Nuclear response and decay processes within beyond mean-field methods

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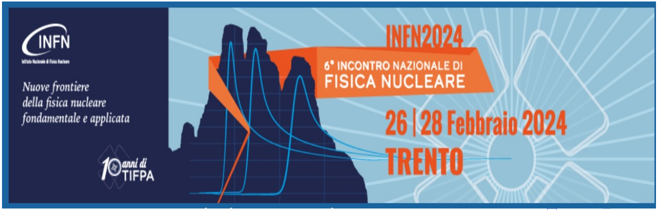
MOdeling
Nuclear
STructure and
REactions



Outline

Nuclear response (and decay processes)

- General features and properties
- Connections with other open questions/investigations

Microscopic description of the nuclear response

- Mean-field approximation: The Random Phase Approximation (RPA)
- Beyond mean-field approaches: The Second RPA and the PVC models

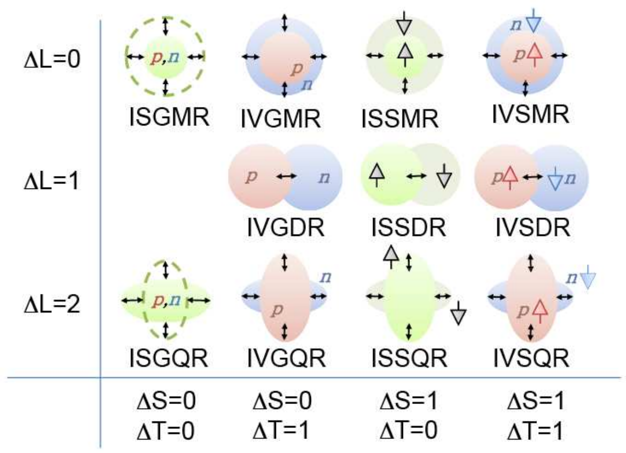
Recent Applications

- The GMR puzzle and nuclear incompressibility
- Gamow-Teller excitations and Beta-decay (and quenching problem)

The nuclear response (NR)

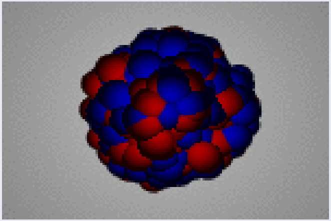
- A standard way to investigate nuclei is to perturb them with a probe (γ, protons, α-particles, ...) $\longmapsto$ **Nuclear Response** (NR)
- A large part of the NR is absorbed by collective excitations where many nucleons participate in a coherent way (for example **Giant Resonances**)
- Their properties are related to the **underlying nuclear interaction**
- NR is very rich and variegate $\longmapsto$ **Challenge for Theory and Experiment**

GRs, a schematic picture: Multipolarity L, Spin S, Isospin T

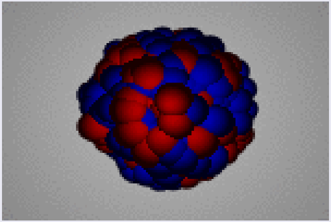


Giant Resonances, a macroscopic picture

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

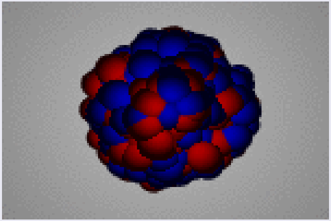


IVGDR (L=1,S=0,T=1): neutrons (n) and protons (p) in opposite phase (isovector)



Giant Resonances, a macroscopic picture

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



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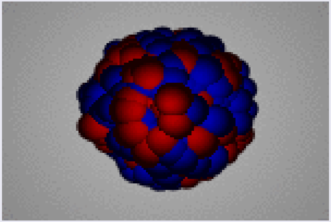
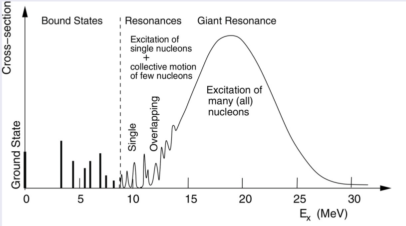


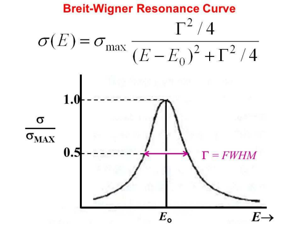
A closer Look to the nuclear response: Main properties

Total Strength

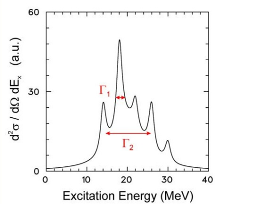


Credit: Hans Pætz gen. Schieck

Centroid (E_0), Width (Γ) and Fine structure



Centroid (E_0), Width (Γ)

