WS 3x60: Multifaceted aspects of collaborative research on nuclear sturcture at UNIMI and INFN-MI
Milano, October 16-19, 2024

Development of quasiparticle vibration coupling theory based on Skyrme density functionals

Yifei Niu

MOE Frontiers Science Center for Rare Isotopes

School of Nuclear Science and Technology

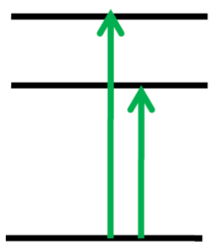
Lanzhou University

Nuclear Collective Vibrations

- **Nuclear collective vibration**

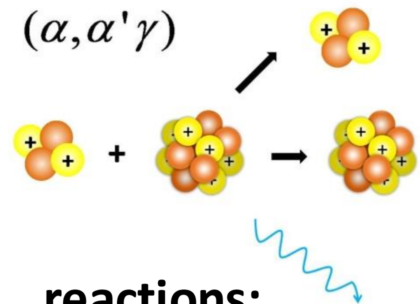
  the vibration excitation of nucleus involving many nucleons

➢ Non-charge-exchange excitations



Z, N

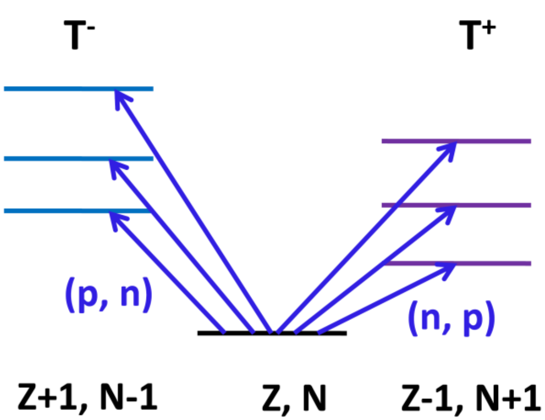
✓ Giant monople resonances (GMR)
✓ Giant dipole resonances (GDR)
✓ Giant quadrupole resonances (GQR)
…



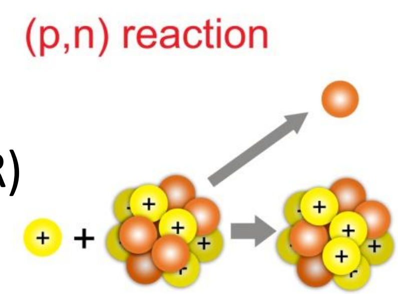
reactions:

Strong **(α, α’ γ),**
EM **(γ, γ’), (γ, n) ,(e, e’)**

➢ Charge-exchange excitations



✓ Isobaric Analogue States (IAS)
✓ Gamow-Teller Resonances (GTR)
✓ Spin-Dipole (SD) excitations
…

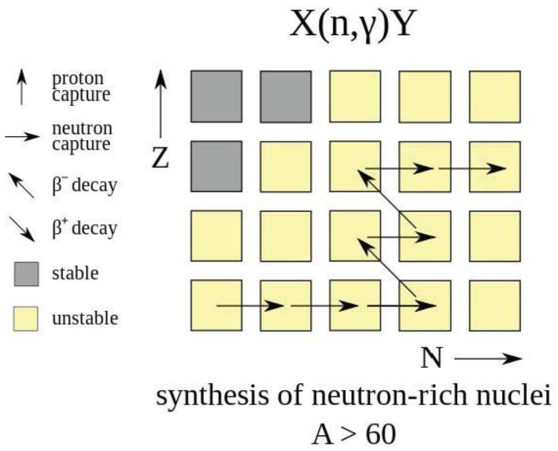


reactions:

Strong **(p,n) T^-, (n,p) T^+**
Weak **β decay, electron capture**

Collective Vibrations Provide Insight to

- ***How were the heavy elements from iron to uranium made?***
- ***What is the equation of state (EOS) of nuclear matter?***
- ***How do stars explode?***
- ***What are the masses of neutrinos?***
- ***What is the interaction between nucleons in nuclear medium that governs the properties of nuclei?***



Microscopic theories

☐ Configuration Interaction Shell Model

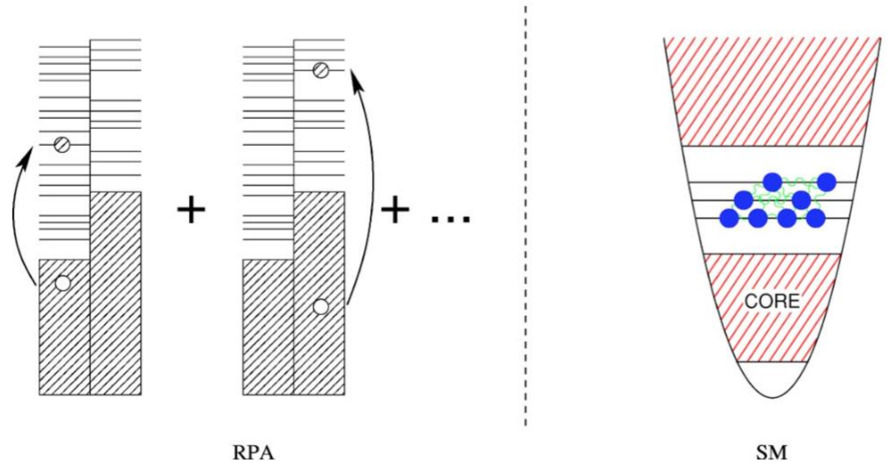
light nuclei or nuclei near magic number

