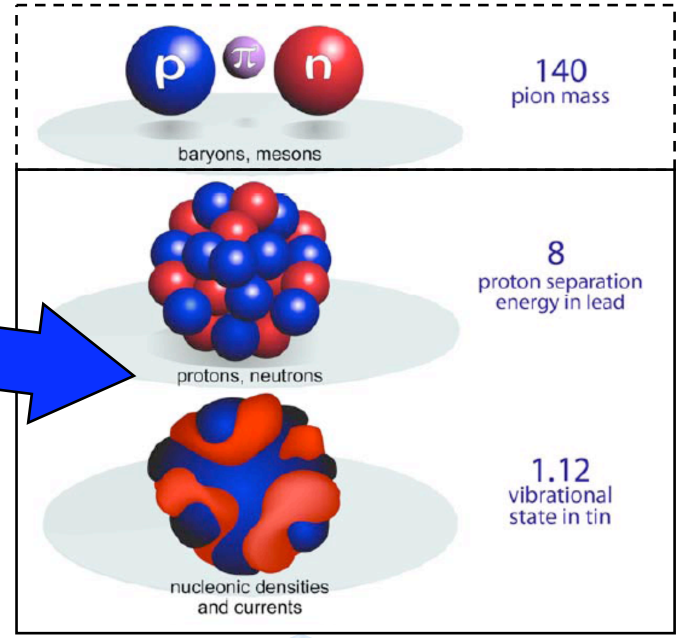
Outline

- Degrees of freedom relevant for a description of nuclear dynamics at ~1-50 MeV excitation energies: single-particle & collective (vibrational); coupling

- Approach: covariant energy density functional (CEDF) theory extended by many-body correlations (Nuclear field theory)

- Towards spectroscopic accuracy:
  Nuclear structure properties
    Nuclear single-particle structure
    Gross and fine structure of nuclear excited states: (dipole)

- Unknown region of the nuclear chart:
  Shell structure and alpha decay properties of Z=120 isotopes



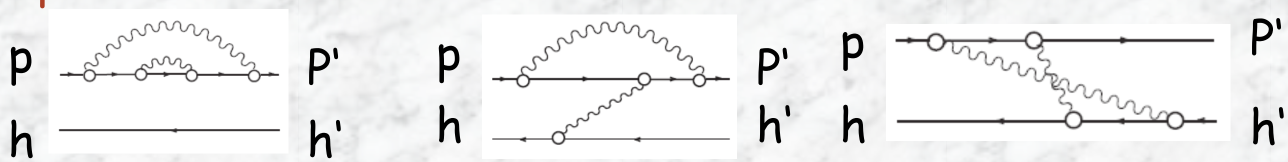
Separation of scales is useful,
but there are important effects
at the borders:
Coupling of the degrees of freedom
= overlap of scales

Dynamics of medium-mass and heavy nuclei at ~1-50 MeV excitation energies: single-particles & vibrations

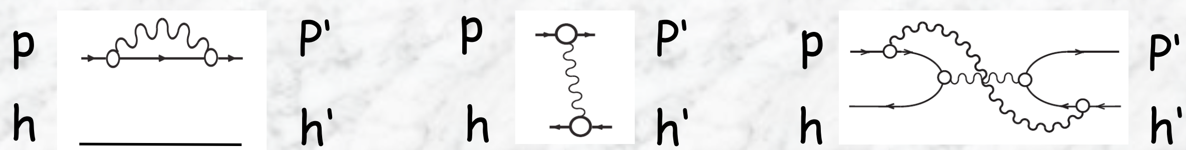
Self-consistent

NpNh:

3p3h excitations: iterative PVC — Nucleons & vibrations



2p2h excitations: Particle-Vibration Coupling (PVC) — Nucleons & vibrations

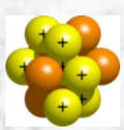


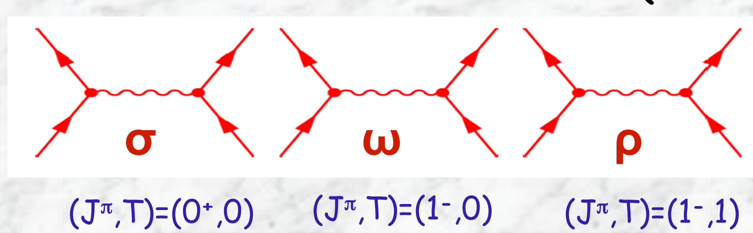
1p1h excitations: Quasiparticle Random Phase Approximation (QRPA) — Vibrations

Self-consistency

$$V = \frac{\delta^2 E[R]}{\delta R^2}$$

Ground state: Relativistic Mean Field (RMF) — Single nucleons

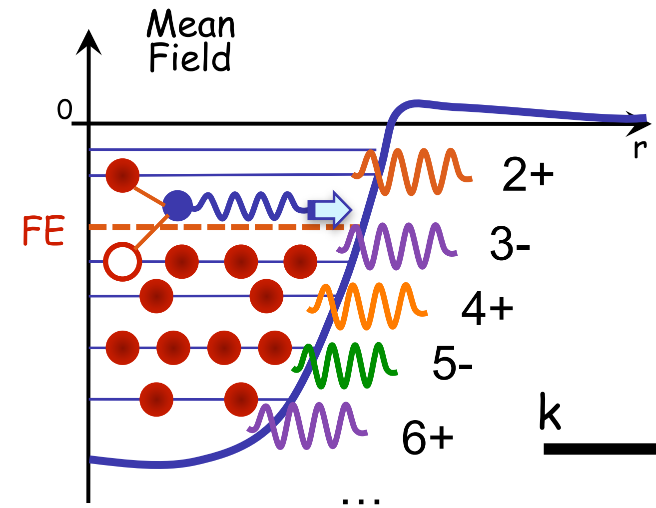




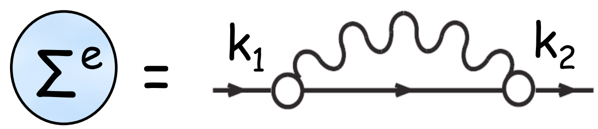
E[R]