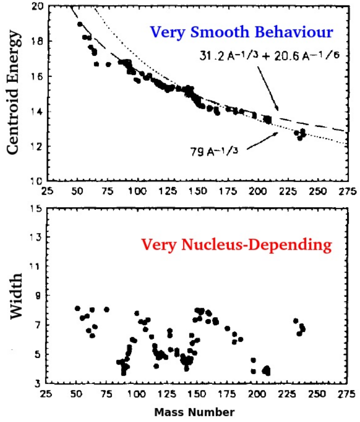


Credit A. Richter

High precision studies$\mapsto$Fine structure

The Giant Dipole Resonance (GDR) case

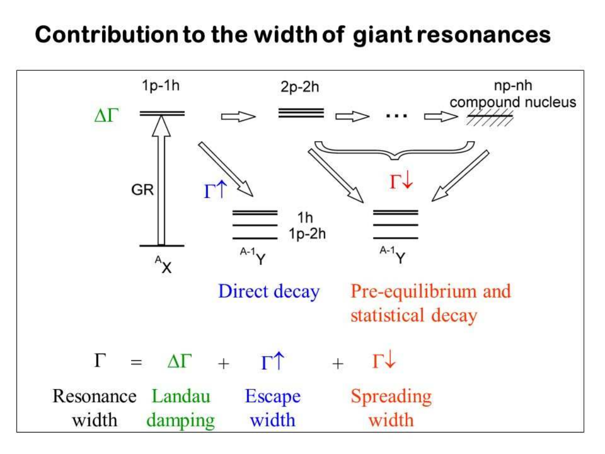
Centroid Energy and Width



From: Ph. Chomaz, N. Frascaria, Physics Reports 252 (1995)

Strong challenge for many-body microscopic theories

The Width of GRs

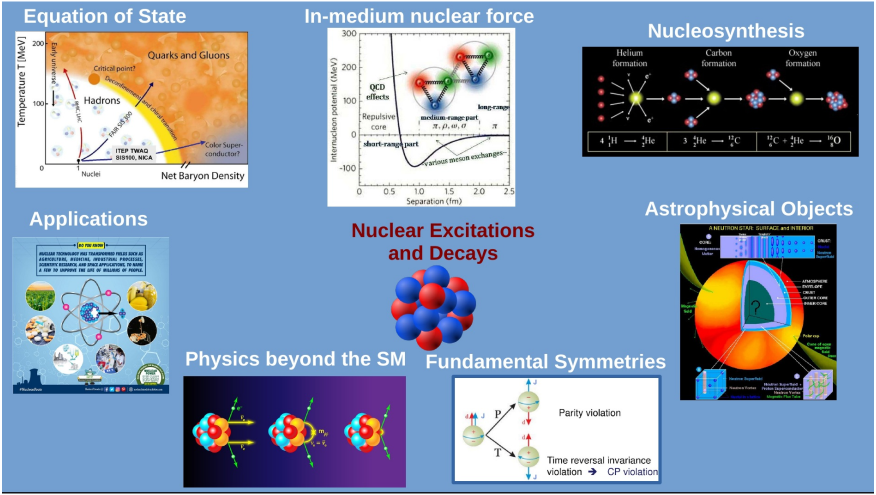


From P. von Neumann-Cosel *et al.*, Eur. Phys. J. A 55, 224 (2019)

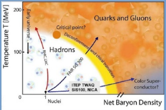
(i) Competition among different mechanisms

(ii) Very nucleus and “channel” depending

Connections with other open questions/investigations

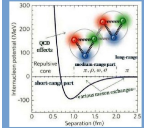


Equation of State (EoS): Main parameters of EoS can be related to the nuclear response



- **Compressibility modulus K** ~ Giant Monopole Resonance
- **Simmetry Energy and its slope** ~ Giant Dipole Resoanance, Pygmy dipole resonance, Isobaric analog state
- **Effective mass** ~ Giant Quadrupole Resonance

In-medium nuclear force, State of art studies: From QCD to V_{nn} (Lattice QCD, EFT, ...)



- **Current challenge**: Binding Energy, Charge radii, low-lying spectroscopy
- **Future challenges**: Nuclear excitations can provide more information and constraints

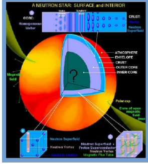
PRL **111**, 122502 (2013) PHYSICAL REVIEW LETTERS week ending 20 SEPTEMBER 2013

