Spherical and deformed nuclei within the EDF framework

Danilo Gambacurta
gambacurta@lns.infn.it
INFN-LNS Catania

WS 3x60: Multifaceted aspects of collaborative research on nuclear sturcture at UNIMI and INFN-MI
17–18 October 2024, Milano, Italy

Outline

Outline

- ...
- ...
- ...

~~Outline~~$\mapsto$ Story-line

- ...
- ...
- ...

~~Outline~~ ↦ Storyline

- The first time I met Gianluca

~~Outline~~ ↦ Storyline

- The first time I met Gianluca
- The first paper with Gianluca (back in time or ... *"ab initio"*)

~~Outline~~ ↦ Storyline

- The first time I met Gianluca
- The first paper with Gianluca (back in time or ... *"ab initio"*)
- The most recent collaboration with Gianluca (deformed nuclei)

~~Outline~~ ↦ Storyline

- The first time I met Gianluca
- The first paper with Gianluca (back in time or ... *"ab initio"*)
- The most recent collaboration with Gianluca (deformed nuclei)
- Future work with Gianluca

Terzo Corso

Otranto 28 Maggio - 2 Giugno 2007

I - Effective interactions for nuclear structure

Otranto,
May 28th-30th, 2007

G. Colò

University of Milano, and INFN

colo@mi.infn.it

II - Exotic nuclei

Otranto,
May 28th-30th, 2007

G. Colò

University of Milano, and INFN

colo@mi.infn.it

III - Time-dependent theories

Otranto,
May 28th-30th, 2007

G. Colò

University of Milano, and INFN

colo@mi.infn.it

Terzo Corso

Otranto 28 Maggio - 2 Giugno 2007

Teachers:
P.F. Bortignon
A. Bracco
L. Coraggio
G. Colò
A. Gargano
P. Finelli
L. Fortunato
R. Fossion
E.D. Lanza
G. Pollarolo
E. Vigezzi
A. Vitturi

I - Effective interactions for nuclear structure

Otranto,
May 28th-30th, 2007

), and INFN
olo@mi.infn.it

II - Exotic n

e-dependent theories

G. Colò
University of Milano, and INFN
colo@mi.infn.it

Otranto,
May 28th-30th, 2007

, and INFN
lo@mi.infn.it

Terzo Corso

Otranto 28 Maggio - 2 Giugno 2007

I - Effective interactions for nuclear structure

Otranto,
May 28th-30th, 2007

G. Colò
University of Milano, and INFN
colo@mi.infn.it

II - Exotic nuclei

Otranto,
May 28th-30th, 2007

G. Colò
University of Milano, and INFN
colo@mi.infn.it

III - Time-dependent theories

Otranto,
May 28th-30th, 2007

G. Colò
University of Milano, and INFN
colo@mi.infn.it

The first time I met Gianluca

Scuola
di Fisica Nucleare
Raimondo Anni

Terzo Corso

Otranto 28 Maggio - 2 Giugno 2007

I - Effective interactions for nuclear structure

Otranto,
May 28th-30th, 2007

G. Colò
University of Milano, and INFN
colo@mi.infn.it

II - Exotic nuclei

Otranto,
May 28th-30th, 2007

G. Colò
University of Milano, and INFN
colo@mi.infn.it

III - Time-dependent theories

Otranto,
May 28th-30th, 2007

G. Colò
University of Milano, and INFN
colo@mi.infn.it

The first paper with Gianluca

Motivations: Effective interactions and Energy Density Functional Theory

- Phenomenological forces like Skyrme (zer-range), or Gogny (finite-range), Covariant (meson-exchange) depending on some parameters
- These parameters are obtained to reproduce some observables (binding energies and charge radii) of atomic nuclei and nuclear matter properties

Advantges

- Relatively (numerically) simple to be treated
- Quite satisfactory description of nuclei along the nuclear chart
- Link with the underlying functional and Equation of State (EoS)