S. E. Koonin et al., Phys. Rep. **278**, 1, 1997
E. Caurier, et al., Rev. Mod. Phys. **77**, 427, 2005

☐ Random Phase Approximation (RPA) based on density functionals

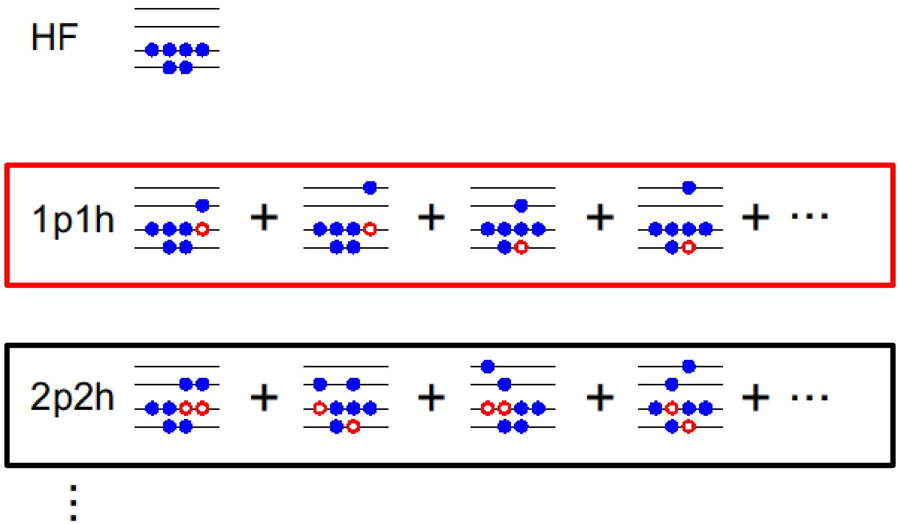
- Non-relativistic density functional
- Relativistic density functional

G. Colo, et al., Comp. Phys. Comm. 184, 142, 2013
N. Paar, et al., Rep. Prog. Phys. 70, 691, 2007



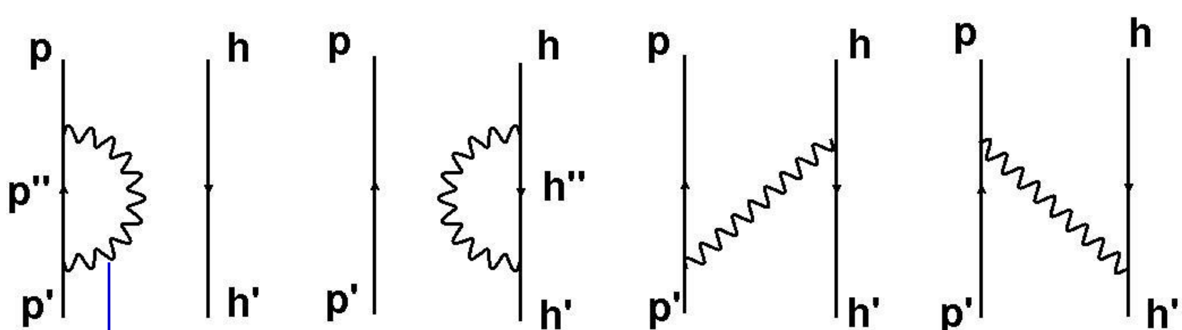
from K. Langanke et al., Rev. Mod. Phys. **75**, 819, 2003

Something in between? --- RPA+PVC model



RPA

- **Second RPA** drozdz et al., PR 197, 1 (1990)
  Gambacurta et al., PRC 81, 054312 (2010)
  Yang et al., PRC 106, 014319 (2022)
- **RPA + PVC (particle vibration coupling)**



Low-lying vibration phonons |N>

$$W^{\downarrow}_{ph,p'h'}(\omega) = \sum_N \frac{\langle ph|V|N\rangle\langle N|V|p'h'\rangle}{\omega - \omega_N}$$

RPA+PVC based on Skyrme density functional

PHYSICAL REVIEW C VOLUME 50, NUMBER 3 SEPTEMBER 1994

Escape and spreading properties of charge-exchange resonances in ^{208}Bi

G. Colò and N. Van Giai
Division de Physique Théorique, Institut de Physique Nucléaire, 91406 Orsay Cedex, France

P.F. Bortignon
Dipartimento di Fisica, Università degli Studi, and Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy

R.A. Broglia
Dipartimento di Fisica, Università degli Studi, and Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy, and Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark
(Received 22 April 1994)