First Principles Description of the Giant Dipole Resonance in ^{16}O

S. Bacca,[1] N. Barnea,[2] G. Hagen,[3,4] G. Orlandini,[5] and T. Papenbrock[4,3]

Pioneering work

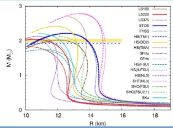
Astrophysical Objects



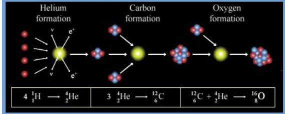
- **EoS** input in Tolman–Oppenheimer–Volkoff (**TOV**) **equation**
- **Radius-mass relation** of N.S. depends on the slope of the symmetry energy
- **Multimessanger Physics** (Terrestrial and Astrophysical observations)

$$\frac{dP(r)}{dr} = -G\frac{[\epsilon(r)+P(r)][M(r)+4\pi r^3 P(r)]}{r^2[1-2GM(r)/r]}$$

$$\frac{dM(r)}{dr} = 4\pi\epsilon(r)r^2, \quad \textbf{TOV Equation}$$



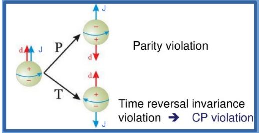
Nucleosynthesis



Low-Lying excitations in neutron rich nuclei: strong impact on the radiative neutron capture (r-process nucleosynthesis) [Nuclear Phys. A 739 (3) (2004)]

Gamow-Teller transitions:
- weak interaction rates in stellar environment [Phys. Rev. Lett. 112 (2014) 252501]
- r-process stellar nucleosynthesis [Phys. Rep. 450 (4) (2007)]

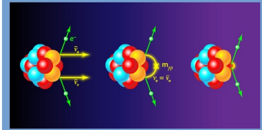
Fundamental Symmetries



Fermi and Gamow-Teller β transitions can provide
- accurate measurements the gA /gV coupling-constant ratio
- or search for symmetry violations, CKM matrix

Electric dipole moment (EDM) violates both P and T symmetry.
- CP violation and the matter-antimatter asymmetry.
- Number of experiments on different systems (nucleons, nuclei, atoms): Octupole-deformed heavy nuclei (Ra, Pa, Hg)

Physics beyond the SM



Neutrinoless double-β decay:
- Lepton number violation
- Majorana neutrino
- neutrino's mass

Set of exact eigenstates of the Hamiltonian H

$$H|\nu\rangle = E_\nu \mid \nu\rangle$$

where $\mid 0\rangle$ is the ground state with energy E_0

Phonon Operators

Let us introduce the operators $Q's$:

$$Q_\nu^\dagger \mid 0\rangle = \mid \nu\rangle, \qquad Q_\nu \mid 0\rangle = 0.$$

Equations of Motion:

$$\langle 0 \mid \left[\delta Q, [H, Q_\nu^\dagger]\right] \mid 0\rangle = \omega_\nu \langle 0 \mid [\delta Q, Q_\nu^\dagger] \mid 0\rangle$$

where

$$\omega_\nu = E_\nu - E_0.$$

Excitation Operators and Equations

RPA Phonon Operators

$$Q_\nu^\dagger = \sum_{ph} X_{ph}^{(\nu)} a_p^\dagger a_h - \sum_{ph} Y_{ph}^{(\nu)} a_h^\dagger a_p$$

RPA Equations of Motion (1$\mapsto$ 1p1h)

$$\begin{pmatrix} \mathcal{A}_{11} & \mathcal{B}_{11} \\ -\mathcal{B}_{11}^* & -\mathcal{A}_{11}^* \end{pmatrix} \begin{pmatrix} \mathcal{X}_1^\nu \\ \mathcal{Y}_1^\nu \end{pmatrix} = \omega_\nu \begin{pmatrix} \mathcal{X}_1^\nu \\ \mathcal{Y}_1^\nu \end{pmatrix}$$

RPA Phonon Operators

$$Q_\nu^\dagger = \sum_{ph} X_{ph}^{(\nu)} a_p^\dagger a_h - \sum_{ph} Y_{ph}^{(\nu)} a_h^\dagger a_p$$

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Second RPA Phonon Operators

$$Q_\nu^\dagger = \sum_{ph} (X_{ph}^{(\nu)} a_p^\dagger a_h - Y_{ph}^{(\nu)} a_h^\dagger a_p)$$

$$+ \sum_{p_1<p_2, h_1<h_2} (X_{p_1 h_1 p_2 h_2}^{(\nu)} a_{p_1}^\dagger a_{h_1} a_{p_2}^\dagger a_{h_2} - Y_{p_1 h_1 p_2 h_2}^{(\nu)} a_{h_1}^\dagger a_{p_1} a_{h_2}^\dagger a_{p_2})$$

