Model developments for superheavy nuclei
Conclusions on FUSHE2012

Recent developments on relativistic models

Elena Litvinova

Western Michigan University

MICHIGAN STATE UNIVERSITY

NSCL

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Future strategies on superheavy elements 2012 (FUSHE2012)

Meeting, collection of material, discussions, future strategies

Nuclear theory for superheavy nuclei: extrapolations

Nuclear dynamics: multinucleon transfer, fusion, fission, quasifission, …

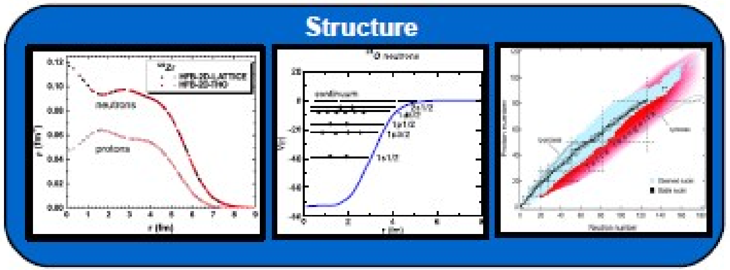
- (Semi)-Phenomenological approaches: coupled-channels, dinuclear system, collective vriables etc. Contradictions between the models, still many open questions.
- Input from nuclear structure/experimental data: masses, fission barriers, transport coefficients.
- Microscopic theory: time-dependent Hartree-Fock-(Bogoliubov) and extensions as a unified picture for structure and dynamics

Nuclear structure: masses, density profiles, shapes, low-energy spectroscopy, …

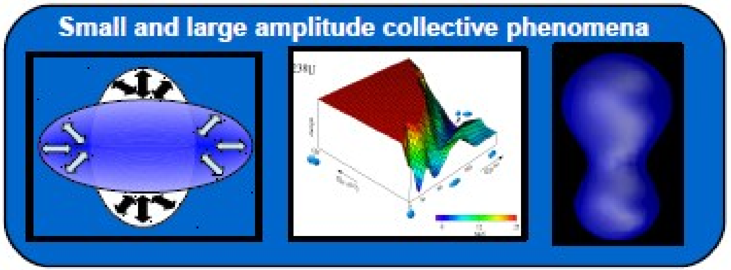
- From macro-micro to fully microscopic models
- Microscopic nuclear structure theories: common building blocks
- Mean-field theories: Skyrme, Gogny, relativistic; succeses and lessons
- Beyond mean-field models: adding correlations

Time-Dependent Hartree-Fock theory

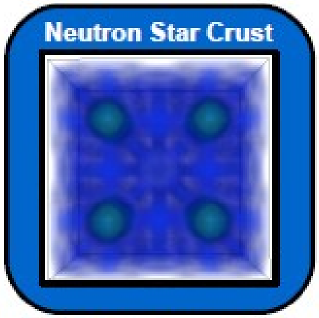
Unified Theory of Structure, Low-E Reactions, and Star Matter



Structure



Small and large amplitude collective phenomena



Neutron Star Crust

- Time-dependent generalization TDDFT (variational or Runge-Gross)

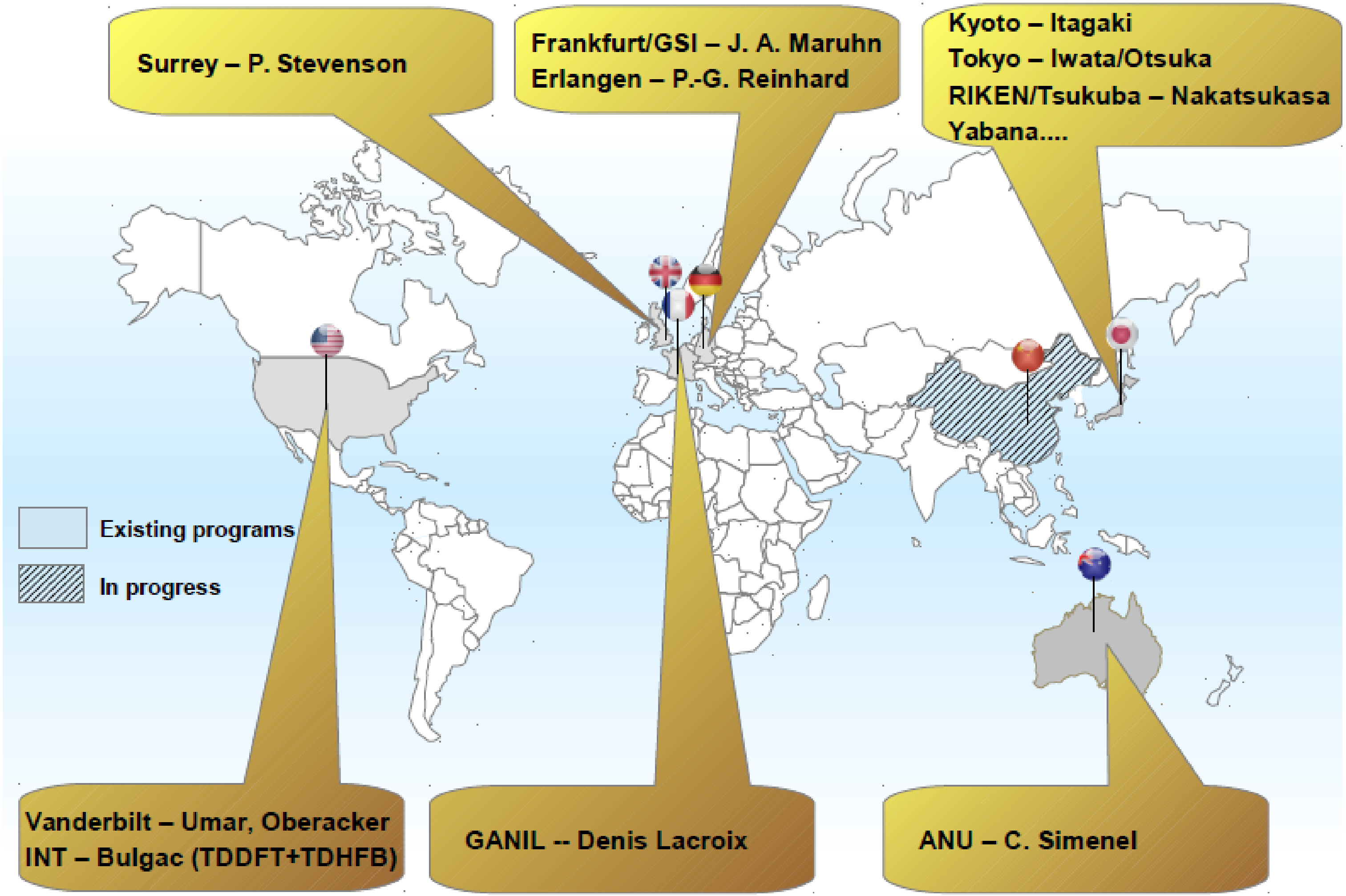
$$\delta S = \delta \int_{t_1}^{t_2} dt \langle \Phi(t) | H_{eff} - i\hbar \partial_t | \Phi(t) \rangle = 0$$

$$i \frac{\partial}{\partial t} \varphi_\alpha = h(\rho, \tau, \boldsymbol{j}, \boldsymbol{s}, \boldsymbol{T}, J_{\mu\nu} \;; \boldsymbol{r}) \varphi_\alpha$$

self-consistent

- Considerable effort testing TDDFT in recent years

Worldwide Nuclear TDDFT Efforts (partial list)



Surrey – P. Stevenson

Frankfurt/GSI – J. A. Maruhn
Erlangen – P.-G. Reinhard

Kyoto – Itagaki
Tokyo – Iwata/Otsuka
RIKEN/Tsukuba – Nakatsukasa
Yabana....

Vanderbilt – Umar, Oberacker
INT – Bulgac (TDDFT+TDHFB)

GANIL -- Denis Lacroix

ANU – C. Simenel

TDHF and beyond: adding correlations

C. Simenel, EPJ A 48, (2012) 152

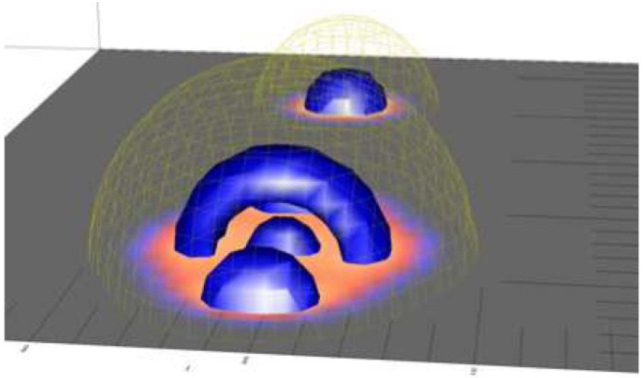


Fig. 4.24. Initial condition of a ^{40}Ca+^{238}U collision visualised with the SDVision code [236]. Two isodensities are shown (yellow grid and blue area). A projection of the density is also shown on the $z = 0$ plane.