Disavantages

- We fit (a few) data to reproduce (a lot) data, not the cleanest way
- We loose connection with the underlying, more fundamental theory (QCD)
- Errors and uncertainties not under control

Current Challenge for the nuclear community

- Ab initio techniques to derive in-medium nuclear interaction from the QCD (effective field theory)

PHYSICAL REVIEW C **84**, 024301 (2011)

Determination of local energy density functionals from Brueckner-Hartree-Fock calculations

D. Gambacurta,[1] L. Li,[2] G. Colò,[3] U. Lombardo,[1] N. Van Giai,[4] and W. Zuo[5]

[1]*Dipartimento di Fisica and INFN-LNS, Via S. Sofia 64, I-95123 Catania, Italy*

[2]*State Key Lab Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*

[3]*Dipartimento di Fisica, Università degli Studi, and INFN Sezione di Milano, via Celoria 16, I-20133 Milano, Italy*

[4]*Institut de Physique Nucléaire, IN2P3-CNRS and Université Paris-Sud, F-91405 Orsay, France*

[5]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

(Received 3 May 2011; published 8 August 2011)

Skyrme-like energy density functionals are built upon new *ab initio* calculations of nuclear matter which reproduce the empirical saturation properties. These calculations are performed in the framework of the Brueckner-Hartree-Fock approximation with consistent two- and three-body forces. The Skyrme parametrizations are obtained from a simultaneous fit of the spin-isospin components of the potential energy of symmetric nuclear matter and of the experimental energies and charge radii of a number of closed-shell and closed-subshell nuclei. These parametrizations are tested on the energies and charge radii of the Sn isotopic chain and on the ^{208}Pb giant resonances, showing a substantial improvement of the LNS functional obtained in a previous fit. The comparison with standard Skyrme forces can give some hints on how to reconcile nuclear matter and finite nuclei.

DOI: 10.1103/PhysRevC.84.024301 PACS number(s): 21.65.Mn, 21.30.−x

PHYSICAL REVIEW C **84**, 024301 (2011)

Determination of local energy density functionals from Brueckner-Hartree-Fock calculations

D. Gambacurta,[1] L. Li,[2] G. Colò,[3] U. Lombardo,[1] N. Van Giai,[4] and W. Zuo[5]

[1] *Dipartimento di Fisica and INFN-LNS, Via S. Sofia 64, I-95123 Catania, Italy*

[2] *State Key Lab Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*

[3] *Dipartimento di Fisica, Università degli Studi, and INFN Sezione di Milano, via Celoria 16, I-20133 Milano, Italy*

[4] *Institut de Physique Nucléaire, IN2P3-CNRS and Université Paris-Sud, F-91405 Orsay, France*

[5] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

(Received 3 May 2011; published 8 August 2011)

Skyrme-like energy density functionals are built upon new *ab initio* calculations of nuclear matter which reproduce the empirical saturation properties. These calculations are performed in the framework of the Brueckner-Hartree-Fock approximation with consistent two- and three-body forces. The Skyrme parametrizations are obtained from a simultaneous fit of the spin-isospin components of the potential energy of symmetric nuclear matter and of the experimental energies and charge radii of a number of closed-shell and closed-subshell nuclei. These parametrizations are tested on the energies and charge radii of the Sn isotopic chain and on the ^{208}Pb giant resonances, showing a substantial improvement of the LNS functional obtained in a previous fit. The comparison with standard Skyrme forces can give some hints on how to reconcile nuclear matter and finite nuclei.

DOI: 10.1103/PhysRevC.84.024301 PACS number(s): 21.65.Mn, 21.30.−x

The first paper with Gianluca

Pseudo Data: BHF energy per particle

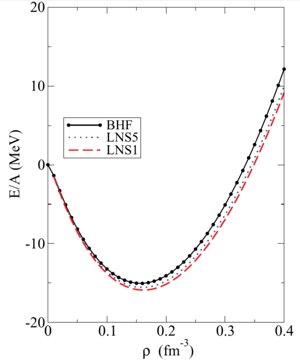


FIG. 6. (Color online) Energy per particle for symmetry nuclear matter: BHF vs. Skyrme parametrizations of Table II.