Second RPA Equations of Motion (1$\mapsto$ 1p1h, 2$\mapsto$ 2p2h)

$$\begin{pmatrix} \mathcal{A}_{11} & \mathcal{A}_{12} & \mathcal{B}_{11} & \mathcal{B}_{12} \\ \mathcal{A}_{21} & \mathcal{A}_{22} & \mathcal{B}_{21} & \mathcal{B}_{22} \\ -\mathcal{B}_{11}^* & -\mathcal{B}_{12}^* & -\mathcal{A}_{11}^* & -\mathcal{A}_{12}^* \\ -\mathcal{B}_{21}^* & -\mathcal{B}_{22}^* & -\mathcal{A}_{21}^* & -\mathcal{A}_{22}^* \end{pmatrix} \begin{pmatrix} \mathcal{X}_1^\nu \\ \mathcal{X}_2^\nu \\ \mathcal{Y}_1^\nu \\ \mathcal{Y}_2^\nu \end{pmatrix} = \omega_\nu \begin{pmatrix} \mathcal{X}_1^\nu \\ \mathcal{X}_2^\nu \\ \mathcal{Y}_1^\nu \\ \mathcal{Y}_2^\nu \end{pmatrix}$$

Energy dependent RPA-like problem by projecting onto the $1p1h$ space

$$\begin{pmatrix} \tilde{\mathcal{A}}_{11}(\omega) & \mathcal{B}_{11} \\ -\mathcal{B}^*_{11} & -\tilde{\mathcal{A}}^*_{11}(\omega) \end{pmatrix} \begin{pmatrix} \mathcal{X}^\nu_1 \\ \mathcal{Y}^\nu_1 \end{pmatrix} = \omega \begin{pmatrix} \mathcal{X}^\nu_1 \\ \mathcal{Y}^\nu_1 \end{pmatrix}$$

$$A_{1,1'} \mapsto \tilde{A}_{1,1'}(\omega) = A^{RPA}_{1,1'} + \sum_{2,2'} A_{1,2}(\omega + i\eta - A_{2,2'})^{-1} A_{2',1'} = A^{RPA}_{1,1'} + A^{Cor}_{1,1'}(\omega)$$

$$A^{Cor}_{ph,p'h'}(\omega) = \sum_{22'} \frac{\langle ph|V|2\rangle\langle 2'|V|p'h'\rangle}{\omega - A_{22'} + i\eta}, \qquad |2\rangle \mapsto \text{2p2h configurations}$$

Particle Vibration Coupling (PVC)

Two-step calculations

(1) Random Phase Approximation (RPA)

$$Q_\nu^\dagger = \underbrace{\sum_{ph} X_{ph}^{(\nu)} \underbrace{a_p^\dagger a_h}_{\text{1p-1h}} - \sum_{ph} Y_{ph}^{(\nu)} \underbrace{a_h^\dagger a_p}_{\text{1h-1p}}}_{\textbf{X and Y are obtained}}$$

(2) Particle Vibration Coupling (PVC)

$$T_\alpha^\dagger = \sum_{ph} (X_{ph}^{(1\alpha)} a_p^\dagger a_h - Y_{ph}^{(1\alpha)} a_h^\dagger a_p) + \underbrace{\sum_{ph,\nu} (X_{ph}^{(2\alpha)} a_p^\dagger a_h Q_\nu^\dagger - Y_{ph}^{(2\alpha)} a_h^\dagger a_p Q_\nu)}_{\textbf{1p1h +RPA phonons coupling}}$$

Energy dependent RPA-like problem by projecting onto the $1p1h$ space

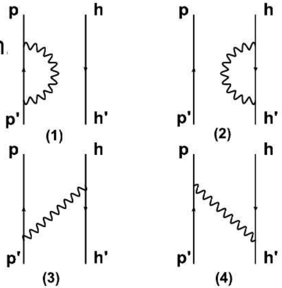
$$\begin{pmatrix} \tilde{\mathcal{A}}_{11}(\omega) & \mathcal{B}_{11} \\ -\mathcal{B}_{11}^{*} & -\tilde{\mathcal{A}}_{11}^{*}(\omega) \end{pmatrix} \begin{pmatrix} \mathcal{X}_1^{\nu} \\ \mathcal{Y}_1^{\nu} \end{pmatrix} = \omega \begin{pmatrix} \mathcal{X}_1^{\nu} \\ \mathcal{Y}_1^{\nu} \end{pmatrix}$$

$$A_{1,1'} \mapsto \tilde{A}_{1,1'}(\omega) = A_{1,1'}^{RPA} + A_{1,1'}^{Cor}(\omega)$$

$$A_{ph,p'h'}^{Cor}(\omega) = \sum_{\alpha} \frac{\langle ph|V|\alpha\rangle\langle\alpha|V|p'h'\rangle}{\omega - E_\alpha + i\eta}, \qquad |\alpha\rangle = |1p1h\rangle \times |\nu\rangle_{RPA}$$

The state α is 1p-1h plus one phonon.

$$\sum_{\alpha} \frac{\langle ph|V|\alpha\rangle\langle\alpha|V|p'h'\rangle}{E - E_\alpha + i\eta}$$



PHYSICAL REVIEW LETTERS **131,** 082501 (2023)

Toward a Unified Description of Isoscalar Giant Monopole Resonances in a Self-Consistent Quasiparticle-Vibration Coupling Approach