Limitation:

No quantum tunneling

Possible solution:

Path integral formulation

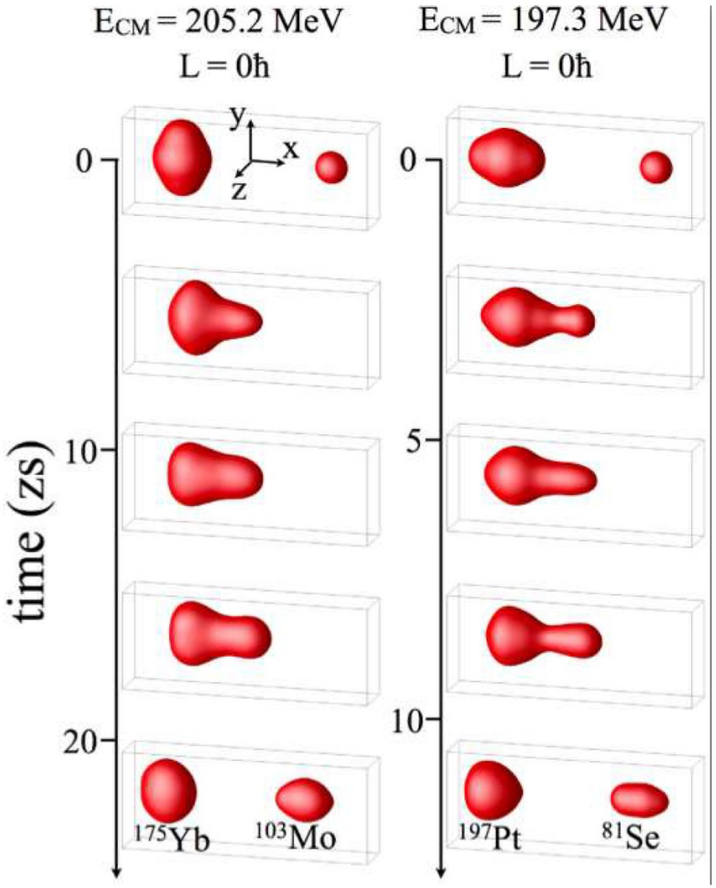


Fig. 4.25. Snapshots of the TDHF isodensity at half the saturation density in the ^{40}Ca+^{238}U system for different initial orientations and $E_{c.m.}$.

Correlations:

- Superfluid pairing
- Coupling between harmonic vibrations
- TDGCM

Building blocks of microscopic nuclear structure models

❖ Degrees of freedom

at ~1-50 MeV excitation energies:

single-particle & collective (vibrational, rotational)

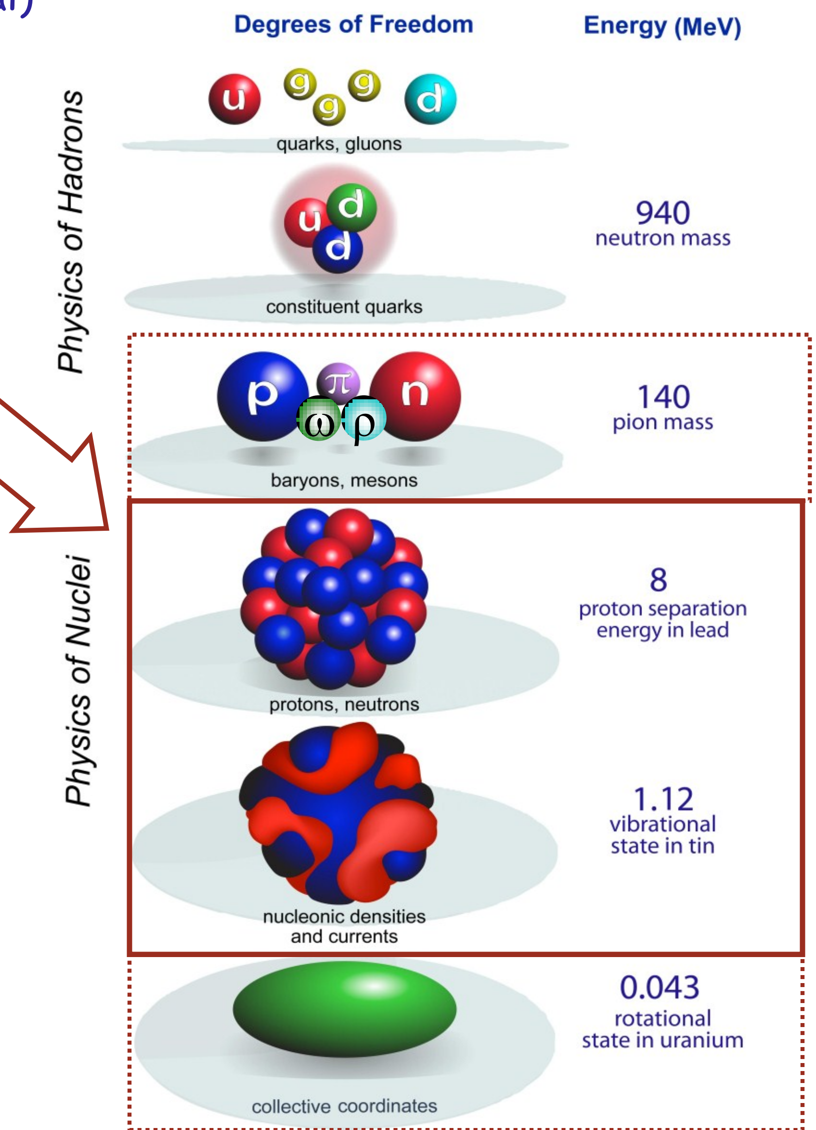
NO complete separation of the scales!

-Coupling between single-particle and collective:

-Coupling to continuum

as nuclei are open quantum systems

Separation of the scales



❖ Symmetries -> Eqs. of motion

Galilean inv. -> Schrödinger Eq.

Lorentz inv. -> Dirac & Klein-Gordon Eqs.

❖ Interaction V_{NN}

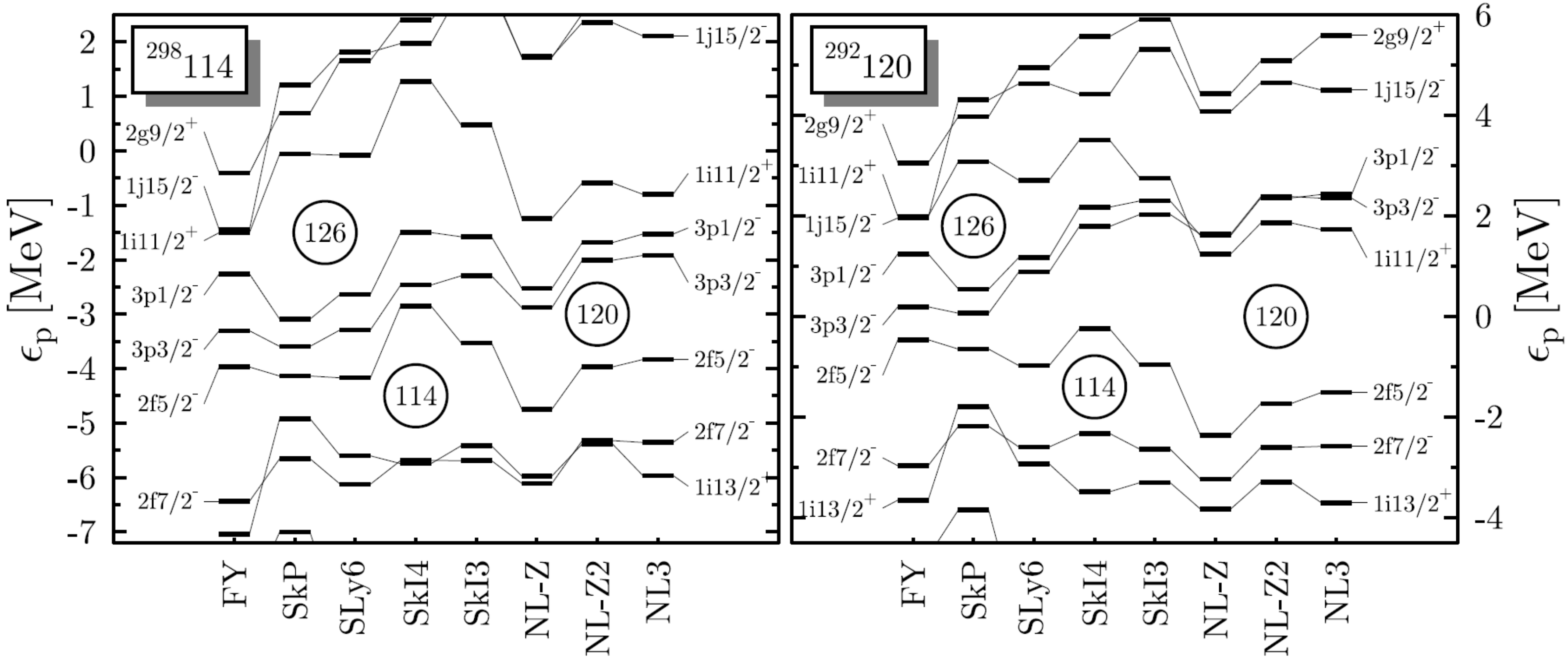
Density functional: an ansatz for in-medium V_{NN}