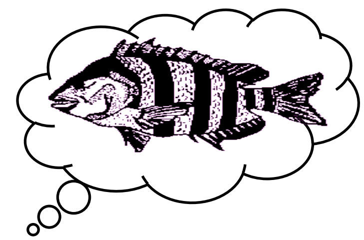
NL3, NL3*

First step beyond relativistic mean field: quasiparticles coupled to vibrations



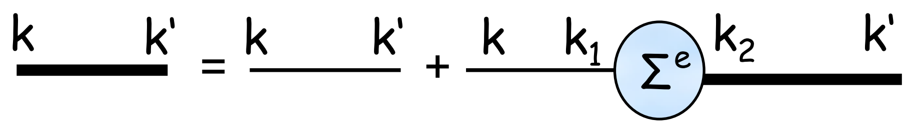
First order coupling:
additional 'potential'





"Fish" diagram

One-body propagation:



(Dyson equation)

One-body Green's function in N-body system (Lehmann):

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

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

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

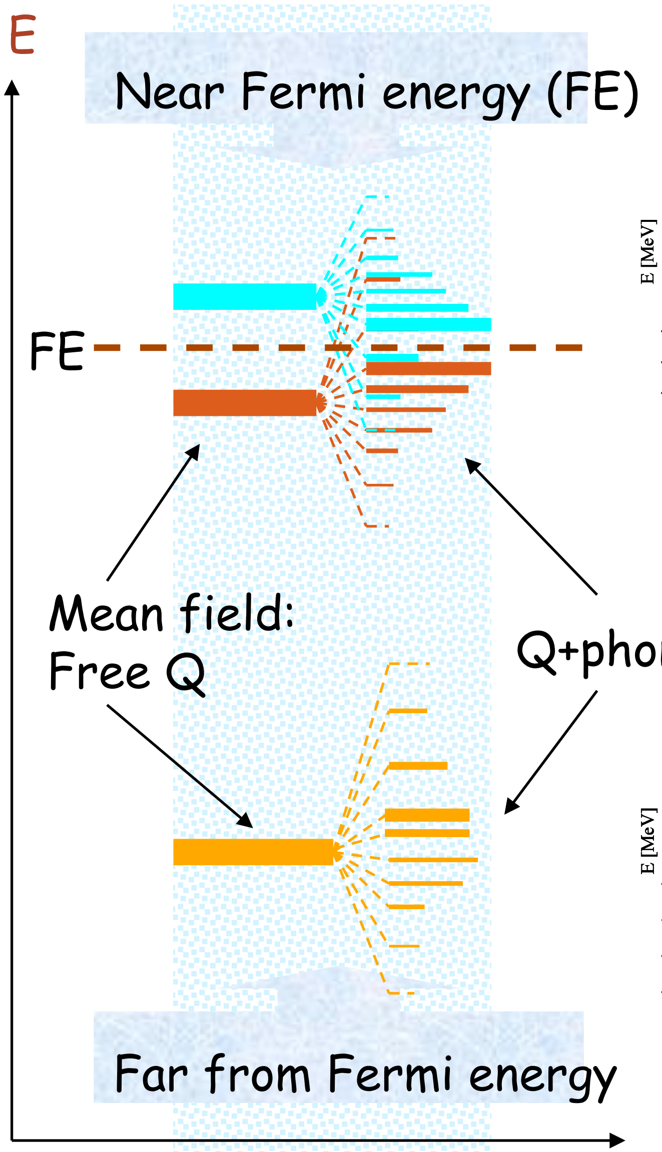
Doubled quasiparticle space:

$$\eta = \pm 1$$

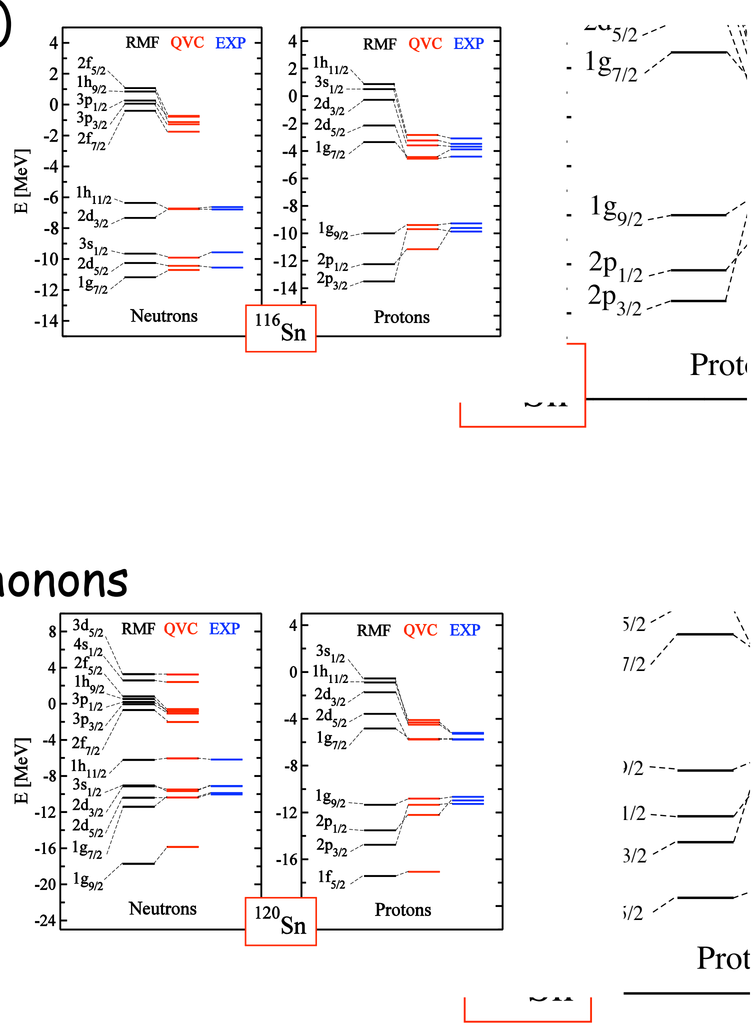
$$\Sigma^{(e)\eta_1\eta_2}_{k_1k_2}(\varepsilon) = \sum_{\eta=\pm1}\sum_{k,\mu} \frac{\gamma^{\eta;\eta_1\eta}_{\mu;k_1k}\;\gamma^{\eta;\eta_2\eta*}_{\mu;k_2k}}{\varepsilon - \eta(E_k + \Omega_\mu - i\delta)}$$

$$G^\eta_k(\varepsilon) = \sum_{\nu,\eta'} \frac{\tilde{S}^{\eta'(\nu)}_k}{\varepsilon - \eta\eta' E^{(\nu)}_k}$$