Z. Z. Li (李征征),[1,2,3] Y. F. Niu (牛一斐),[1,2,*] and G. Colò[3,4,†]
[1]*School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*Frontiers Science Center for Rare Isotope, Lanzhou University, Lanzhou 730000, China*
[3]*Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy*
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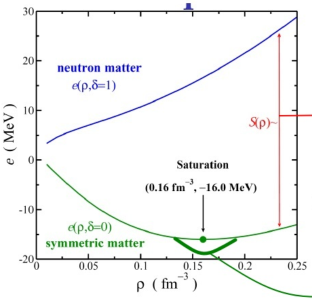
The nuclear incompressibility is a key parameter of the nuclear equation of state that can be extracted from the measurements of the so-called "breathing mode" of finite nuclei. The most serious discrepancy so far is between values extracted from Pb and Sn, that has provoked the longstanding question "Why is tin so soft?". To solve this puzzle, a fully self-consistent quasiparticle random-phase approximation plus quasiparticle-vibration coupling approach based on Skyrme-Hartree-Fock-Bogoliubov is developed. We show that the many-body correlations introduced by quasiparticle-vibration coupling, which shift the isoscalar giant monopole resonance energy in Sn isotopes by about 0.4 MeV more than the energy in ^{208}Pb, play a crucial role in providing a unified description of the isoscalar giant monopole resonance in Sn and Pb isotopes. The best description of the experimental strength functions is given by SV-K226 and KDE0, which are characterized by incompressibility values $K_\infty = 226$ MeV and 229 MeV, respectively, at mean field level.

- **Nuclear equation of state**



Nuclear matter (NM)	Symmetric NM	symmetry energy

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\delta^2$$

$$\delta \equiv (\rho_n - \rho_p)/\rho \qquad \xi = \frac{\rho-\rho_0}{3\rho_0}$$

$$\frac{E}{A}(\rho,\delta=0) = \epsilon_0 + \frac{1}{2}K\xi^2 + o(\xi^3)$$

Nuclear Incompressibility

EoS: heavy-ion collisions, neutron stars, supernova explosioons, nuclear structure, ...

K_A can be obtained from centroid energy of GMR

$$E_{ISGMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$

K_A: the compression modulus of the nucleus with mass number A

From K_A to K_∞

$$K_A = aK_\infty + b.$$

$$E_{\mathrm{ISGMR}} = a'\sqrt{K_\infty} + b'$$

K_∞ : incompressibility of nuclear matter

Garg and Colo, PPNP 101, 55 (2018)

From ^{208}Pb and ^{90}Zr: $K_\infty = 240 \pm 20$ MeV

IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 37 (2010) 064038 (10pp) doi:10.1088/0954-3899/37/6/064038

Focus issue on open problems in nuclear structure theory

Do we understand the incompressibility of neutron-rich matter?

J Piekarewicz

Department of Physics, Florida State University, Tallahassee, FL 32306, USA

Nuclear Physics A
Volume 788, Issues 1–4, 15 May 2007, Pages 36-43

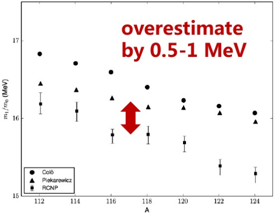
The Giant Monopole Resonance in the Sn Isotopes: Why is Tin so "Fluffy"?

U. Garg [a], T. Li [a], S. Okumura [b], H. Akimune [c], M. Fujiwara [b], M.N. Harakeh [d],

In even-even 112-124Sn, the ISGMR centroid energy is overestimated by about 1 MeV by the same models which reproduce the ISGMR energy well in 208Pb.

PRL 99, 162503 (2007) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2007

Isotopic Dependence of the Giant Monopole Resonance in the Even-A $^{112-124}$Sn Isotopes and the Asymmetry Term in Nuclear Incompressibility



From Sn isotopes: $K_\infty \sim 205$ MeV

QRPA and PVC calculations in Pb and Sn isotopes:

PHYSICAL REVIEW LETTERS **131,** 082501 (2023)