- ❖ Skyrme
- ❖ Gogny
- ❖ Fayans
- ❖ Relativistic (meson-exchange, Coulomb)

Beyond DFT: restoration of broken symmetries, adding correlations/couplings

MM, Skyrme and Relativistic functionals: shell structure of SHN

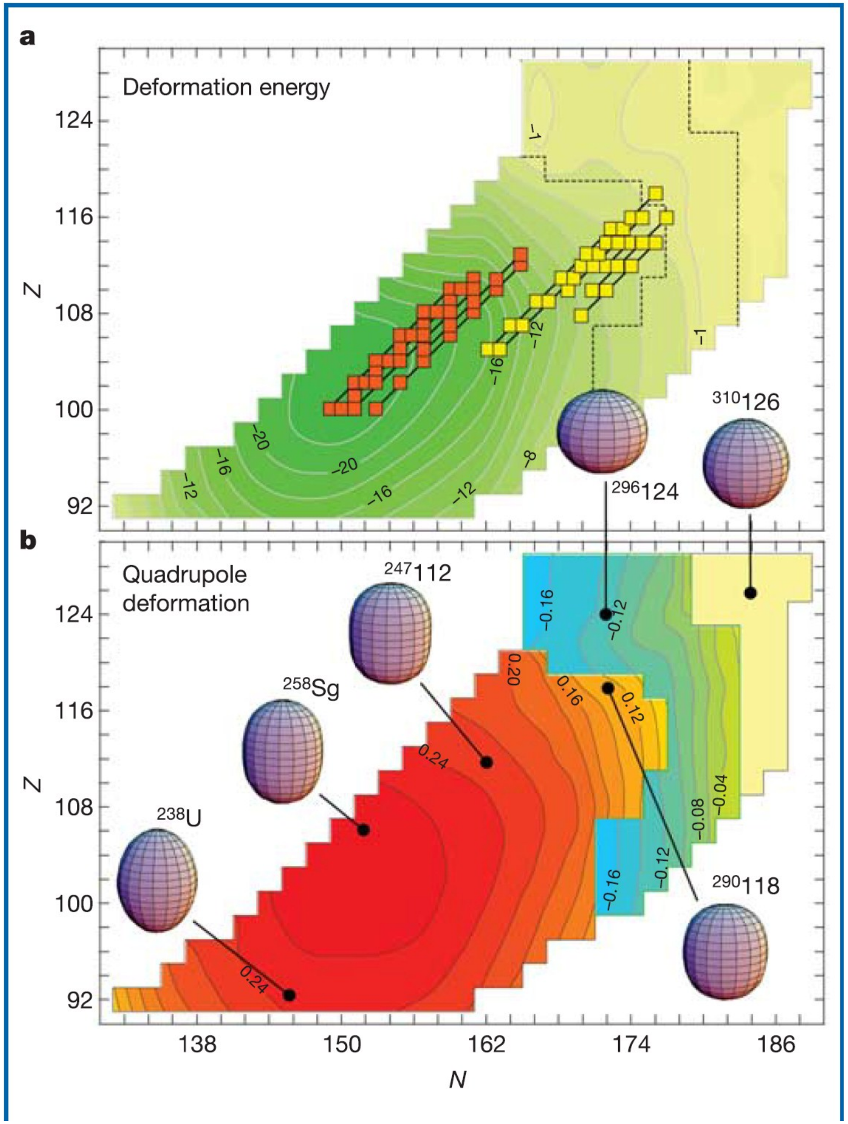
M. Bender, K. Rutz, P-G Reinhard, J. Maruhn, W. Greiner,
Phys. Rev. C 60, 034304

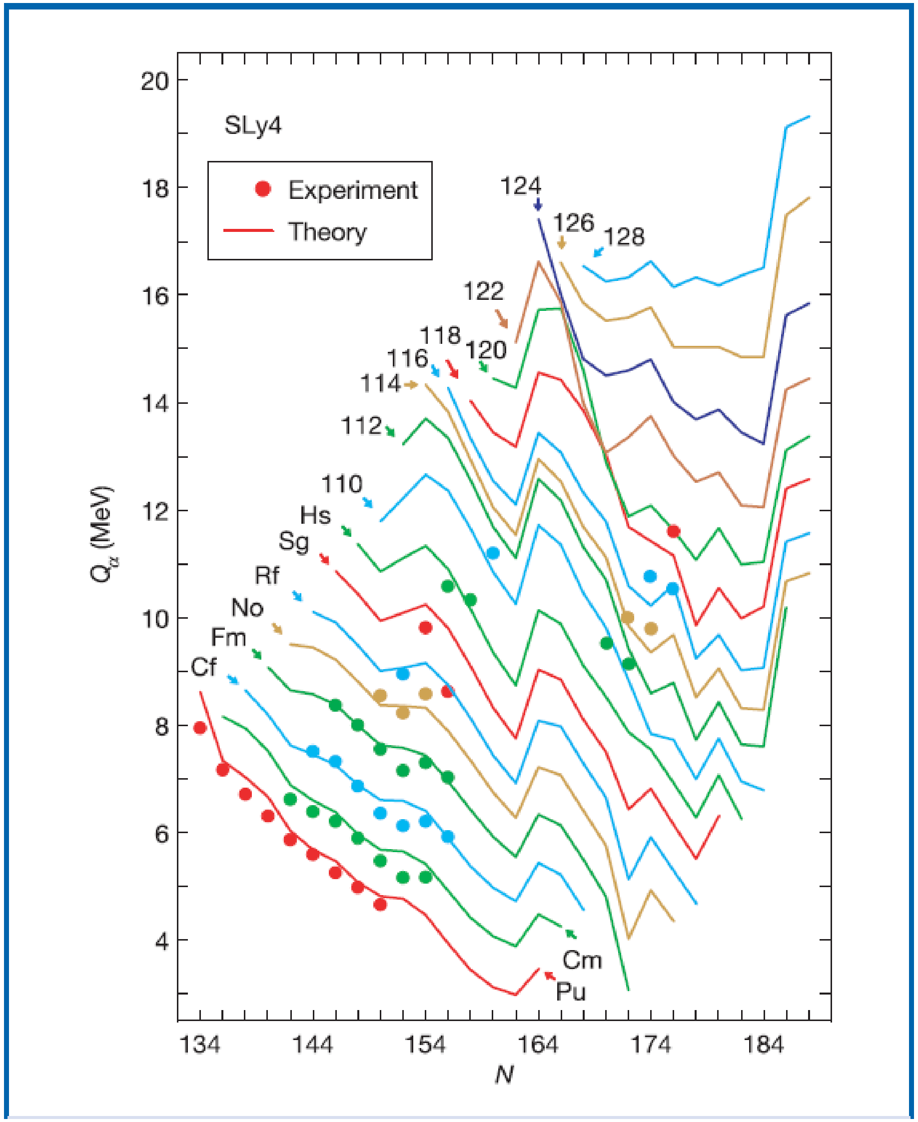


Challenges for theory in prediction of the island of (enhanced) stability:

(i) Models are extrapolated beyond the regions of their adjustments;
(ii) S.p. level spacing is much smaller than in lighter nuclei;
small changes can open/close shell gaps;
(iii) Strong Coulomb fields: larger corrections than in lighter nuclei.