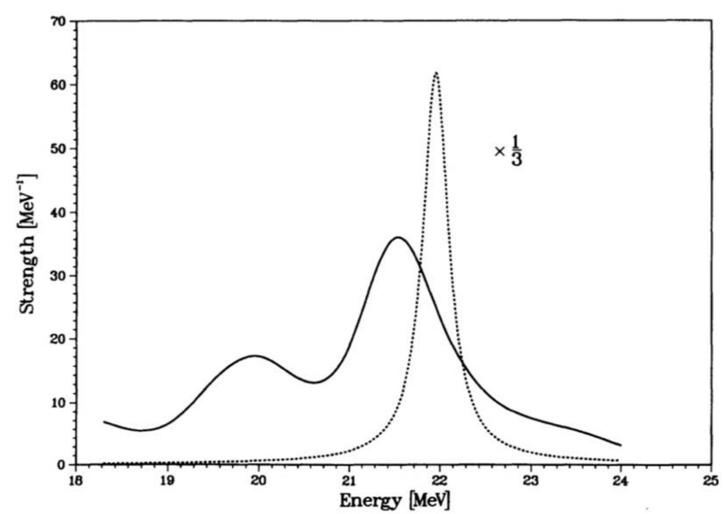
- RPA+PVC equation

$$\begin{pmatrix} \mathcal{D} + \mathcal{A}_1(\omega) & \mathcal{A}_2(\omega) \\ \mathcal{A}_3(\omega) & -\mathcal{D} + \mathcal{A}_4(\omega) \end{pmatrix} \begin{pmatrix} F^{(\nu)} \\ \bar{F}^{(\nu)} \end{pmatrix} = \left(\Omega_\nu - i\frac{\Gamma_\nu}{2}\right) \begin{pmatrix} F^{(\nu)} \\ \bar{F}^{(\nu)} \end{pmatrix},$$

- Strength function

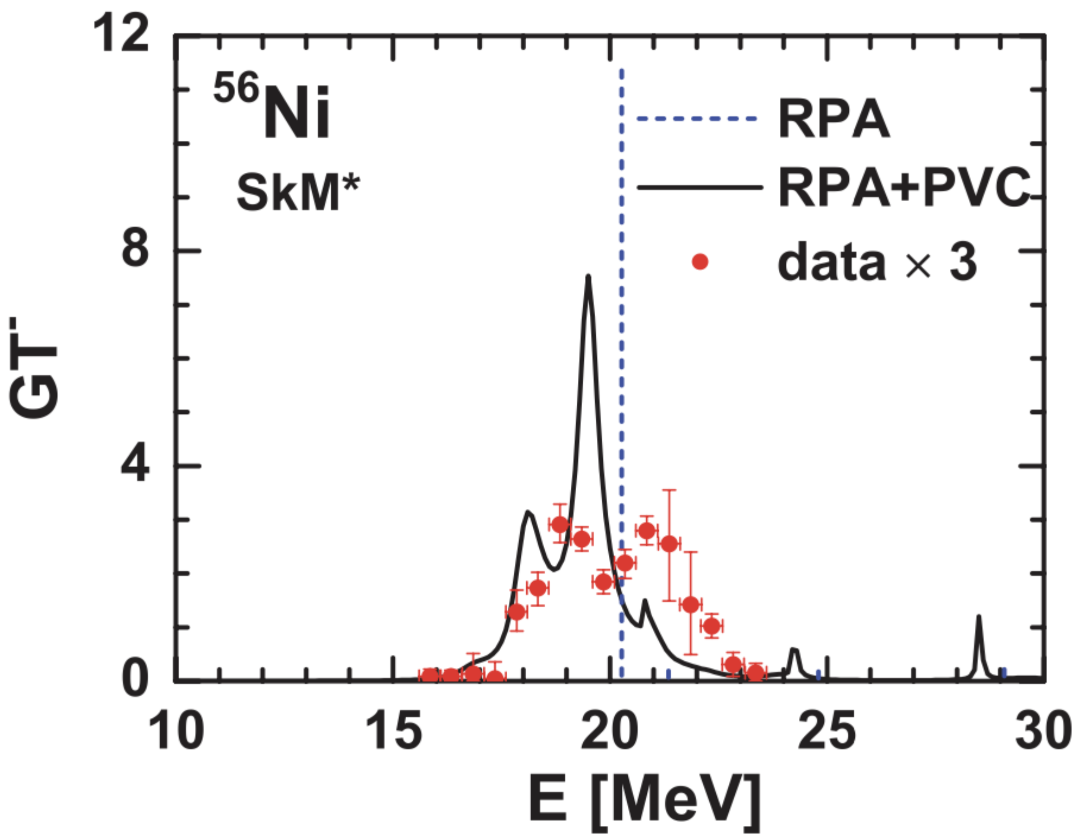
$$S(\omega) = -\frac{1}{\pi}\mathrm{Im}\sum_\nu \langle 0|O|\nu\rangle^2 \frac{1}{\omega - \Omega_\nu + i\frac{\Gamma_\nu}{2}}$$

- Gamow-Teller Resonance of ^{208}Pb



RPA+PVC based on Skyrme density functional

- Achieve the full self-consistency: to include full Skyrme interactions
  - ✓ Reproduction of double-peak structure of GT resonance in ^{56}Ni