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



Level schemes

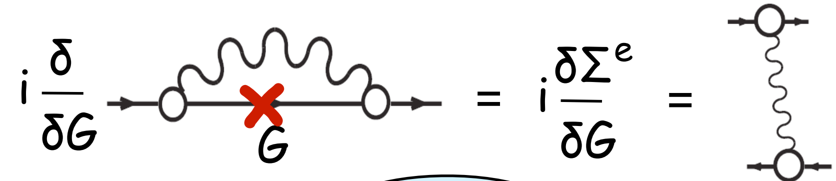


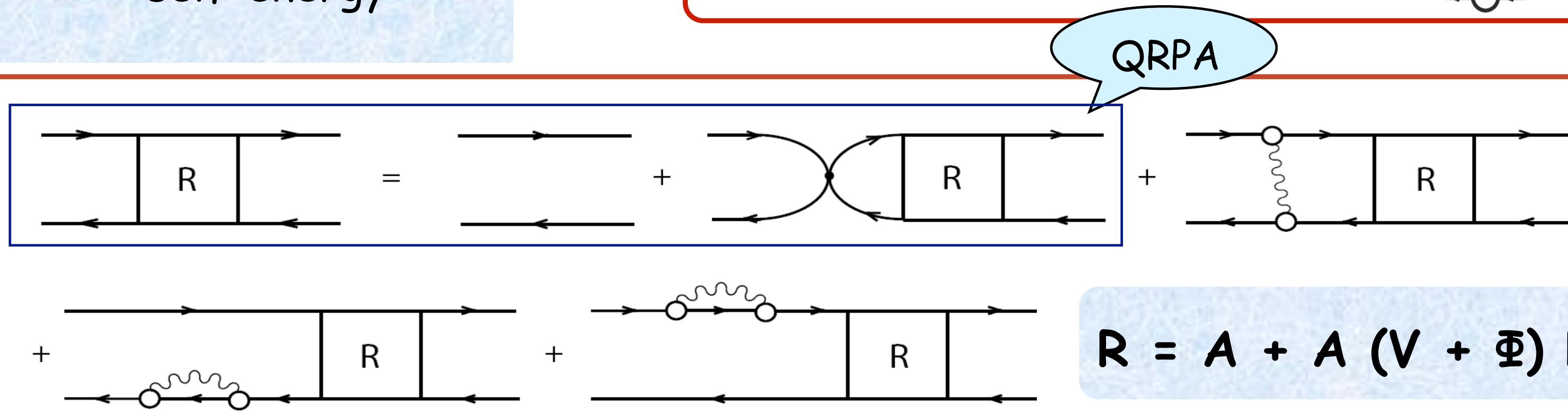
Spectroscopic factors in ^{119,121}Sn:

(nlj)	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

Excited states: nuclear response function

Functional derivative of the nucleon self-energy





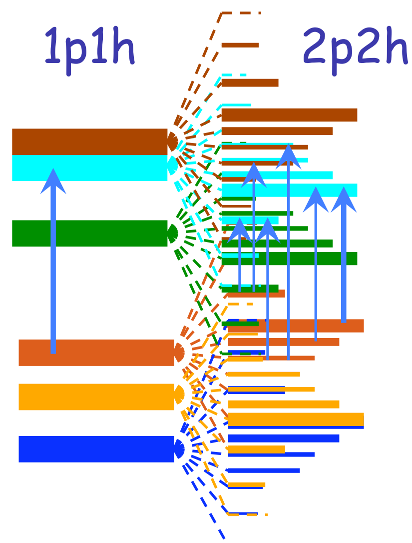
$$R = A + A\,(V + \Phi)\,R$$

Nuclear response function R: two-body propagation in the nuclear medium

Bethe-Salpeter equation (BSE) in the p-h channel

1p1h: static

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

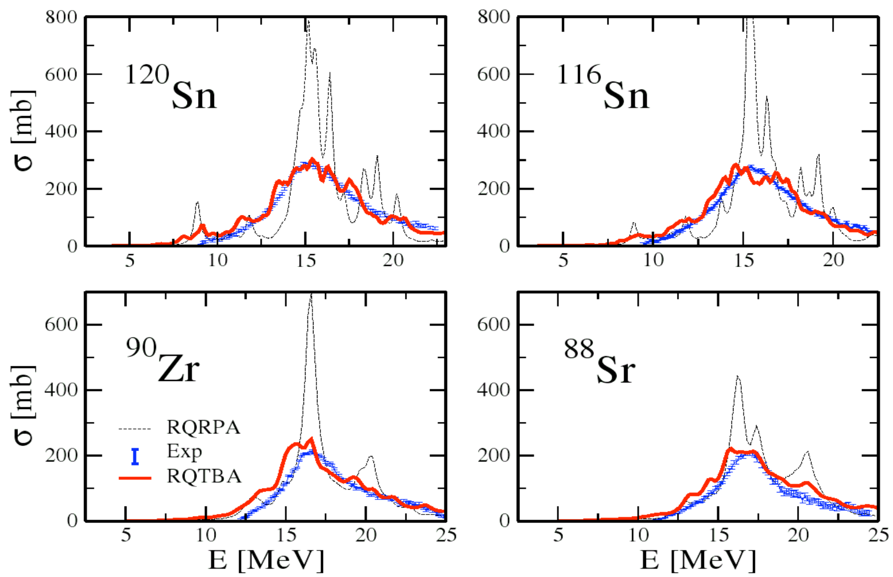


2p2h: Energy-dependent

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

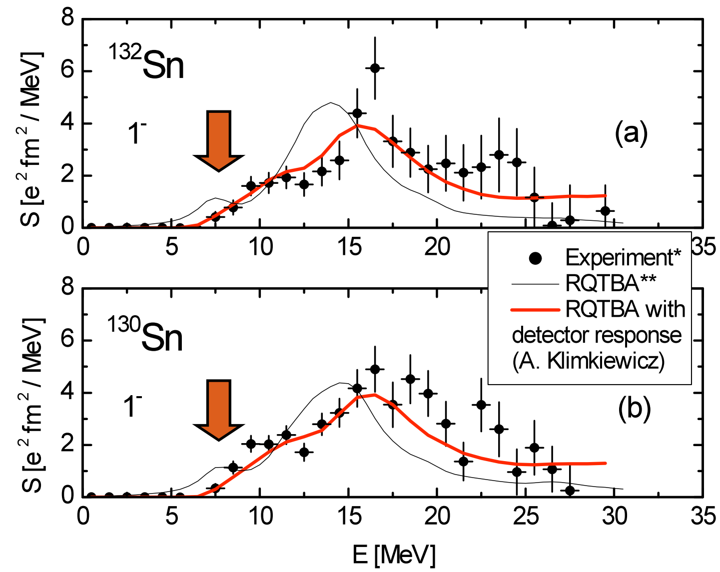
Dipole strength in neutron-rich nuclei: importance for astrophysics

Test case: stable nuclei



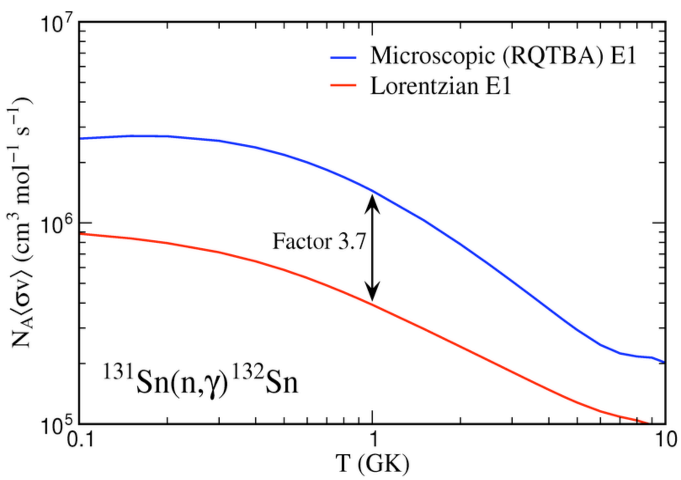
*E. L., P. Ring, and V. Tselyaev, Phys. Rev. C 78, 014312 (2008)

Neutron-rich Sn



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

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

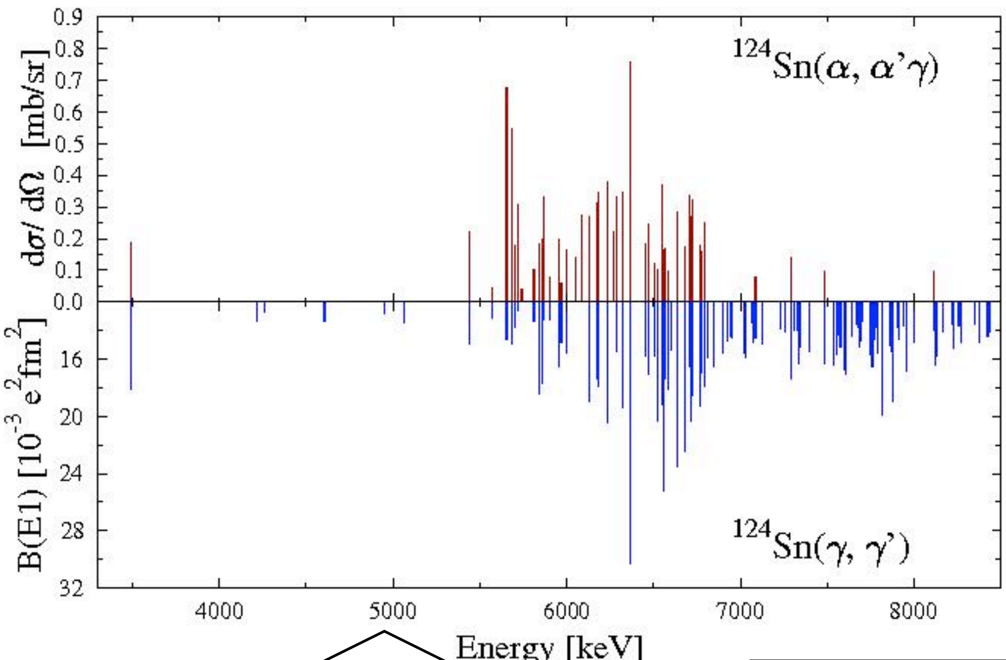


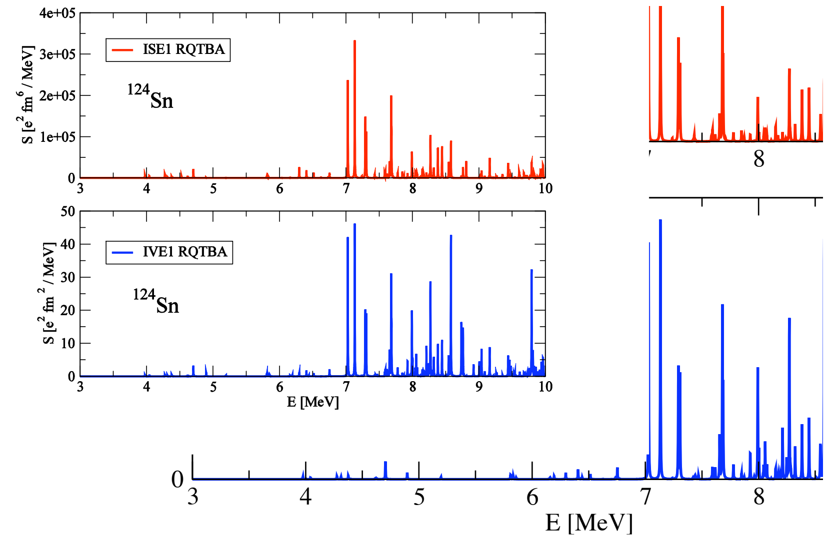
Input for r-process nucleosynthesis: (n,γ) cross sections and reaction rates: G. Martinez-Pinedo & Coll.