Skyrme functonal(SLy4): Shapes and Q_α values

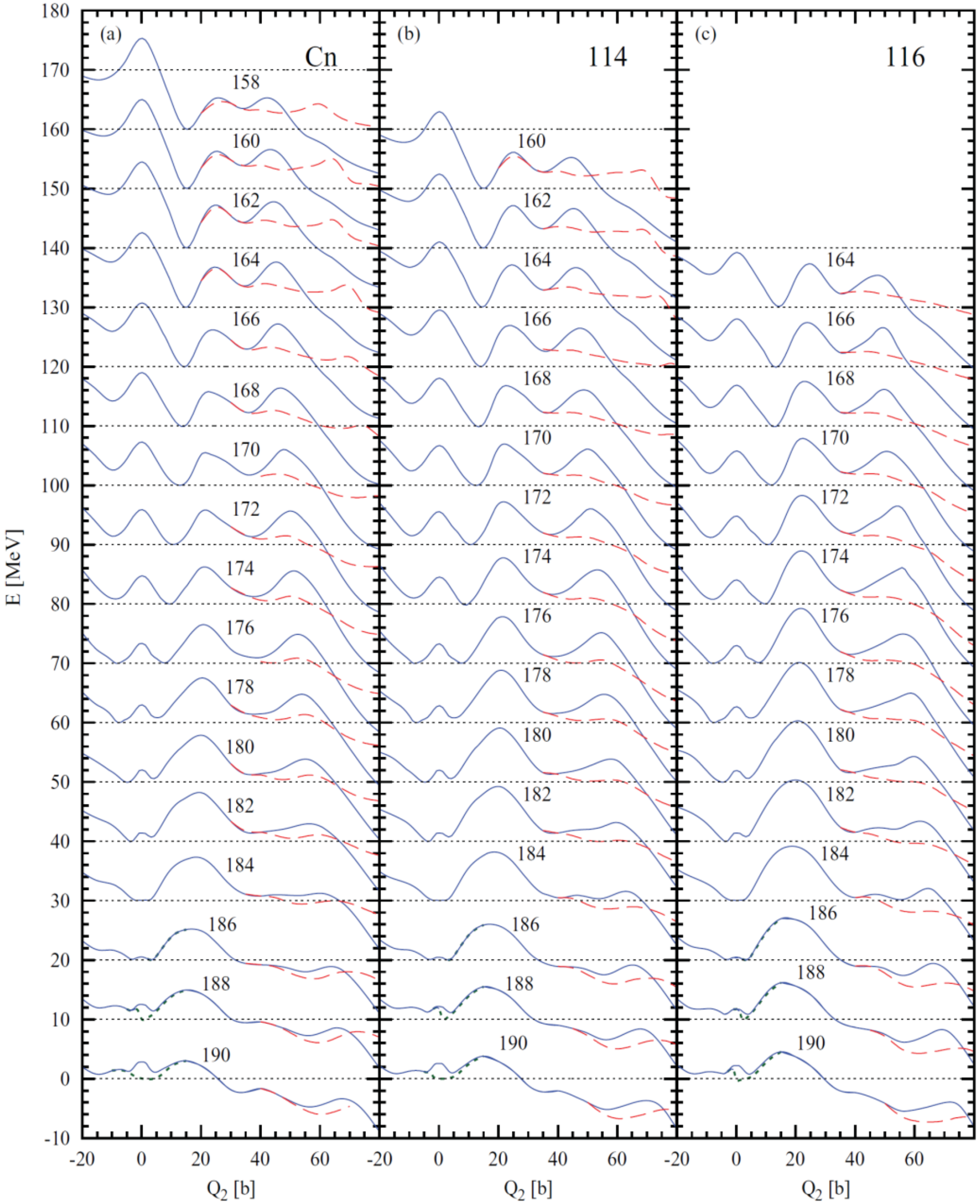


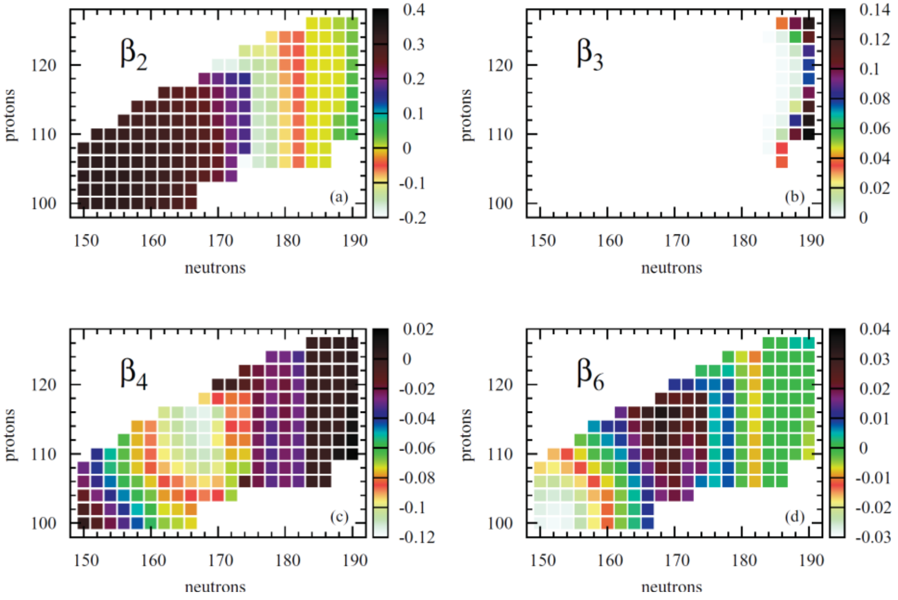


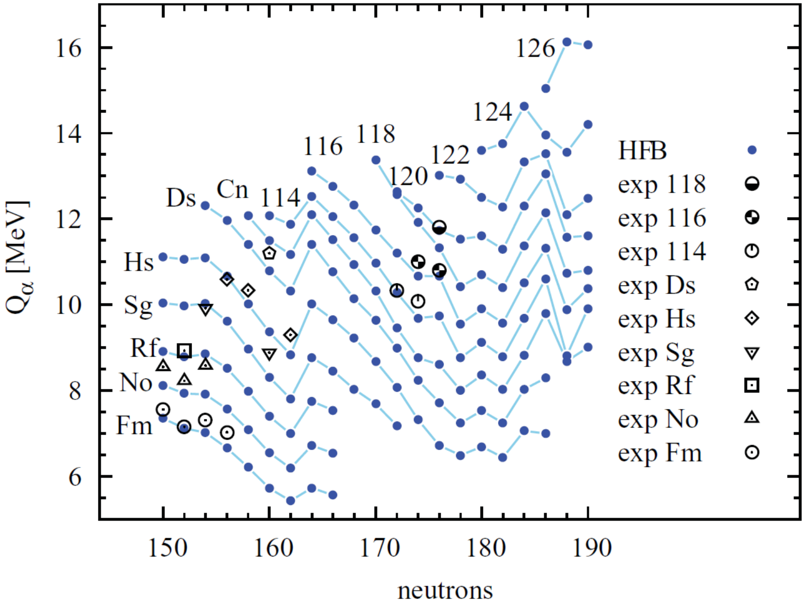
S. Ćwiok, P.-H. Heenen, W. Nazarewicz, *Nature* 285 (2005) 705

Gogny forces: Fission barriers, deformations, Q_α

M. Warda, J.L. Egido, PRC 86, 014322 (2012)







Beyond mean-field: restoration of broken symmetries, Generator coordinate method

M. Bender, P.-H. Heenen, J. Phys. Conf. Series 420 (2013) 012002

Particle number projection, angular-momentum projected GCM

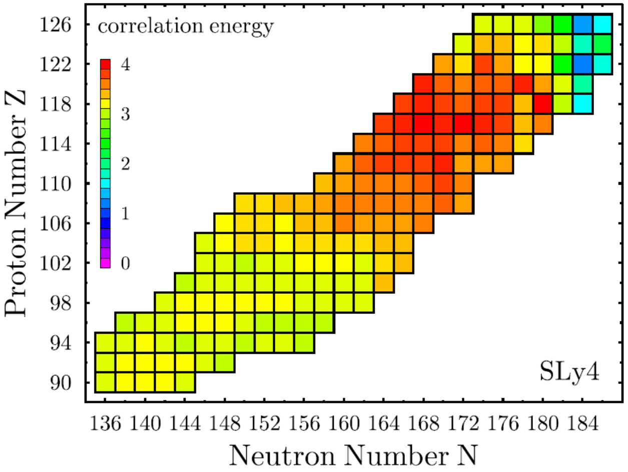


Figure 12. Quadrupole correlation energy in MeV from projection on angular momentum $J = 0$ and mixing of axial configurations of different quadrupole [redacted] cf. [73]. Calculations were done with the SLy4 Skyrme parametrisation.