Pseudo Data: spin-isospin decomposition

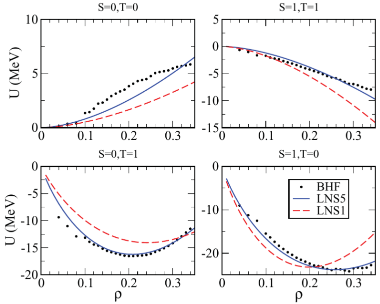
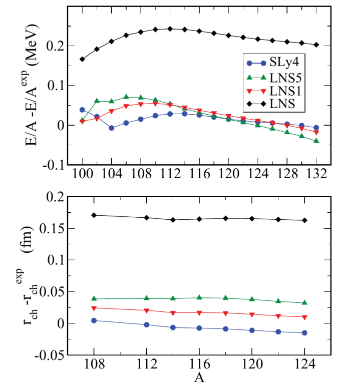


FIG. 5. (Color online) Spin-isospin components of the potential energy from the BHF calculations compared with the results from LNS5 and LNS1.

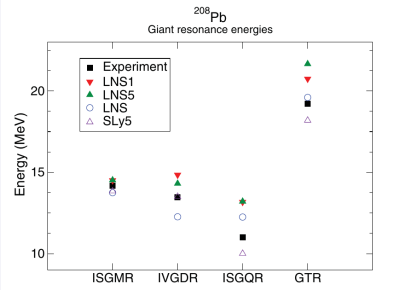
The first paper with Gianluca

Binding energies and charge radii in tin isotopes



LNS from L. G. Cao *et al.* PRC 73, 014313 (2006).

Giant Resonances in ^{208}Pb



PHYSICAL REVIEW C **104**, 024315 (2021)

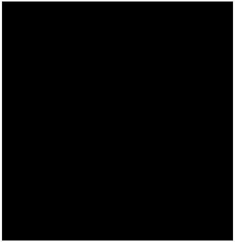
Nuclear energy density functionals grounded in *ab initio* calculations

F. Marino,[1,2,*] C. Barbieri,[1,2] A. Carbone,[3] G. Colò,[1,2] A. Lovato,[4,5] F. Pederiva,[6,5] X. Roca-Maza,[1,2]
and E. Vigezzi[2]

PHYSICAL REVIEW C **107**, 044311 (2023)

Perturbed nuclear matter studied within density functional theory with a finite number of particles

F. Marino,[1,2,*] G. Colò,[1,2] X. Roca-Maza,[1,2] and E. Vigezzi[2]
[1]*Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, 20133 Milano, Italy*
[2]*INFN, Sezione di Milano, 20133 Milano, Italy*



Terzo Corso

Otranto 28 Maggio - 2 Giugno 2007

I - Effective interactions for nuclear structure

Otranto,
May 28th-30th, 2007

G. Colò
University of Milano, and INFN
colo@mi.infn.it

II - Exotic nuclei

Otranto,
May 28th-30th, 2007

G. Colò
University of Milano, and INFN
colo@mi.infn.it

III - Time-dependent theories

Otranto,
May 28th-30th, 2007

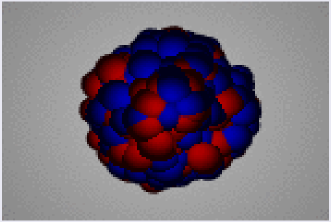
G. Colò
University of Milano, and INFN
colo@mi.infn.it