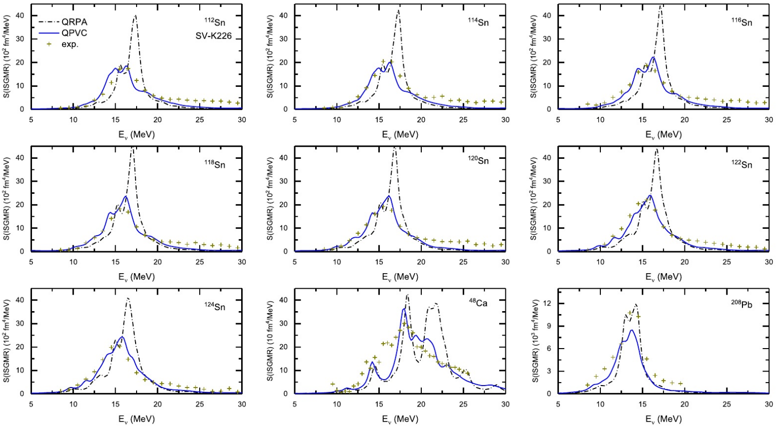
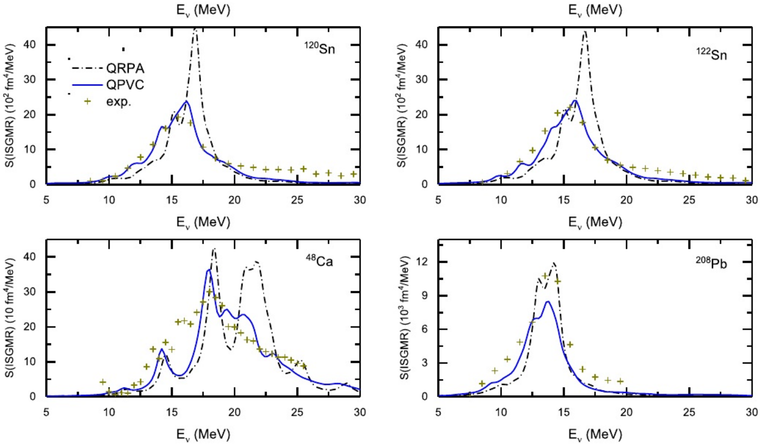
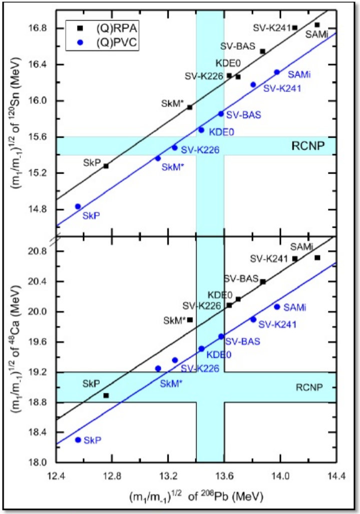


FIG. 1. ISGMR strength functions in even-even $^{112-124}$Sn, ^{48}Ca, and ^{208}Pb isotopes, calculated either by (Q)RPA using a smoothing with Lorentzian having a width of 1 MeV [dash-dotted (black) line], or (Q)RPA + (Q)PVC [solid (blue) line]. The SV-K226 Skyrme force is used. The experimental data are given by green crosses [8,15,45].



E_ν (MeV)
S(ISGMR) (10^2 fm^4/MeV)
^{120}Sn
QRPA
QPVC
exp.
^{122}Sn
^{48}Ca
S(ISGMR) (10 fm^4/MeV)
^{208}Pb
S(ISGMR) (10^3 fm^4/MeV)

Simultaneous reproduction of GMR centroid in Ca, Pb and Sn:



Systematic study of the consistency between ISGMR energies in different nuclei.

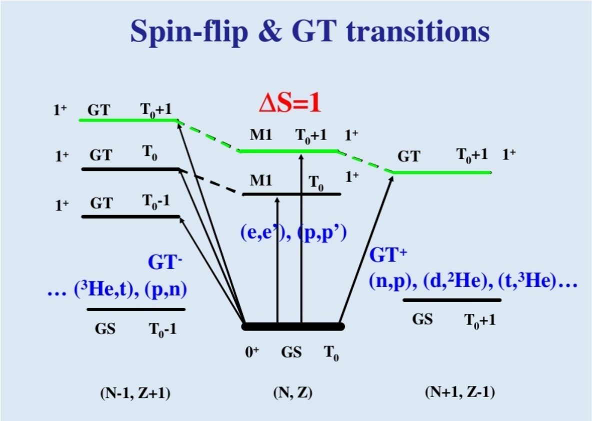
PVC coupling plays a key-role

- QRPA => QPVC

Simultaneous description of Sn (or Ca) and Pb is much improved!

- Best descriptions:

SV-K226 $K_\infty = 226$ MeV
KDE0 $K_\infty = 229$ MeV
consistent with $K_\infty = 240 \pm 20$ MeV