Isospin structure of the pygmy dipole resonance in ^{124}Sn

Experiment (J. Endres, D. Savran et al.)

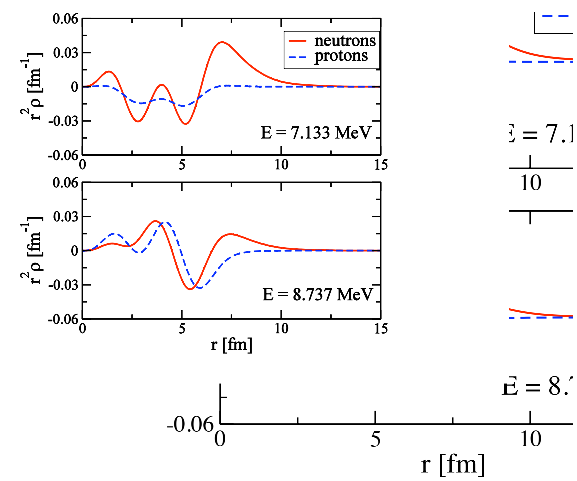
Theory: RQTBA





Hadron vs Coulomb excitation

Transition densities



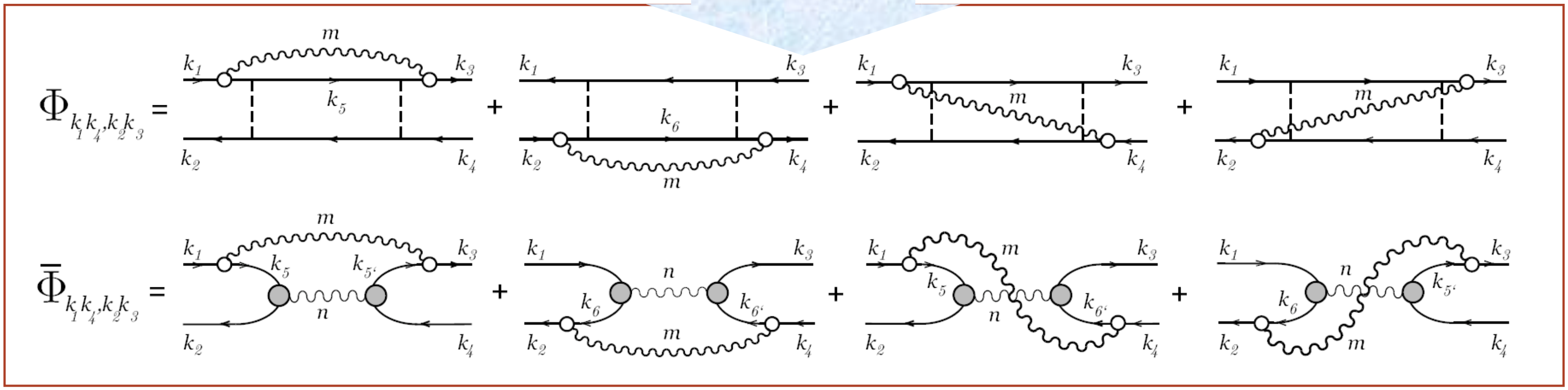
J. Endres, E. L.,…, V. Ponomarev, P. Ring et al. ,
PRL 105, 212503 (2010)

Fine structure of spectra: next-order correlations from "2q+phonon" to "2 phonons"

P. Schuck, Z. Phys. A 279, 31 (1976)
V.I. Tselyaev, PRC 75, 024306 (2007)

& Mode Coupling Theory
Time Blocking Approximation

Replacement of the uncorrelated propagator inside the Φ amplitude by QRPA response



Nuclear response: $R = A + A\,(V + \bar{\Phi})\,R$

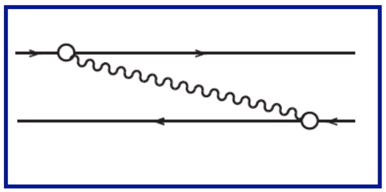
Poles may appear at lower energies:

'2q+phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu k}\, a_{ijk\mu}/(\omega - E_{i'} - E_k - \Omega_\mu)$

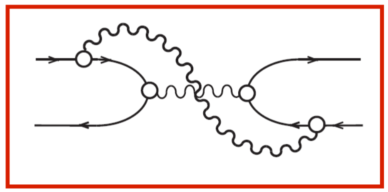
'2 phonon' response:
$\Phi_{iji'j'}(\omega) \sim \Sigma_{\mu\nu}\, a_{iji'j'}/(\omega - \Omega_\nu - \Omega_\mu)$