Giant Resonances, a macroscopic picture

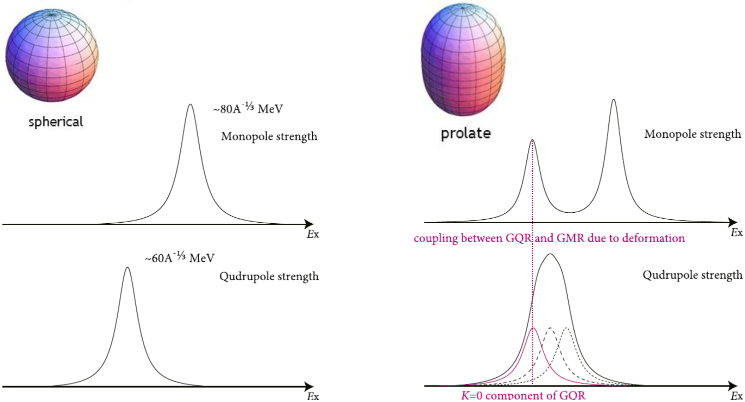
Time-dependent EDF approaches

- Study of the excited states and multipole response
- Random Phase Approximation (RPA) or TDHF, is the standard tool with the EDF framework
- Collective excitations and their impact on EoS
- Increasing number of experiments focus on deformed nuclei

ISGMR (L=0,S=0,T=0): n and p in phase (isoscalar), compression (breathing) mode



$E_{ISGMR} \propto \sqrt{K_A} \sim \sqrt{K_\infty}, \qquad K_\infty = 240 \pm 20 MeV$ from ^{208}Pb and from ^{90}Zr
See Garg and Colo' PNPP 101,55 (2018)



U. Garg, G. Colò / Progress in Particle and Nuclear Physics 101 (2018) 55–95

The most recent collaboration with Gianluca: deformed nuclei

PHYSICAL REVIEW C **93**, 044324 (2016)

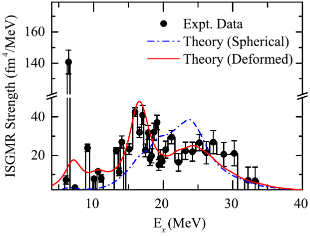
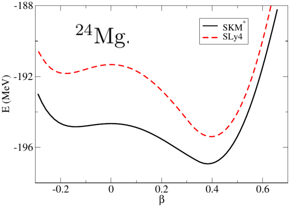
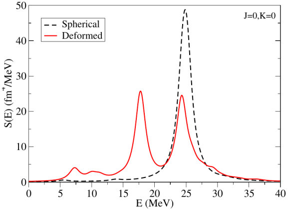


FIG. 5. ISGMR strength distributions in ^{24}Mg. The dash-dotted (blue) and solid (red) lines show microscopic calculations for spherical and prolate ground-state deformation, respectively.

Calculations by K. Yoshida were used to show that the double peak is related to deformation.

D.G. G. Colò, A. Pastore,
J. Phys.: Conf. Ser. 1643 012129,2020





Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Isoscalar monopole and quadrupole modes in Mo isotopes: Microscopic analysis

Gianluca Colò [a,b,*], Danilo Gambacurta [c,d], Wolfgang Kleinig [e], Jan Kvasil [f], Valentin O. Nesterenko [e,g,h], Alessandro Pastore [i]

PHYSICAL REVIEW C **109**, 044315 (2024)

Symmetry-restored Skyrme-random-phase-approximation calculations of the monopole strength in deformed nuclei

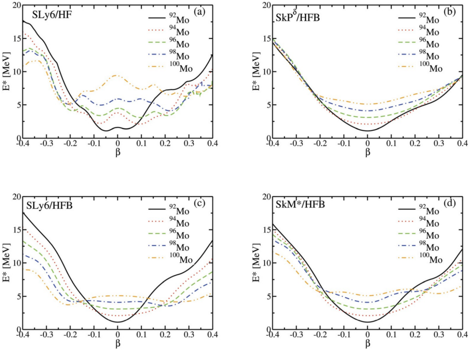
A. Porro,[1,2,3,*] G. Colò,[4,5,†] T. Duguet,[1,6,‡] D. Gambacurta,[7,§] and V. Somà[1,‖]