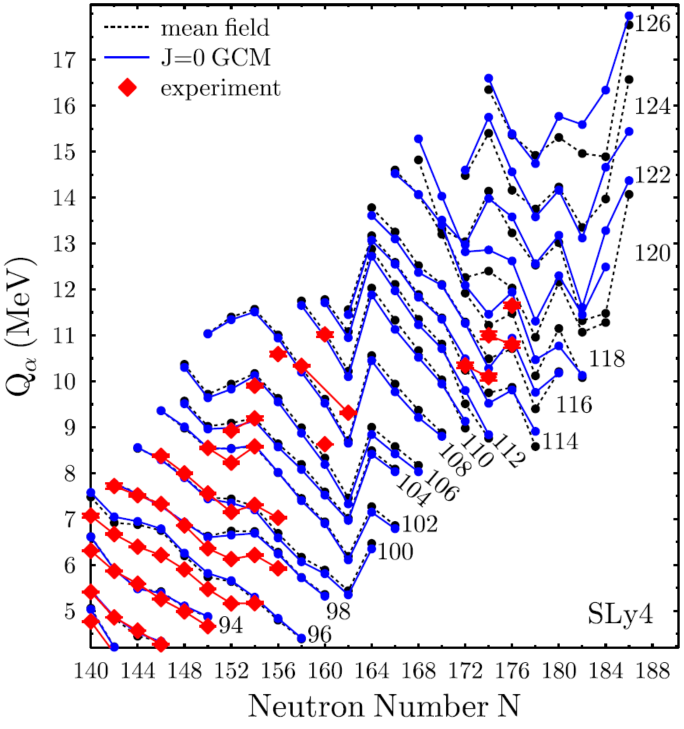


Figure 13. Q_α values of even-even nuclei from self-consistent mean-field and beyond-mean-field calculations [78] with the Skyrme interaction SLy4 compared with data where available [85]. Lines connect values for isotopic chains as indicated by the labels.

GCM with Gogny forces: T.R. Rodriguez et al.

Relativistic approaches to nuclear structure

❖ 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

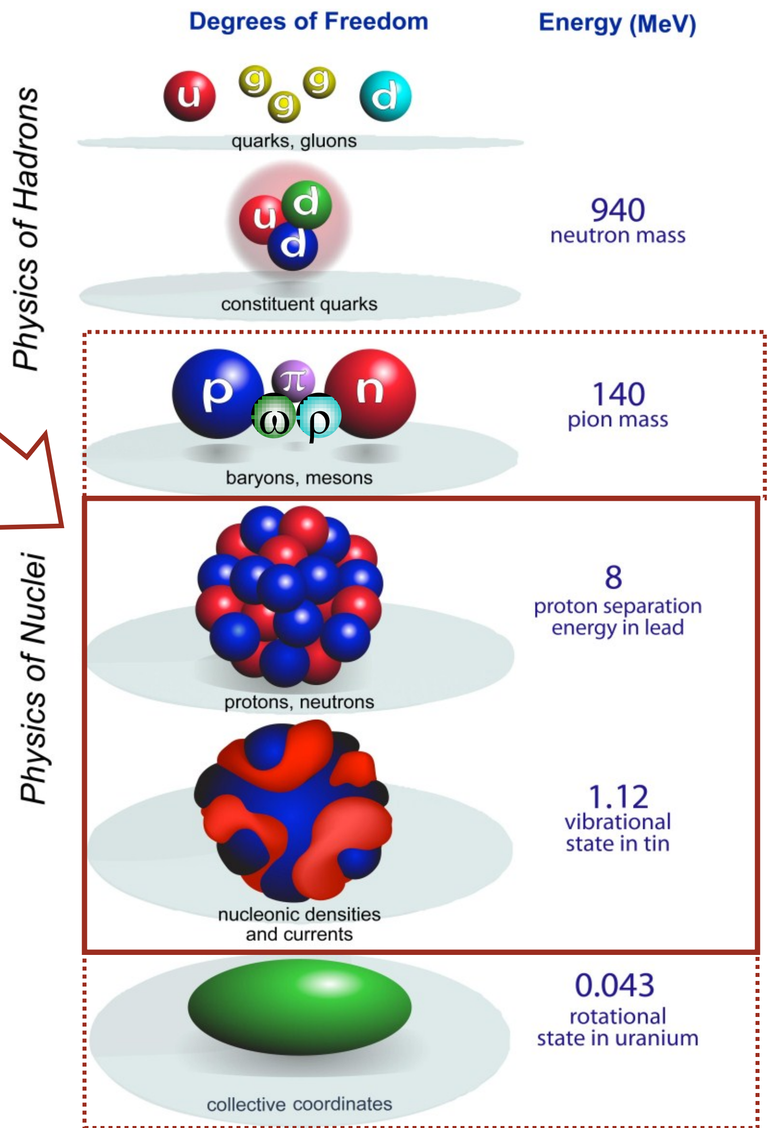
❖ Symmetries -> Eqs. of motion

~~Galilean inv. -> Schrödinger Eq.~~
Lorentz inv. -> Dirac & Klein-Gordon Eqs.

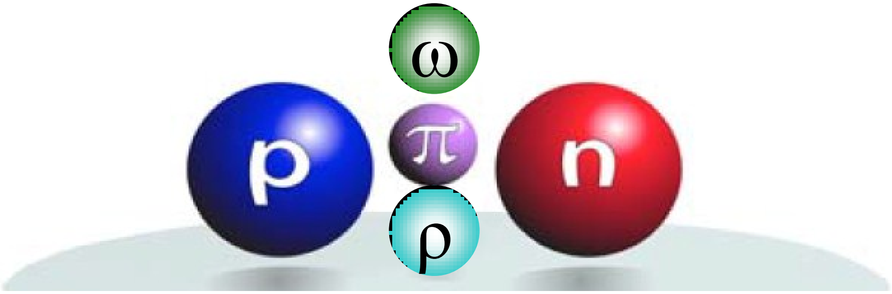
❖ Interaction V_{NN}

1. **Density functional:** an ansatz for in-medium V_{NN} (as the first approximation)
2. Beyond DFT (self-consistently): Adding non-localities/correlations/couplings/deformations

Separation of the scales

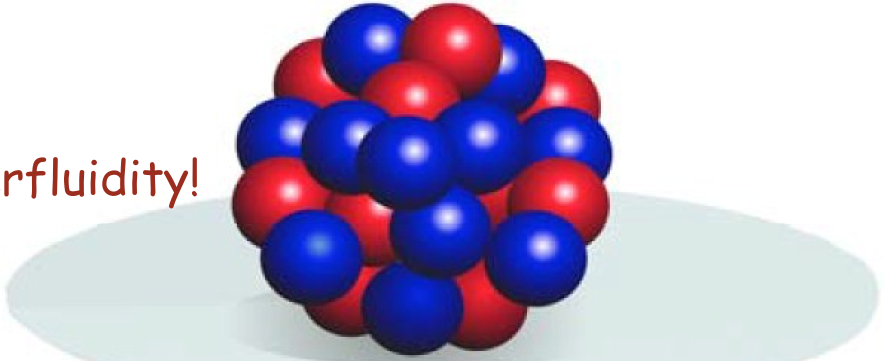


Covariant nuclear field theory: Nucleons, mesons, phonons

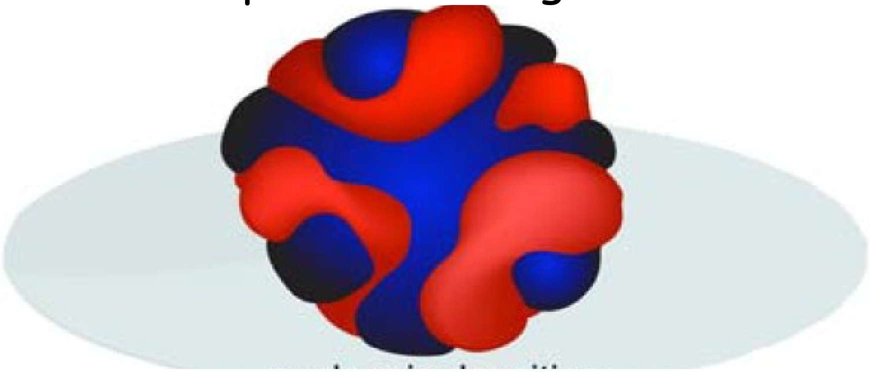


m_π ~140 MeV, m_ρ ~770 MeV, m_ω ~783 MeV

+ superfluidity!