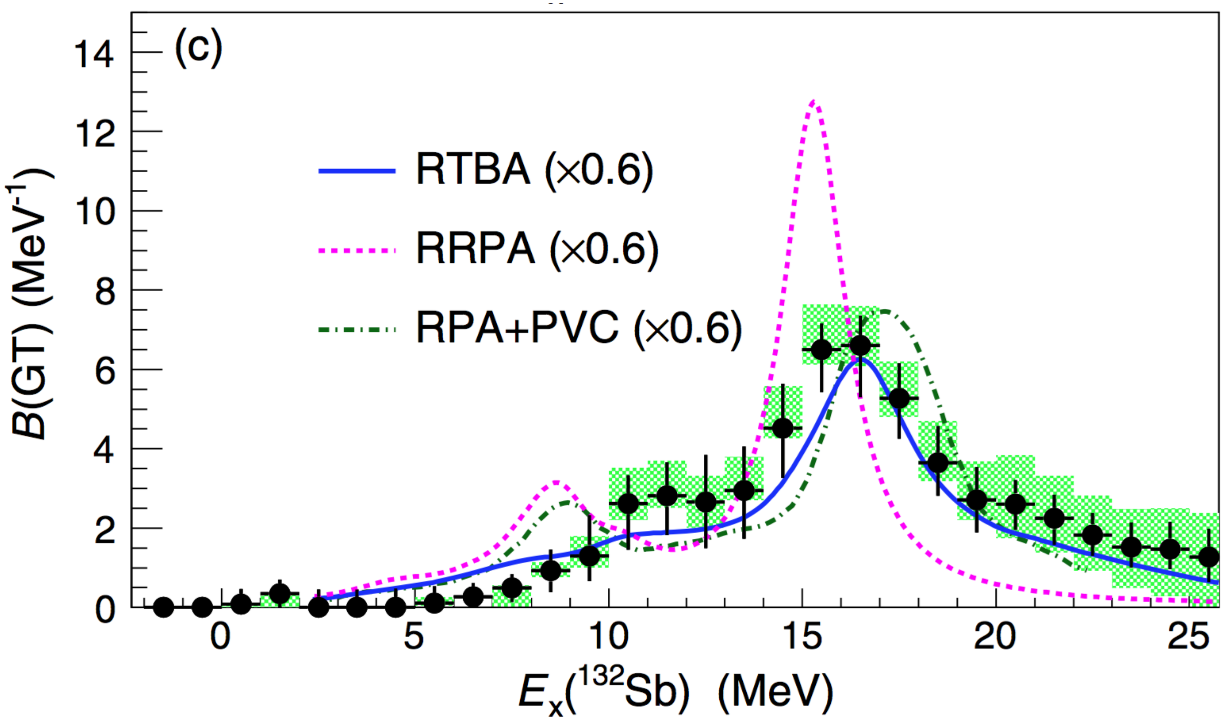
Y. F. Niu, G. Colo, M. Brenna, P.F. Bortignon, and J. Meng, **PRC** 85, 034314 (2012)

Exp: (p,n) reaction with Tp=296 MeV @ NSCL, MSU

Sasano et al., PRL 107, 202501 (2011)

RPA+PVC based on Skyrme density functional

- Achieve the full self-consistency: to include full Skyrme interactions
  - ✓ Prediction of GT resonance in unstable nucleus ^{132}Sn



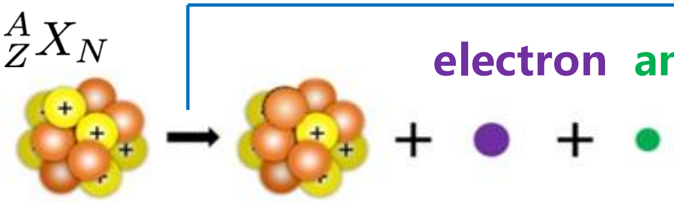
Yasuda, Sasano, et al., PRL 121, 132501 (2018)

Exp: (p,n) reaction @ RIBF, RIKEN
Yasuda, Sasano, et al., PRL 121, 132501 (2018)
RPA+PVC: Y. F. Niu, G. Colo and E. Vigezzi, **PRC** 90, 054328 (2014)
RTBA: E. Litvinova et al., PLB 730, 307 (2014)
RRPA: H. Z. Liang, and Z. M. Niu private communication

β-decay Half-life Is a Hard Problem

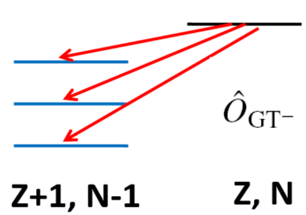
- **β-decay**

dominant nuclear transition



Gamow-Teller transition

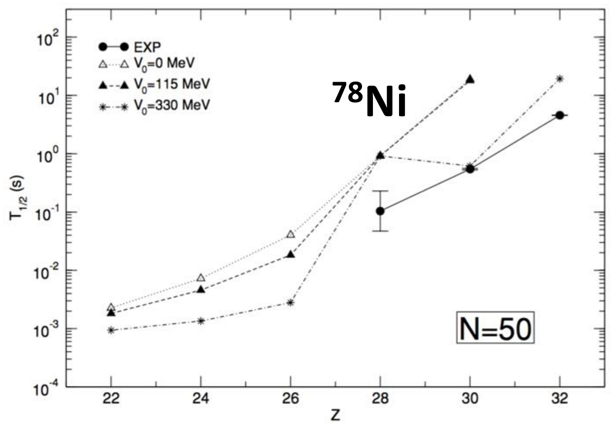
T^- ΔS=1 ΔL=0 ΔT=1



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

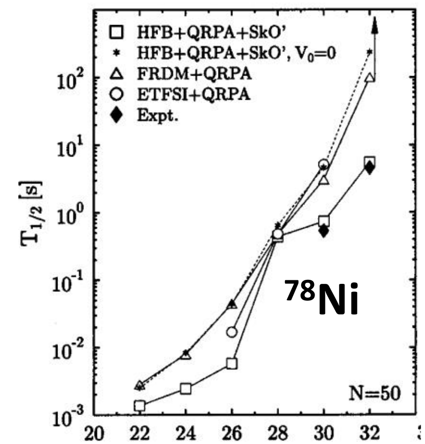
- **RHB+QRPA**

(quasiparticle random phase approximation)