The most recent collaboration with Gianluca: deformed nuclei

Physics Letters B 811 (2020) 135940

Isoscalar monopole and quadrupole modes in Mo isotopes: Microscopic analysis

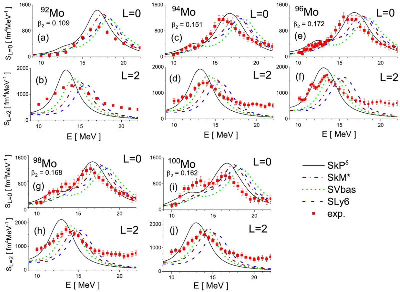
Gianluca Colò [a,b,*], Danilo Gambacurta [c,d], Wolfgang Kleinig [e], Jan Kvasil [f], Valentin O. Nesterenko [e,g,h], Alessandro Pastore [i]



Physics Letters B 811 (2020) 135940

Isoscalar monopole and quadrupole modes in Mo isotopes: Microscopic analysis

Gianluca Colò [a,b,*], Danilo Gambacurta [c,d], Wolfgang Kleinig [e], Jan Kvasil [f], Valentin O. Nesterenko [e,g,h], Alessandro Pastore [i]



RCNP (α, α') data

The "shoulder" is due to the monopole-quadrupole coupling (see for example ^{98}Mo)

Table 1
Incompressibility K_∞ and isoscalar effective mass m^*/m for the Skyrme forces SVbas, SLy6, SkM*, and SkP$^\delta$.

	SVbas	SLy6	SkM*	SkP$^\delta$
K_∞ [MeV]	234	230	217	202
m^*/m	0.9	0.69	0.79	1

GQR (SVbas) GMR (SkP$^\delta$)

Warning: no simultaneous description and K too low

Deformed RPA calculations break (on purpose) the **rotational symmetry**.
Excited states **do not have a good angular momentum J**.
Restoration of J is needed!!!

$$| KM\rangle \mapsto | JM\rangle = P^J_{KM} | KM\rangle = \frac{2J+1}{8\pi^2}\int d\Omega\, \mathcal{D}^{J*}_{MK}(\Omega)\mathcal{R}(\Omega) | KM\rangle$$

$$|\omega\rangle = Q^\dagger_\omega|\mathrm{RPA}\rangle \equiv \sum_{ph}\left(X^\omega_{ph} a^\dagger_p a_h|\mathrm{RPA}\rangle - Y^\omega_{ph} a^\dagger_h a_p|\mathrm{RPA}\rangle\right)$$

$$\langle \mathrm{RPA}\|T_\lambda\|\omega\rangle = N_0 N_\omega (2J_0+1)(-1)^{J_0-K_0}\sum_{ph}\sum_{\mu=-\lambda}^{+\lambda}\left\{X^\omega_{ph}+(-1)^\mu Y^\omega_{ph}\right\}\begin{pmatrix} J_0 & \lambda & J_\omega \\ -K_0 & \mu & K_0-\mu\end{pmatrix}\langle \mathrm{HF}|T_{\lambda\mu}P^{J_\omega}_{K_0-\mu,K_{ph}} c^\dagger_p c_h|\mathrm{HF}\rangle$$

$$N_i^{-1} = \sqrt{\langle\Phi_i|P^{J_i}_{K_iK_i}|\Phi_i\rangle} \qquad P^J_{MK} = \frac{2J+1}{2}\int_{-1}^{+1} \mathrm{d}(\cos\beta)\, d^J_{MK}(\beta)\, e^{-i\beta J_y}$$

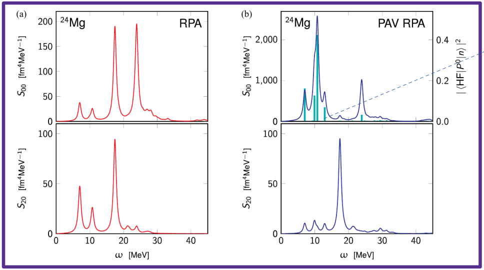
Projected transition amplitudes

PHYSICAL REVIEW C **109**, 044315 (2024)