Fine features of dipole spectra: two-phonon effects

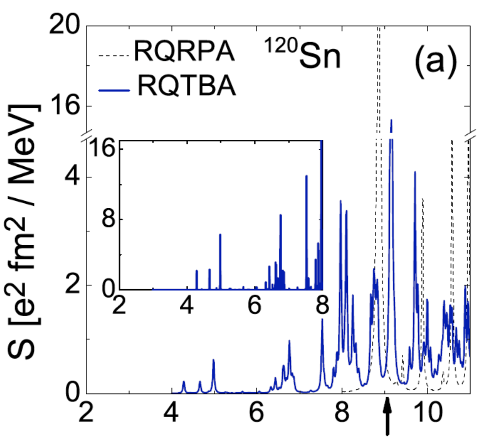
2q+phonon

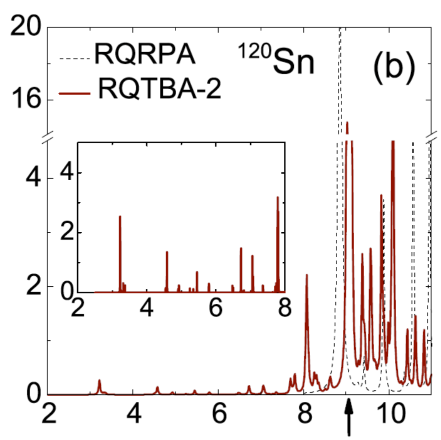


2 phonon



^{120}Sn





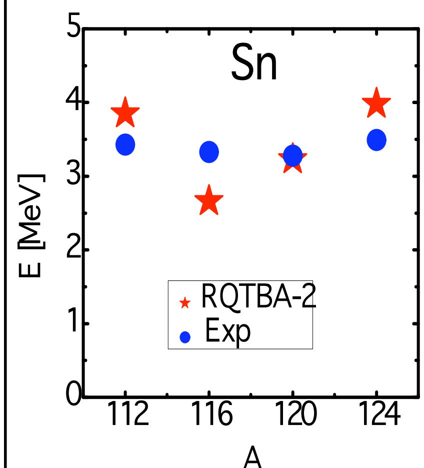
E.L., P.Ring, V.Tselyaev, PRL 105, 02252 (2010)

First two-phonon state 1^-_1

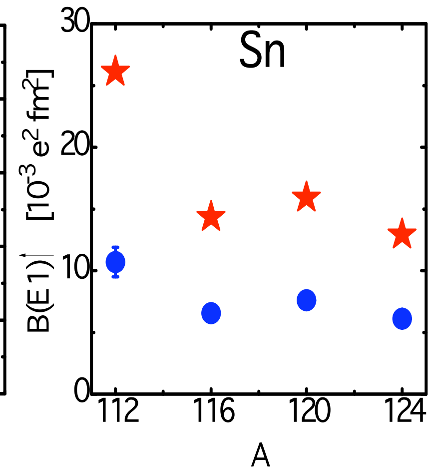
$$3^- \otimes 2^+$$

$$E(1^-_1) \approx E(2^+_1) + E(3^-_1)$$

$E(1^-_1)$



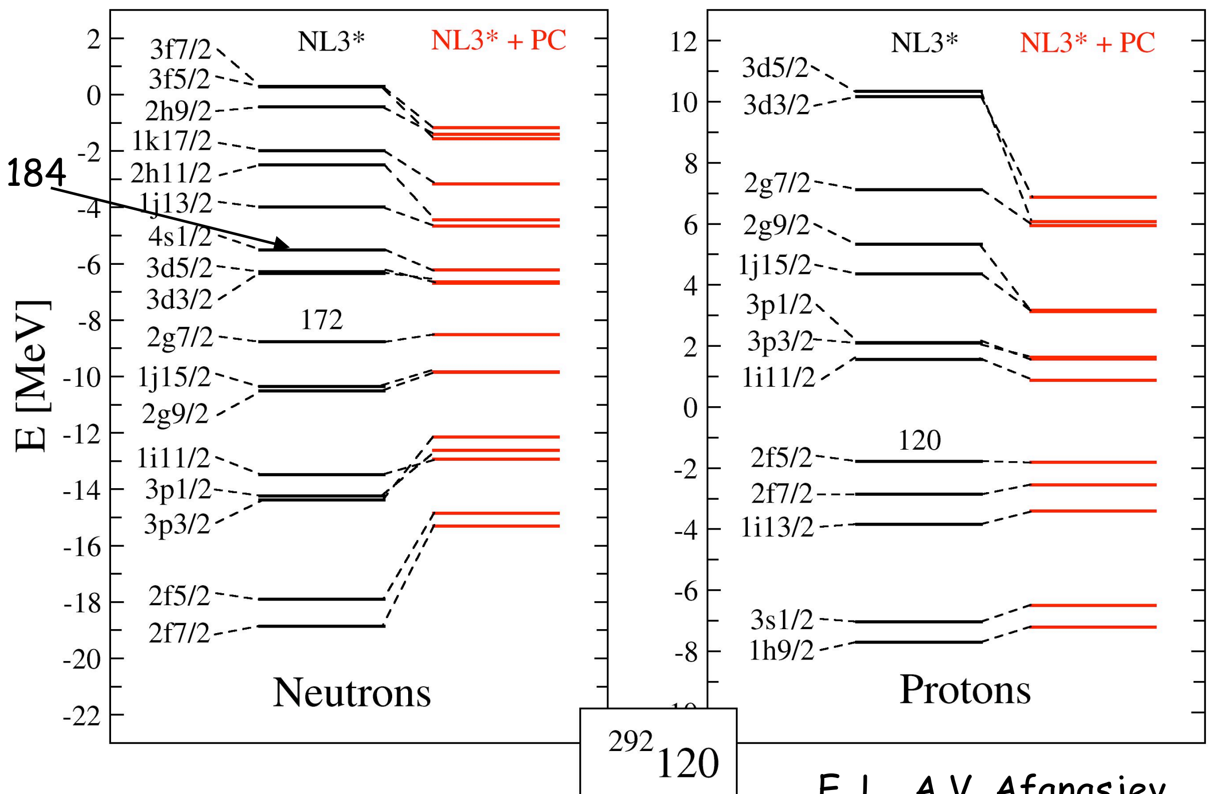
$B(E1)\uparrow$



Experiment:
I.Pysmenetska et al., PRC73 (2006) 017302

Vibrational correction to single-particle spectra of superheavy elements (SHE): are there „spherical shell closures" in $^{292}120$?