Niksic, et al., PRC 71, 014308 (2005)

- **Skyrme HFB+QRPA**

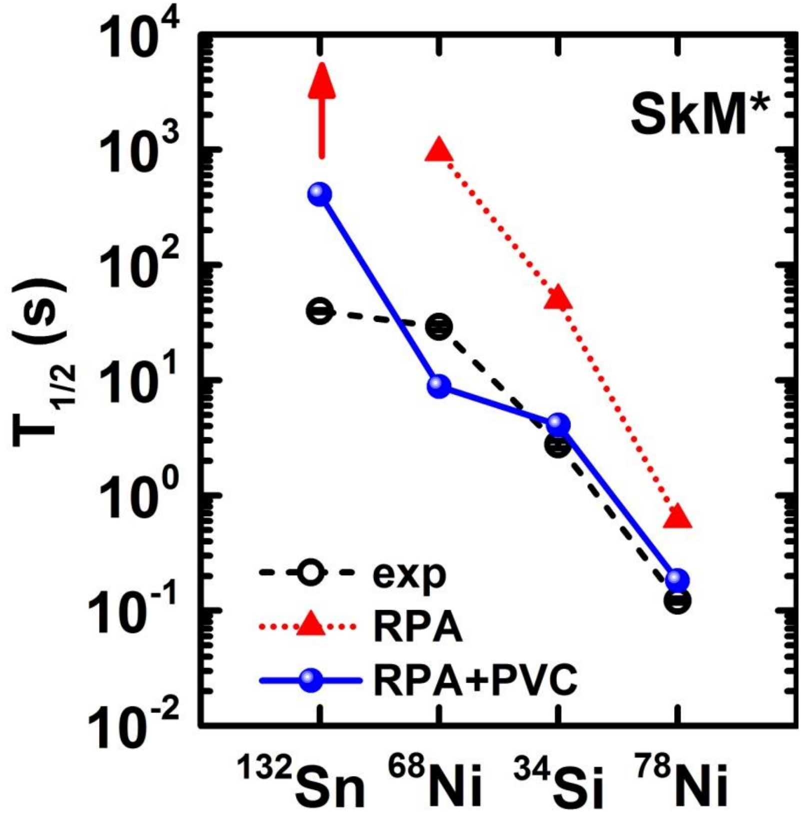


Engel, et al., PRC 60, 014302 (1999)

- **Half-lives are overestimated**
- **More correlations beyond RPA model ?**

β-Decay Half-Lives in Magic Nuclei

- **Improved description of β-decay half-lives**

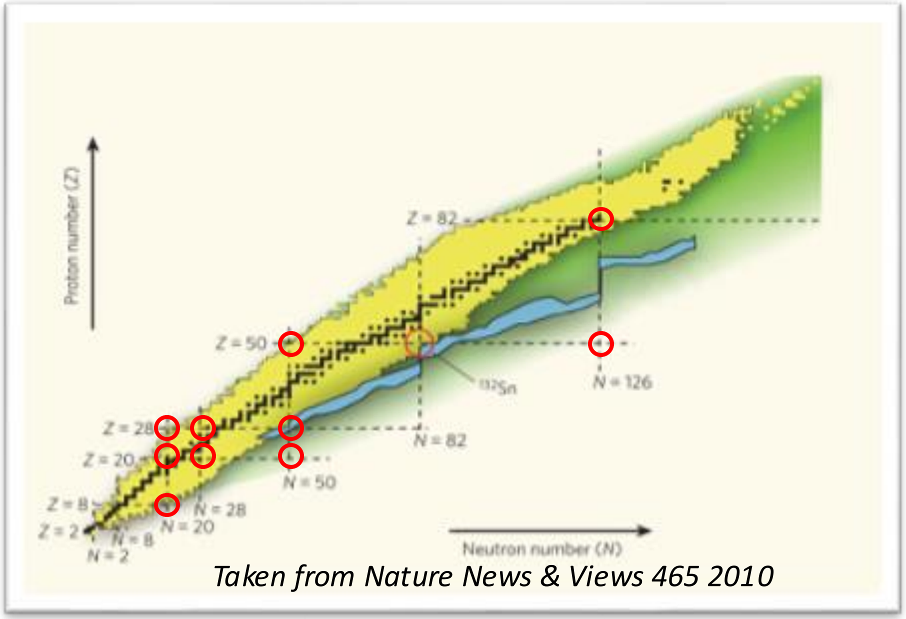


✓ **Reduce half-lives systematically** ✓ **Reproduce β-decay half-lives**

Y.F. Niu, Z. M. Niu, G. Colo, and E. Vigezzi, **PRL** 114, 142501 (2015)

Exp: G. Audi, F. G. Kondev, M. Wang, W. J. Huang, and S. Naimi, CPC 41, 030001 (2017)