Symmetry-restored Skyrme-random-phase-approximation calculations of the monopole strength in deformed nuclei

A. Porro[1,2,3,*] G. Colò[4,5,†] T. Duguet[1,6,‡] D. Gambacurta[7,§] and V. Somà[1,‖]

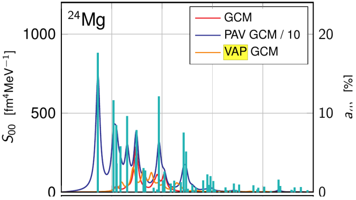
First ever Projected Skyrme-RPA calculations



Low-lying spurious strength appears due to the coupling with (spurious) rotational motion

Similar behaviour in projected generator coordinate method (PGCM) calculations with Projection after Variation (PAV) approach

It was shown to disappear in its full variation after projection (VAP) counterpart.



A. Porro et al. arXiv:2407.01325

Need of VAP-RPA calculations!

VAP-(Q)RPA calculations

- Variation After Projection approach
- Projected (Q)RPA equations of motion
- Projecting the matrix elements of residual interaction (two-body operator)

Outlook and Future Work

VAP-(Q)RPA calculations

- Variation After Projection approach
- Projected (Q)RPA equations of motion
- Projecting the matrix elements of residual interaction (two-body operator)

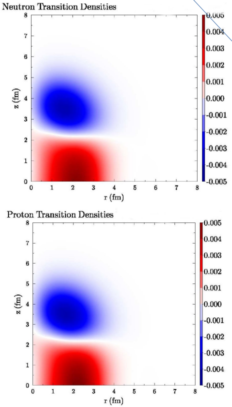
Beyond mean-field correlations in RPA-like theories

- Particle Vibration Coupling (coupling with low-lying phonons)
- Second RPA (2 particle-2 hole configurations)
- Comparing and "merging" them

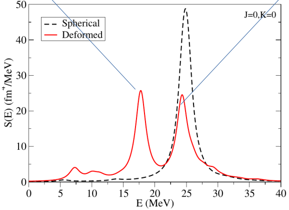
Thanks For Your Attention !!!

The most recent collaboration with Gianluca: deformed nuclei

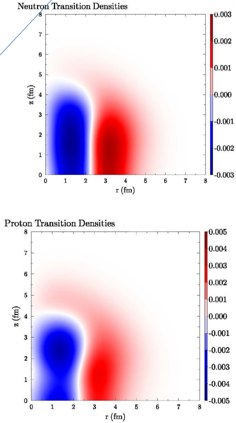
17.76 MeV



Transition densities in the cylindrical coordinates(z,r)



24.29 MeV



The most recent collaboration with Gianluca: deformed nuclei

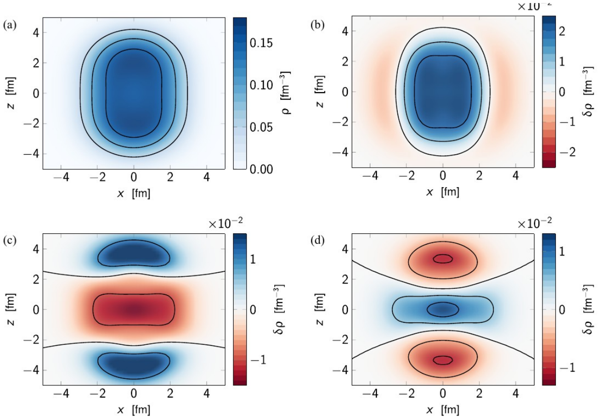


FIG. 4. ^{24}Mg (a) one-body intrinsic matter density of the HF ground state, (b) intrinsic RPA transition matter density to the ISGMR phonon at 23.9 MeV, (c) intrinsic RPA transition matter density to the ISGQR phonon at 17.5 MeV, and (d) intrinsic RPA transition matter density to the phonon at 10.8 MeV.