1. Vibrational 1-, 2+, 3-, 4+, 5-, 6+ spectra of the SHE Z=120 nuclei have been calculated microscopically.
2. Beyond relativistic mean field: coupling to ~100 phonons 2+, 3-, 4+, 5-, 6+ below 15 MeV.
3. Influence of many-body correlations like phonon coupling (PC) on the SHE shell structure is significant.
4. The vibrations affect very little the Z=120 shell gap supporting the earlier relativistic mean field prediction while the N=172 shell gap becomes questionable.



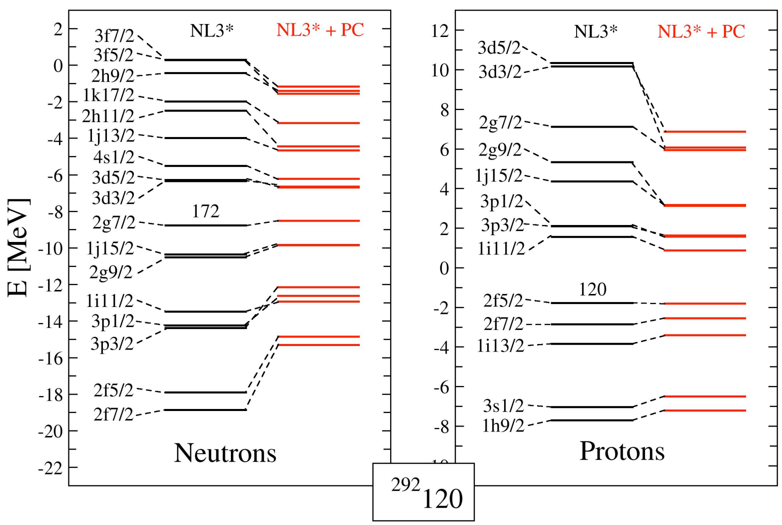
E. L., A.V. Afanasjev, PRC (2011), in press

Lowest collective 2+ and 3- states in $^{292}120$

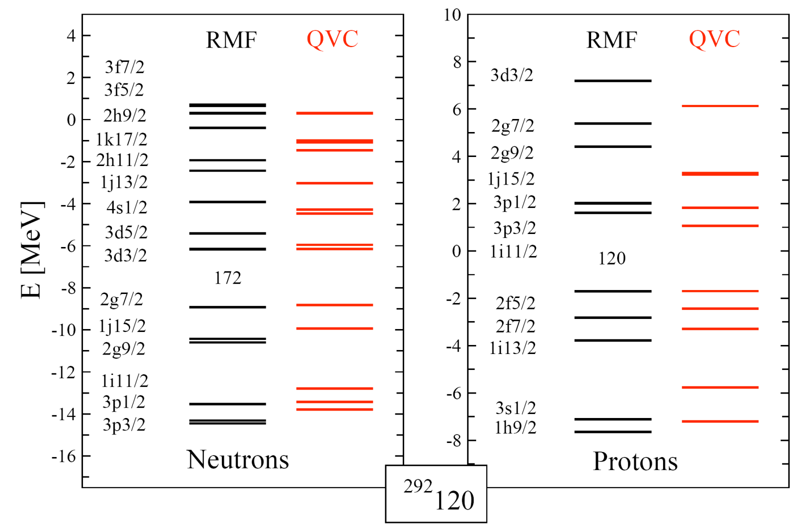
E (2+) [MeV]	B(E2)↑ [e^2 fm^4]
1.41	7.1×10^4
3.18	3.5×10^4
4.82	1.4×10^4
E (3-) [MeV]	**B(E3)↑ [e^2 fm^6]**
2.20	1.04×10^6
5.76	7.2×10^5
6.29	1.4×10^5

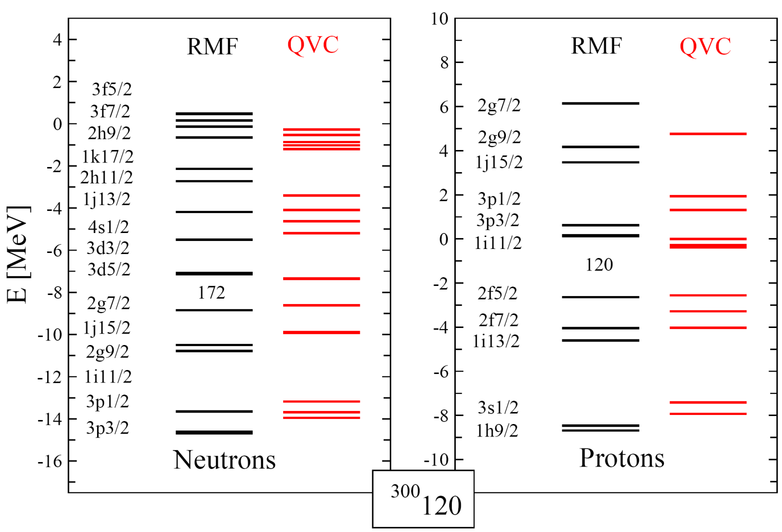
„Semi-magic" Z = 120 isotopes with N = 172-184: neutron pairing + phonon coupling