RPA+PVC: only for magic nuclei…



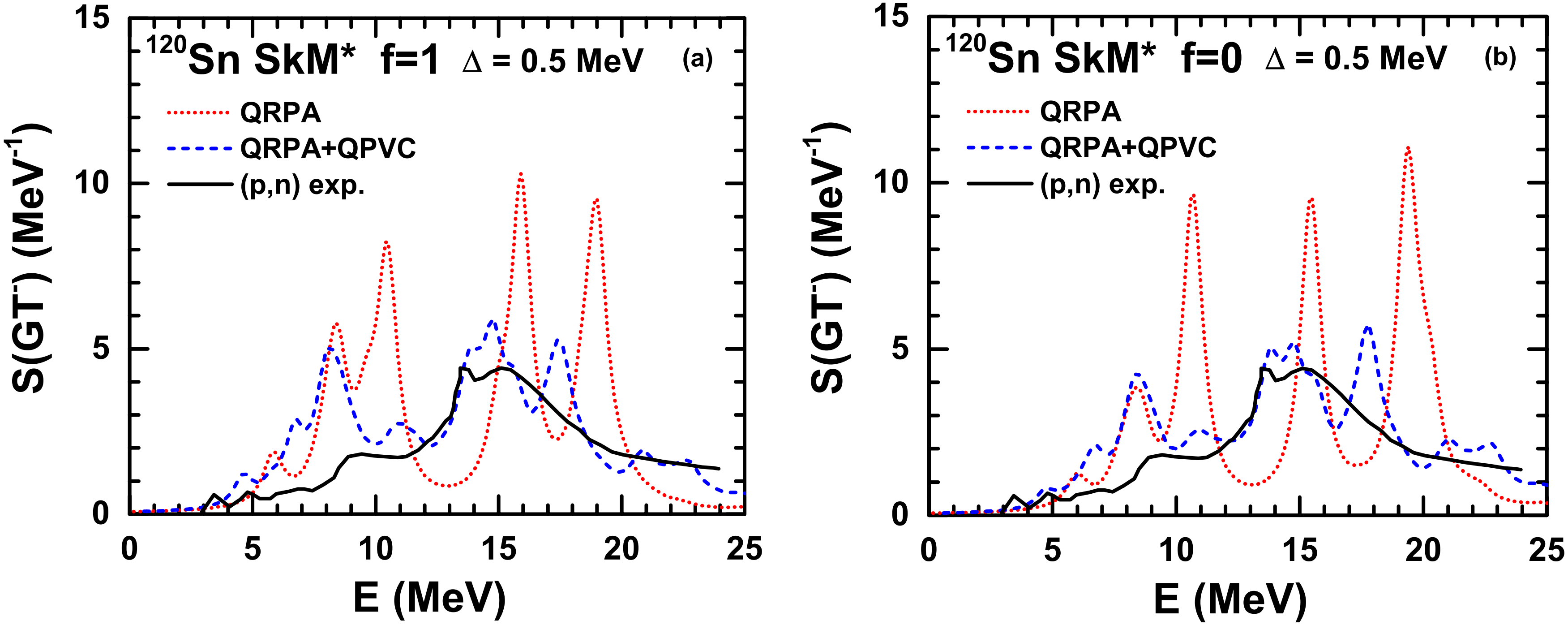
Taken from Nature News & Views 465 2010

- To include pairing correlations for superfluid nuclei

Quasiparticle RPA + quasiparticle vibration coupling
(**QRPA**) + (**QPVC**)

- ✓ for the study of Gamow-Teller resonance in superfluid nuclei
- ✓ for the study of β-decay half-lives in the whole isotopic chain