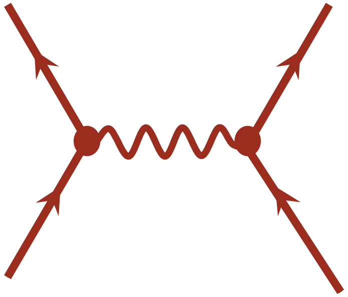


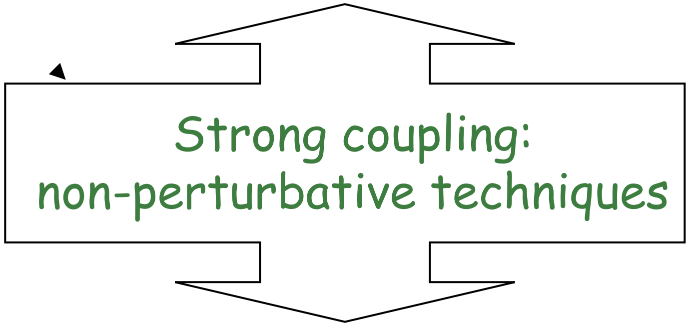
Nucleon separation energies: ~1-10 MeV



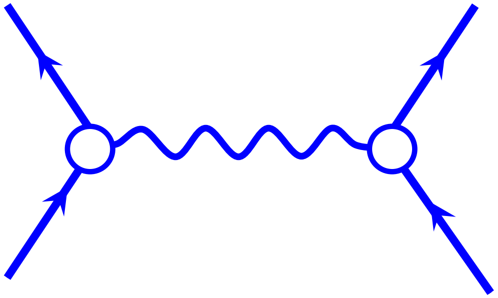
Emerging collective phonons: ~1-10 MeV

Short range:
Mean-field approximation



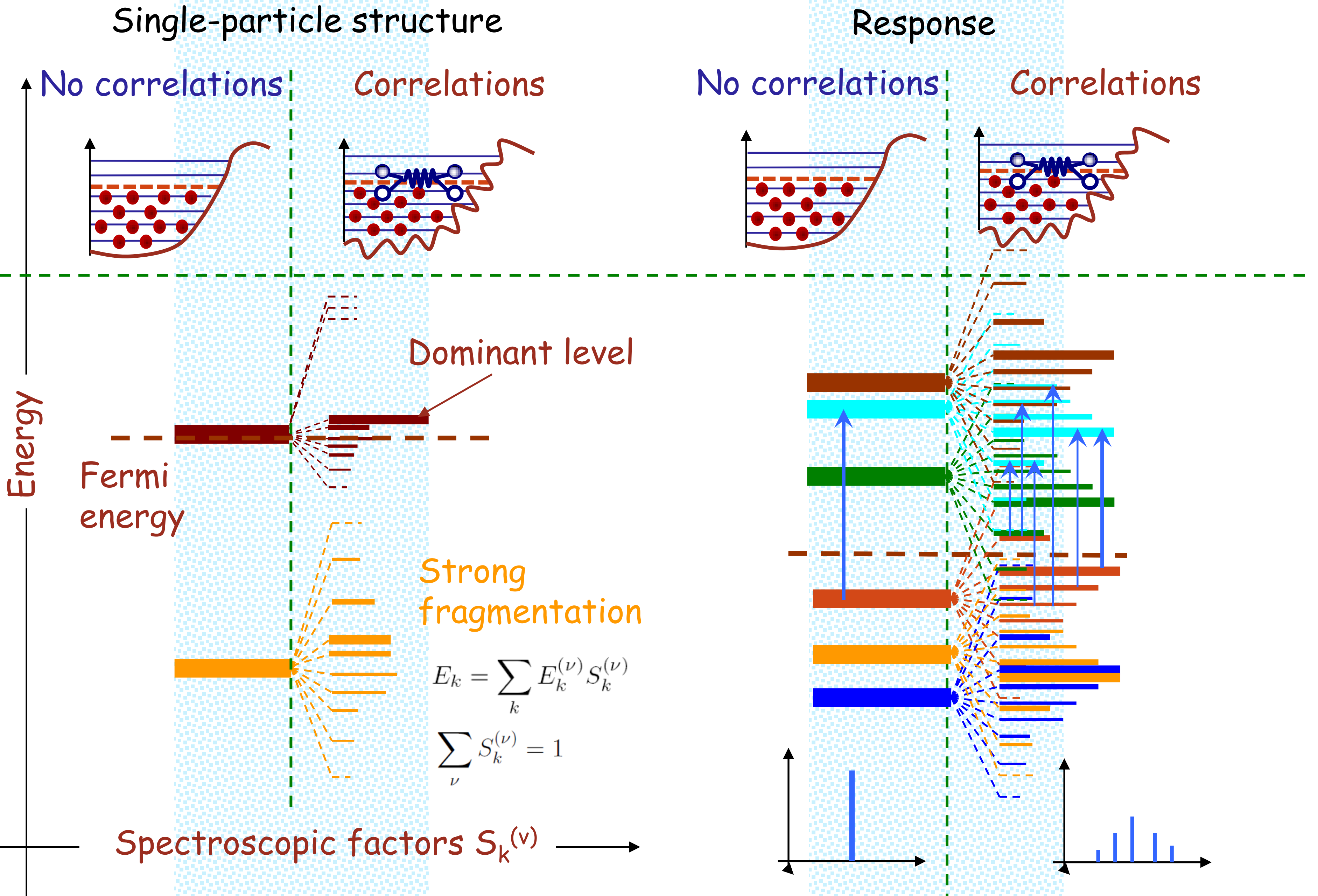


Strong coupling:
non-perturbative techniques



Long range:
Time blocking

Fragmentation of states in odd and even systems (schematic)



Single-particle structure

Response

No correlations

Correlations

No correlations

Correlations

Dominant level

Energy

Fermi energy

Strong fragmentation

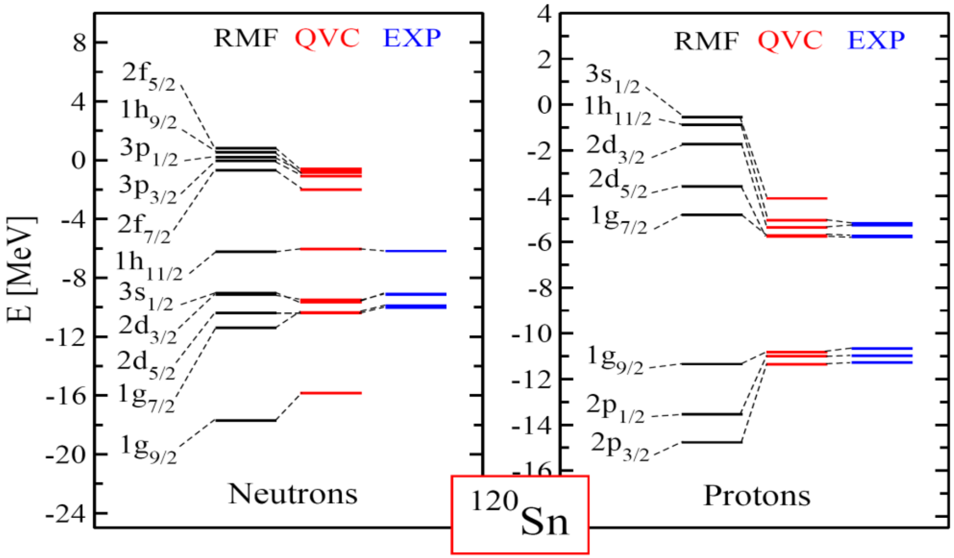
$$E_k = \sum_k E_k^{(\nu)} S_k^{(\nu)}$$

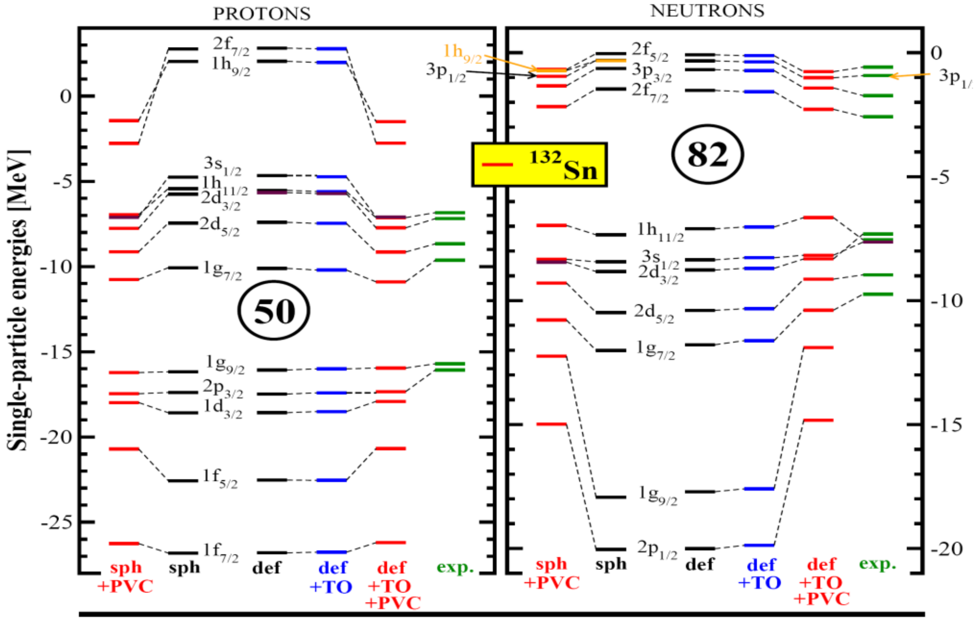
$$\sum_\nu S_k^{(\nu)} = 1$$

Spectroscopic factors $S_k^{(\nu)}$

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)

Spin-orbit splittings: Tensor force or meson-nucleon dynamics?