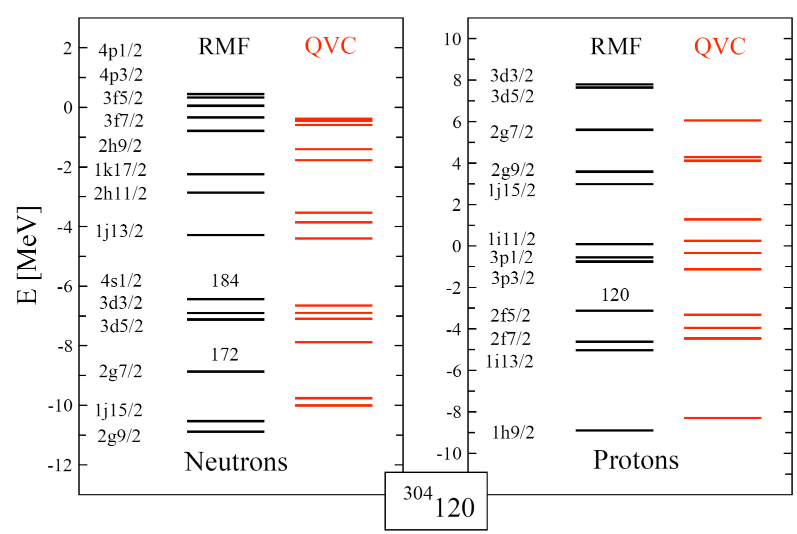
No pairing



Pairing

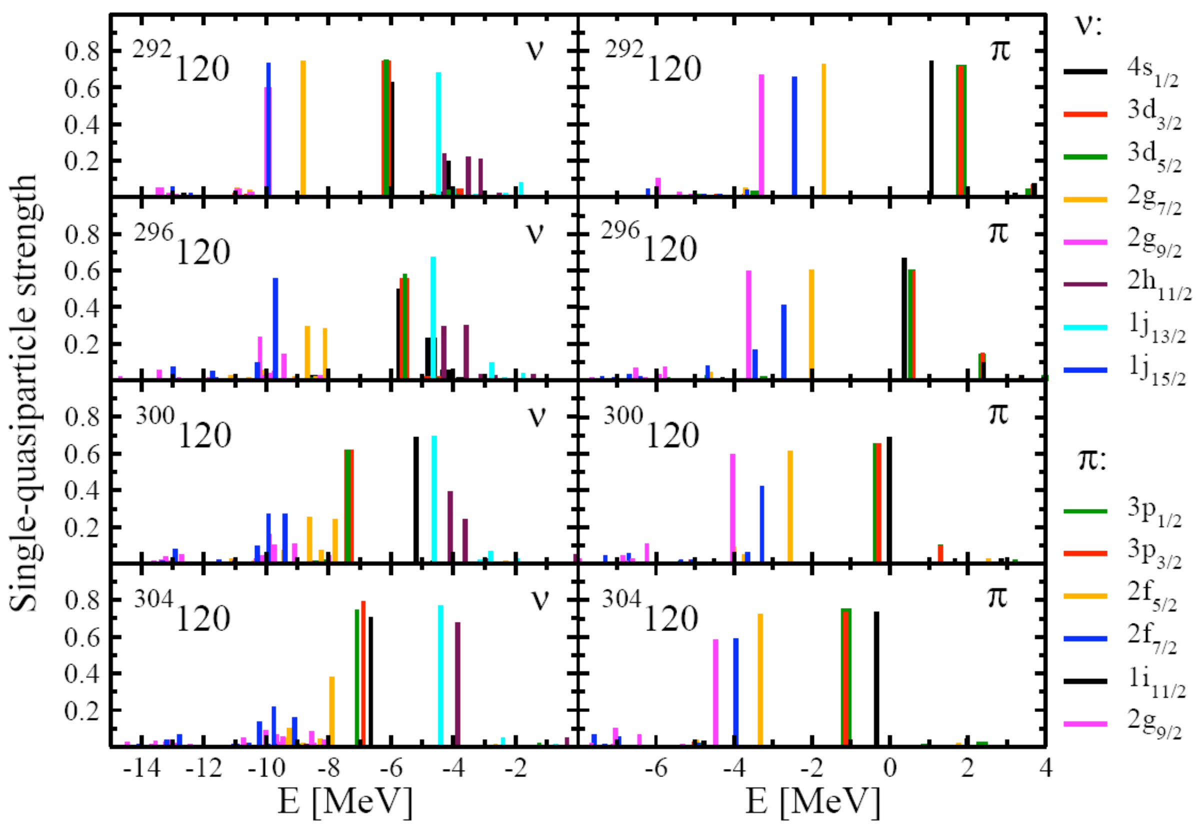




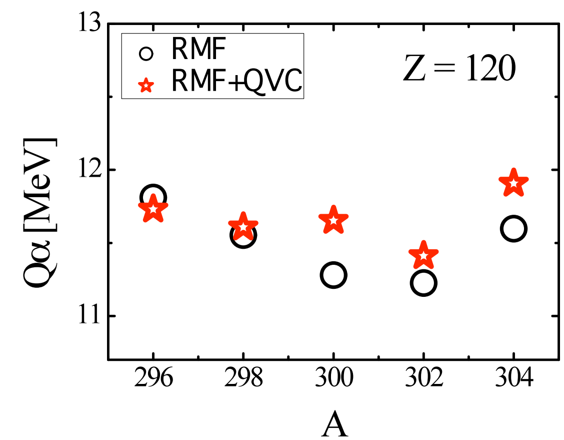


Shell evolution in superheavy Z = 120 isotopes: Quasiparticle-vibration coupling in relativistic framework

1. Relativistic Mean Field: spherical minima
2. Small amplitude vibrations: RQRPA
3. Very soft nuclei: large amount of low-lying collective vibrational modes (~80 phonons below 15 MeV)



Vibration corrections to alpha decay energies Qα [MeV]



Vibrational corrections:

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

Shell stabilization & vibration stabilization/destabilization (?)

Outlook

Goal:

Constructing a universal nuclear many-body theory
for high-precision calculations of nuclear masses
and low-energy phenomena; theory with high
predictive power

Strategy (for heavy systems):
DFT extended by relevant many-body correlations

More correlations => better agreement to data &
More definite conclusions about the quality
of the underlying functional

Methodology:
Covariant DFT + many-body Green's function
(nuclear field theory) techniques

Constraints
on the form of underlying DF, its parameters,
many-body coupling schemes:
high-resolution spectral data and data about drip-line nuclei

Thanks for collaboration:

Anatoli Afanasjev (Mississippi State University)

Hans Feldmeier (GSI)

Hans Peter Loens (GSI)

Karlheinz Langanke (GSI)

Tomislav Marketin (University of Zagreb)

Gabriel Martínez-Pinedo (GSI)

Thomas Rauscher (Basel University)

Peter Ring (Technische Universität München)

Friedrich-Karl Thielemann (Basel University)

Victor Tselyaev (St. Petersburg State University)

Dario Vretenar (University of Zagreb)