GT Strength Distribution



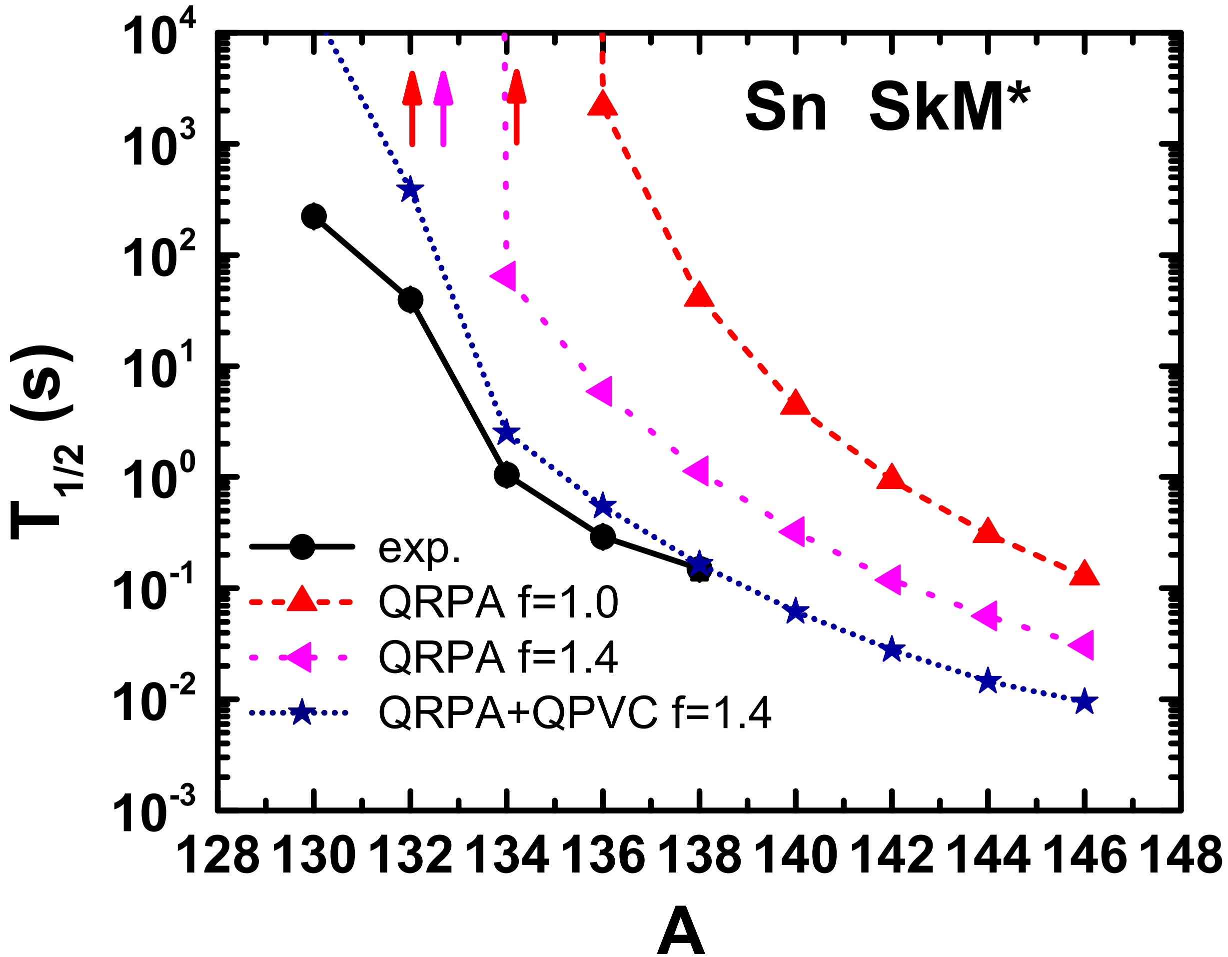
- (p,n) data: normalized by unit cross section $\sigma(0^\circ) = \hat{\sigma} F(q,\omega) B(\mathrm{GT})$
  Sasano, et al., PRC 79, 024602 (2009)

✓ QRPA + QPVC

- Develop a width of 5.3 MeV (6.4 MeV from exp.), reproduce exp. profile in GTR
- Overestimate the low-lying strength

Niu, Colo, Vigezzi, Bai, Sagawa, **PRC** 94, 064328 (2016)

β-Decay Half-Lives in Sn isotopes

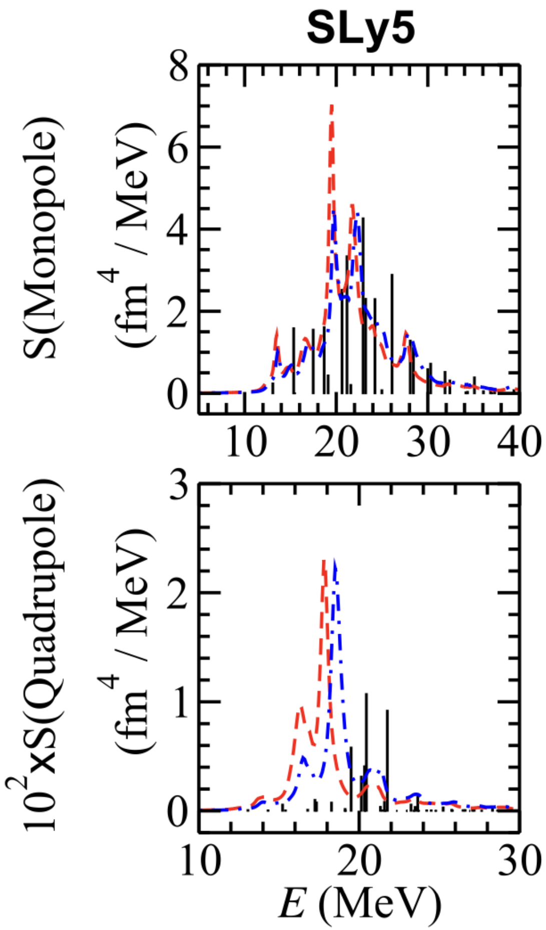


- Isoscalar Pairing:
  effective for Sn isotopes
  (nuclei above N=82 closed shell)
- Isoscalar Pairing + QPVC:
  reduce the half-lives