A. Afanasjev and E. Litvinova, arXiv:14094855

Energy splittings between dominant states which are used to adjust the mean-field tensor interaction. Here no tensor.

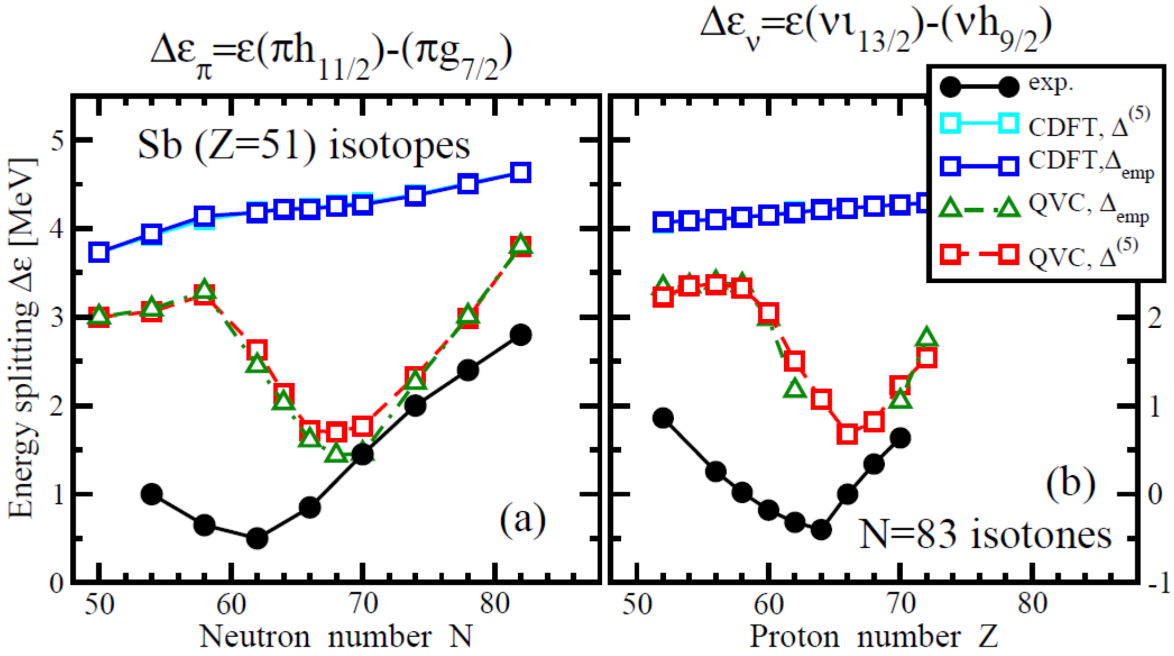
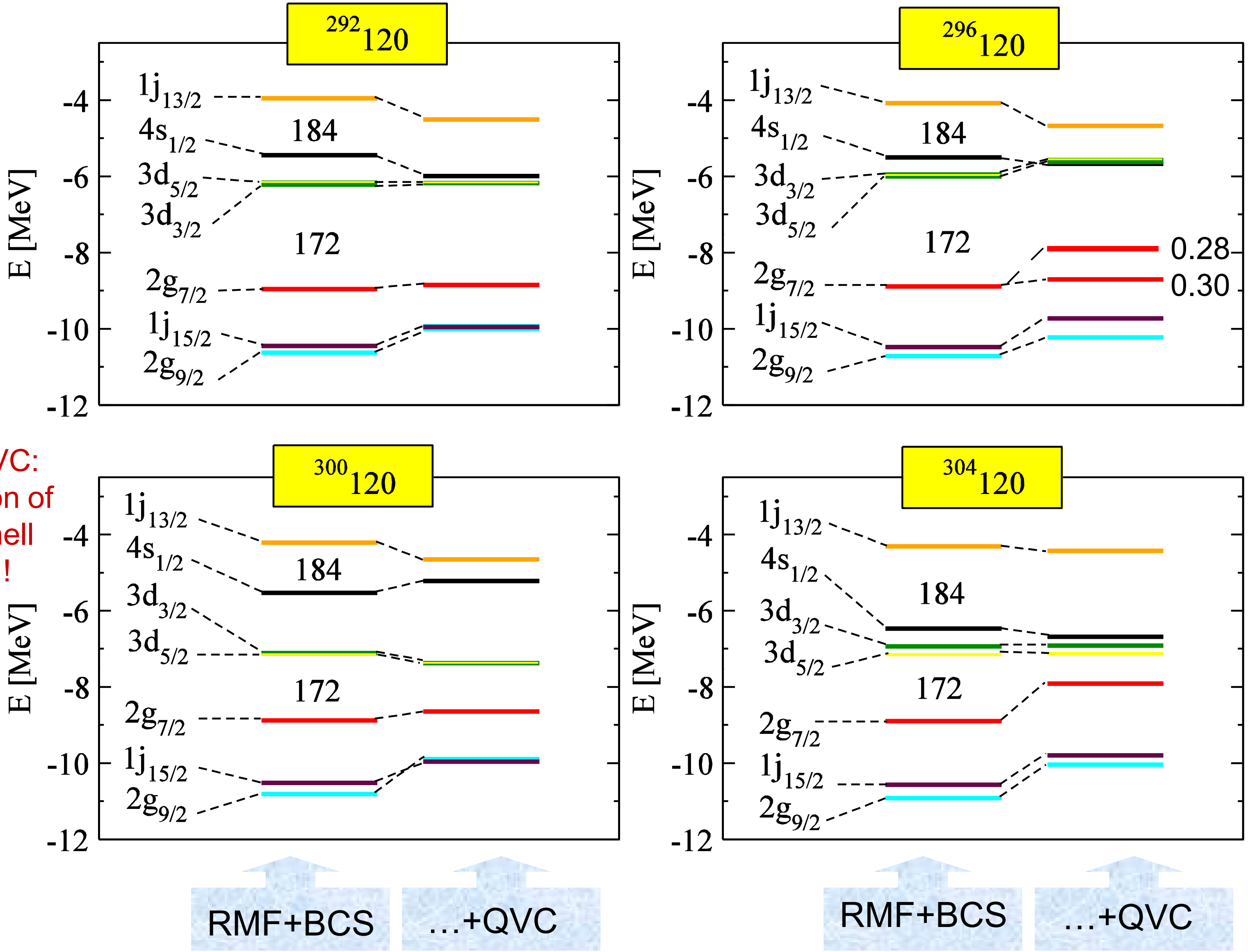


FIG. 4. (Color online) The energy splittings between the indicated states obtained in experiment, covariant density functional theory (CDFT) and QVC calculations. The results of the calculations with two pairing schemes are shown. Experimental data are taken from Ref. [25].

A conventional description including isoscalar phonons is used in the quasiparticle-vibration coupling (QVC) self-energy. The discrepancies at larger isospin asymmetries may point out to the missing isospin vibrations.

Pion dynamics is to be included in the QVC
In progress.

RMF+QVC: Dominant neutron states in Z = 120



Comparable Spectroscopic strengths

PC+QVC: Formation of the „shell gap“ !