Gamow-Teller transition

ΔS=1 ΔL=0 ΔT=1

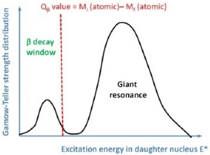
operator

$$\hat{O}_{\mathrm{GT}^-} = \sum_{i=1}^{A} \vec{\sigma}(i) \cdot \tau_-(i)$$

Transition probability

$$B(\mathrm{GT}^-) = \sum_{\nu} |\langle \nu | \hat{O} | 0 \rangle|^2$$

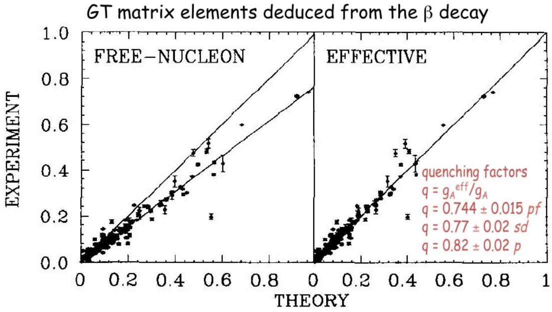
$$S_{GT^-} - S_{GT^+} = 3(N - Z).$$



Courtesy of Muhsin N. Harakeh/ and of Y. Niu

The quenching problem

- Computed GT matrix elements **are larger** than the experimental ones.
- The problem is "cured" by **quenching** the strength by $q \sim 0.7$ or using effective axial constant g_A (~ 1) instead of the "bare" value ~ 1.27.



(from Brown & Wildenthal, Ann.Rev.Nucl. Part.Sci.**38**,(1988)29)

Shell Model calculations

The quenching problem

- Computed GT matrix elements **are larger** than the experimental ones.
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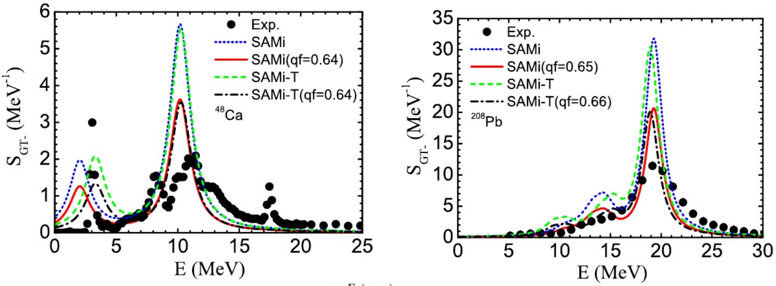

$$qf = \frac{\sum_{E_x=0}^{E_x(\max)} B(GT : E_x)_{\text{expt}}}{\sum_{E_x=0}^{E_x(\max)} B(GT)_{\text{calc}}}$$

Li-Gang Cao , Shi-Sheng Zhang, and H. Sagawa, PHYSICAL REVIEW C 100, 054324 (2019)

RPA calculations

Theory vs Experiment: the quenching problem

The quenching problem

- Computed GT matrix elements **are larger** than the experimental ones.
- The problem is "cured" by **quenching** the strength by $q \sim 0.7$ or using effective axial constant g_A (~ 1) instead of the "bare" value ~ 1.27.

Possible causes fall in two main classes:

- **Nuclear many- body correlations that escape calculations**: (truncation of the model space, short-range correlations, multi-phonon states, multi particle-hole excitations, ...)
- **Non-nucleonic degrees of freedom**: (Many-nucleon weak currents, Δ-isobar excitations, in-medium modification of pion physics, ...)

Gamow-Teller excitations and beta-decay

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Gamow-Teller Strength in ^{48}Ca and ^{78}Ni with the Charge-Exchange Subtracted Second Random-Phase Approximation

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We develop a fully self-consistent subtracted second random-phase approximation for charge-exchange processes with Skyrme energy-density functionals. As a first application, we study Gamow-Teller excitations in the doubly magic nucleus ^{48}Ca, the lightest double-β emitter that could be used in an experiment, and in ^{78}Ni, the single-beta-decay rate of which is known. The amount of Gamow-Teller strength below 20 or 30 MeV is considerably smaller than in other energy-density-functional calculations and agrees better with experiment in ^{48}Ca, as does the beta-decay rate in ^{78}Ni. These important results, obtained without *ad hoc* quenching factors, are due to the presence of two-particle–two-hole configurations. Their density progressively increases with excitation energy, leading to a long high-energy tail in the spectrum, a fact that may have implications for the computation of nuclear matrix elements for neutrinoless double-β decay in the same framework.

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See also D. Gambacurta and M. Grasso Phys. Rev. C 105, 014321 (2022)

GT$^-$ Strength Distribution ^{48}Ca, SGII interaction

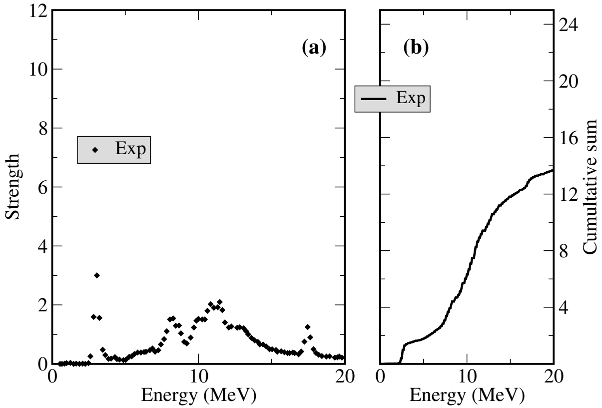

Figure: (a) GT$^-$ strength distributions in RPA and SSRPA compared with data.
(b) Cumulative strengths up to 20 MeV.
Data from: K. Yako *et al.*, Phys. Rev. Lett. 103, 012503 (2009)

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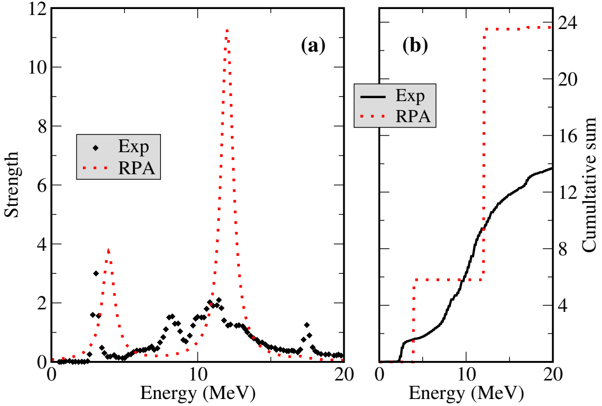

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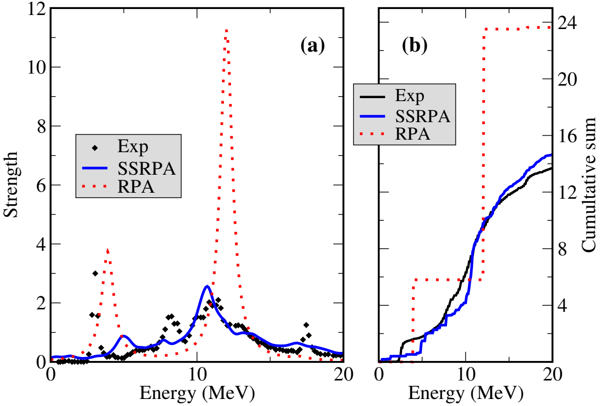

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GT$^-$ Strength Distribution ^{48}Ca

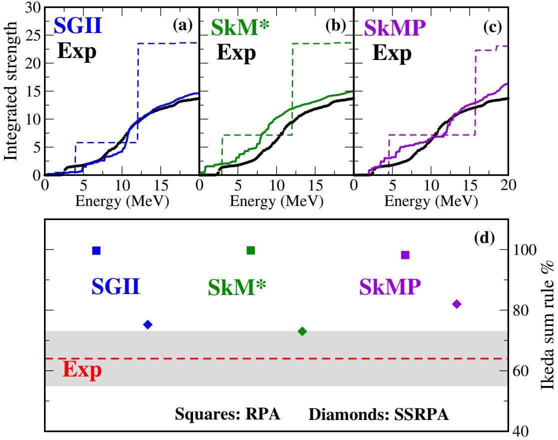

Figure: (a), (b), (c) Strengths integrated up to 20 MeV with different parameterizations.

(d) RPA and SSRPA percentages of the Ikeda sum rule below 30 MeV compared with the experimental one.

GT$^-$ Strength Distribution and β-decay half-life ^{78}Ni

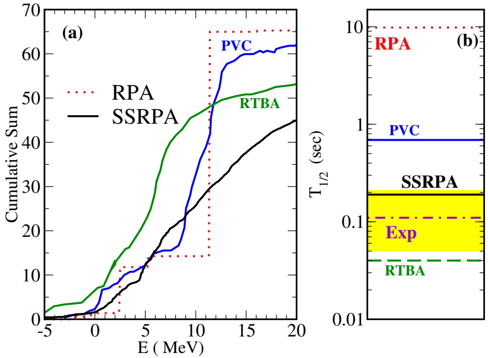

Figure: (a) Cumulative sum for the nucleus ^{78}Ni within the SSRPA, PVC and RTBA models;
(b) β-decay half-life for ^{78}Ni. **No quenching, bare $g_a = 1.27$;**
Data from: P. T. Hosmer *et al.* Phys. Rev. Lett. 94, 112501 (2005)
PVC: Y. F. Niu, G. Coló and E. Vigezzi, Phys. Rev. C 90, 054328 (2014)
RTBA:C. Robin and E. Litvinova, Phys. Rev. C 98, 051301(R), 2018

Perspectives

Theory

- More systematic applications of the Second RPA and PVC models
- Comparing Second RPA and PVC ...
- "Merging" Second RPA and PVC:
  PVC coupling with collective phonons:
  Second RPA: coupling of 1ph and 2ph degrees of freedom

Exp

- Giant Resonances in *exotic* and weakly bound nuclei (LNS, SPES, ...)
- Giant Resonances in deformed nuclei ...
- β-decay in plasma (PANDORA)
- Neutrinoless double-β decay (we need more accurate NMEs)
- NUMEN project: DCEX calculations based on BMF methods

The End!

Thank you!