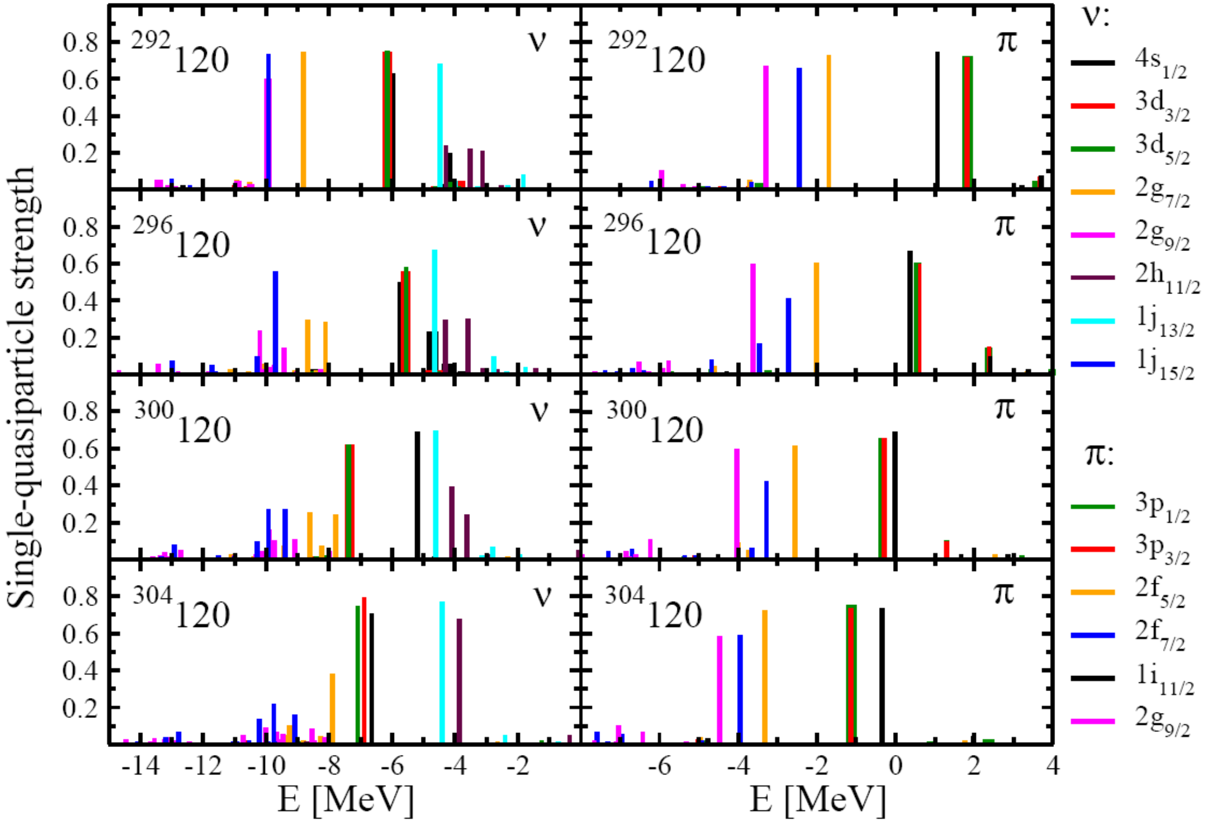
Delocalization of the shell closures

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

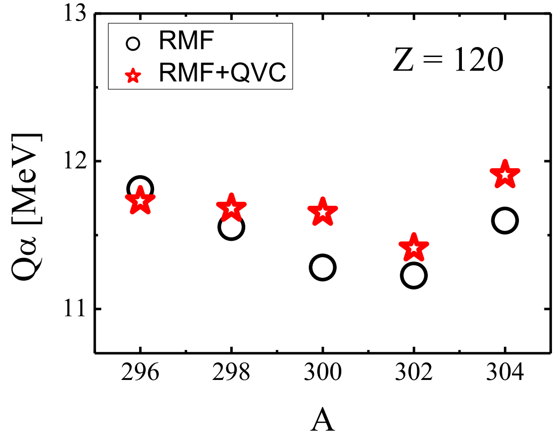
1. Relativistic Mean Field: spherical minima
2. π: collapse of pairing, clear shell gap
3. ν: survival of pairing coexisting with the shell gap
4. Very soft nuclei: large amount of low-lying collective vibrational modes (~100 phonons below 15 MeV)

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 α-decay Q-values



Vibrational corrections:

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

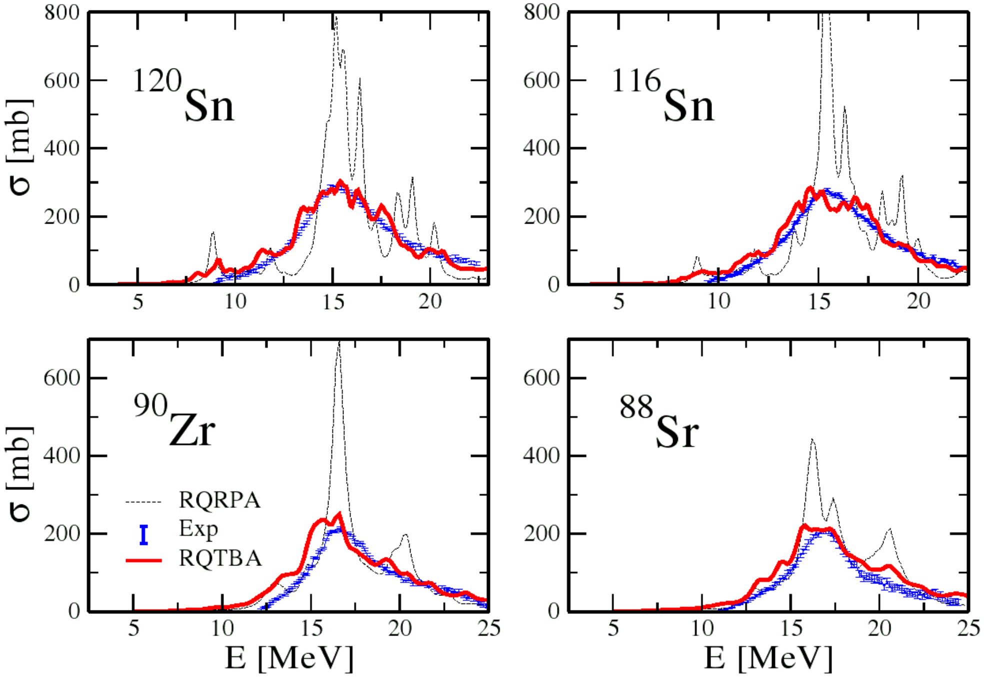
Shell stabilization & vibration stabilization/destabilization (?)

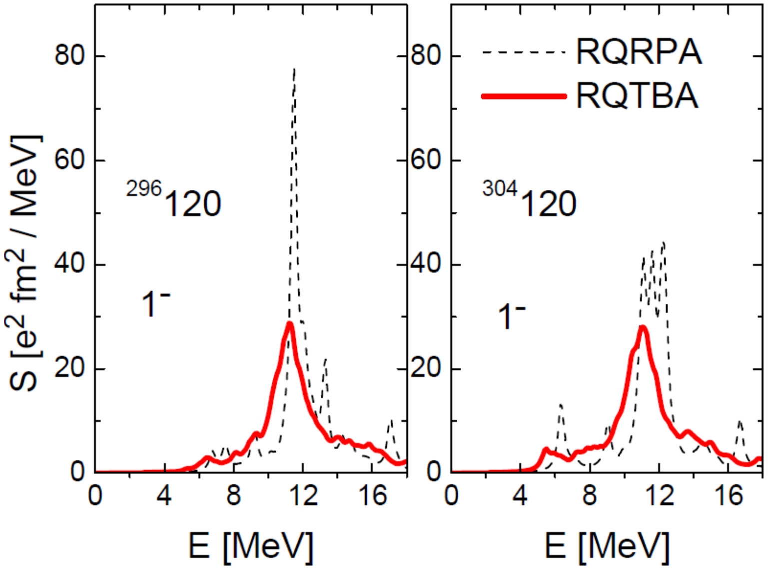
E.L., PRC 85, 021303(R) (2012)

Covariant NFT for nuclear response (RQTBA)

E. Litvinova, P. Ring, V. Tselyaev, PRC **88**, 044320 (2013).
PRL 105, 022502 (2010)
PRC 78, 014312 (2008).

Giant resonances (here dipole)





From giant resonances' widths to transport coefficients

Perspectives: inclusion higher-order correlations
Description of low-energy spectroscopy:

J. Endres et al. PRL 105, 212503 (2010), PRC 85, 064331 (2012).
E. Lanza et al., PRC 89, 041601(R) (2014).
R. Massarczyk et al. PRC 86, 014319 (2012).
B. Ozel-Tashenov, PRC (2014).

And other…

Summary and outlook

- Nuclear Dynamics:

1. Extremely complicated.
2. Phenomenological theories contradict each other and contain adjustable parameters. Although (therefore?) quite uccessful.
3. Fully microscopic description of nuclear structure and dynamics in the framework of the time-dependent Hartree-Fock method and extensions.

- Nuclear structure:

1. Skyrme, Gogny, Relativistic, Fayans functionals: impressive developments.
2. Recent progress: adding correlations, such as particle number and angular momentum projection, Generator Coordinate Method, particle-vibration coupling,...
3. Relativistic approach: from the covariant density functional theory to covariant nuclear field teory.

Recent developments:

- Self-consistent theory including meson degrees of freedom, particle-vibration coupling and nuclear superfluidity;
- Covariant response theory for multiphonon coupling
- Inclusion of pion dynamics

Many thanks for collaboration:

Nuclear structure:

P. Ring (Munich)
V. Tselyaev (St. Petersburg)
D. Vretenar (Zagreb)
W. Nazarewicz (MSU)
A. Afanasjev (MisSU)
M. Bender (Bordeaux)
P.-H. Heenen (Brussels)

Dynamics:

B. Avez
D. Boilley (GANIL)

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