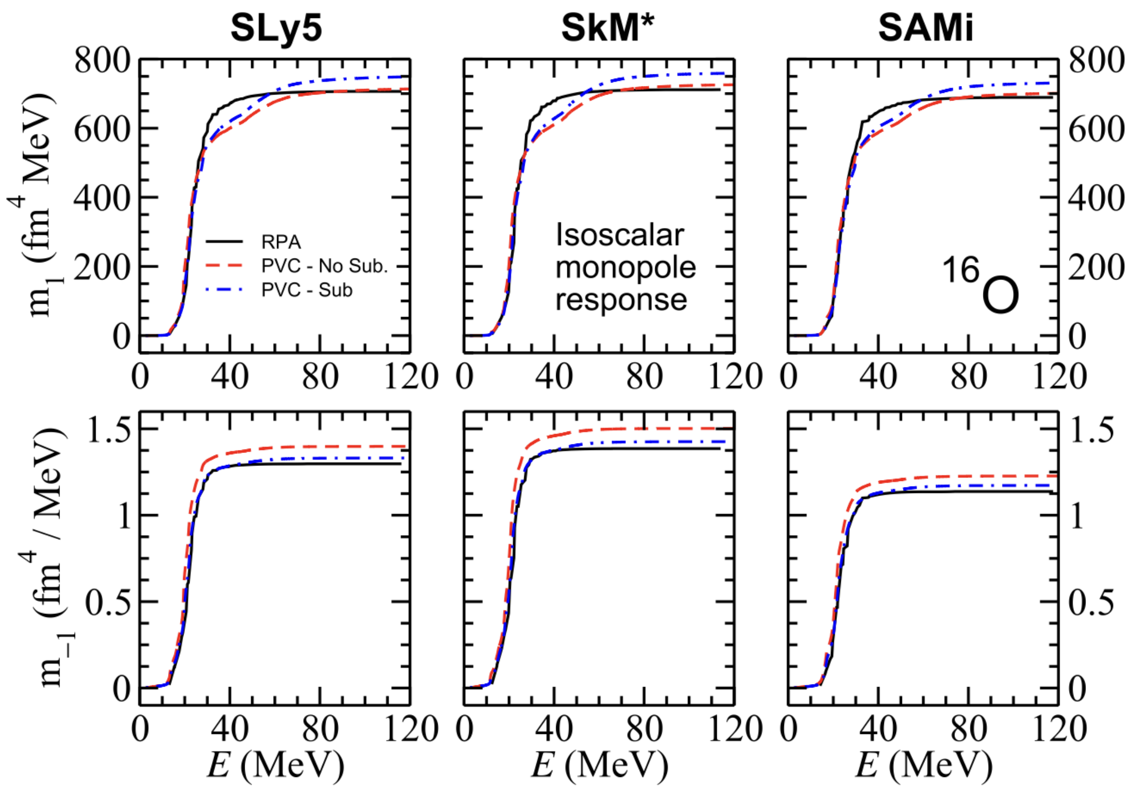
Y. F. Niu, Z. M. Niu, G. Colo, and E. Vigezzi, **PLB** 780, 325 (2018)

RPA+PVC for non-charge-exchange excitations

- Giant Resonances



- Effect of subtraction method on sum rules



X. Roca-Maza, Y. F. Niu, G. Colo, and P. F. Bortignon, **JPG 44**, 044001 (2017)

QRPA+QPVC for non-charge-exchange excitations

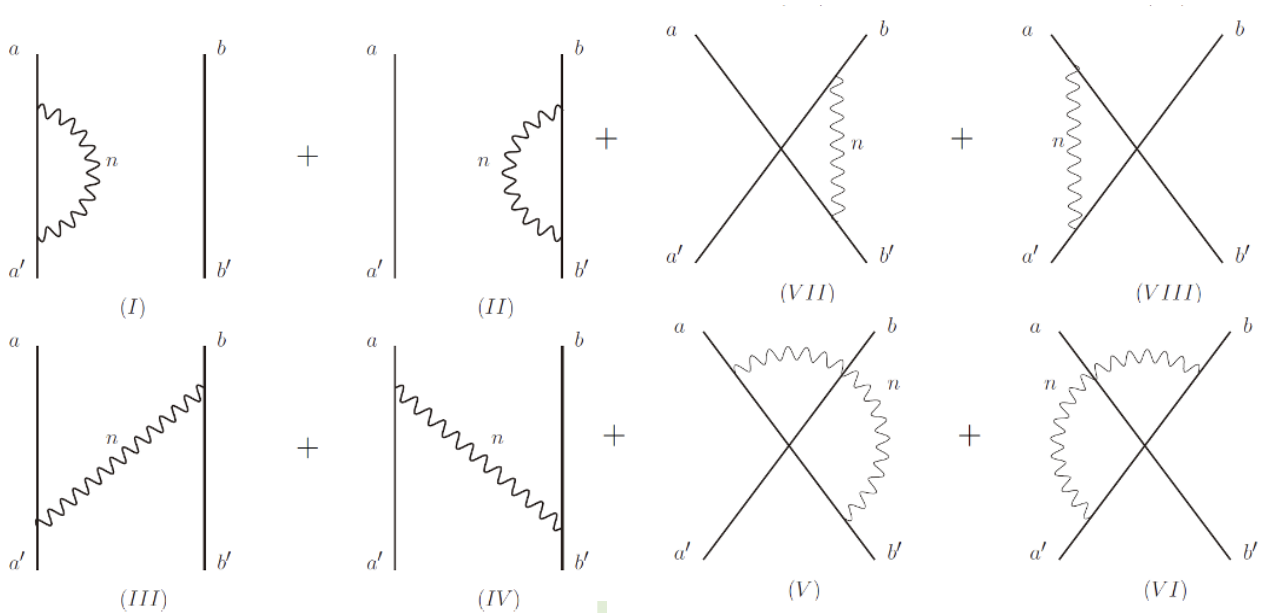
➢ To include pairing correlations for open-shell nuclei

- Quasiparticle RPA + quasiparticle vibration coupling
  (**QRPA**) + (**QPVC**)

✓ QPVC effect

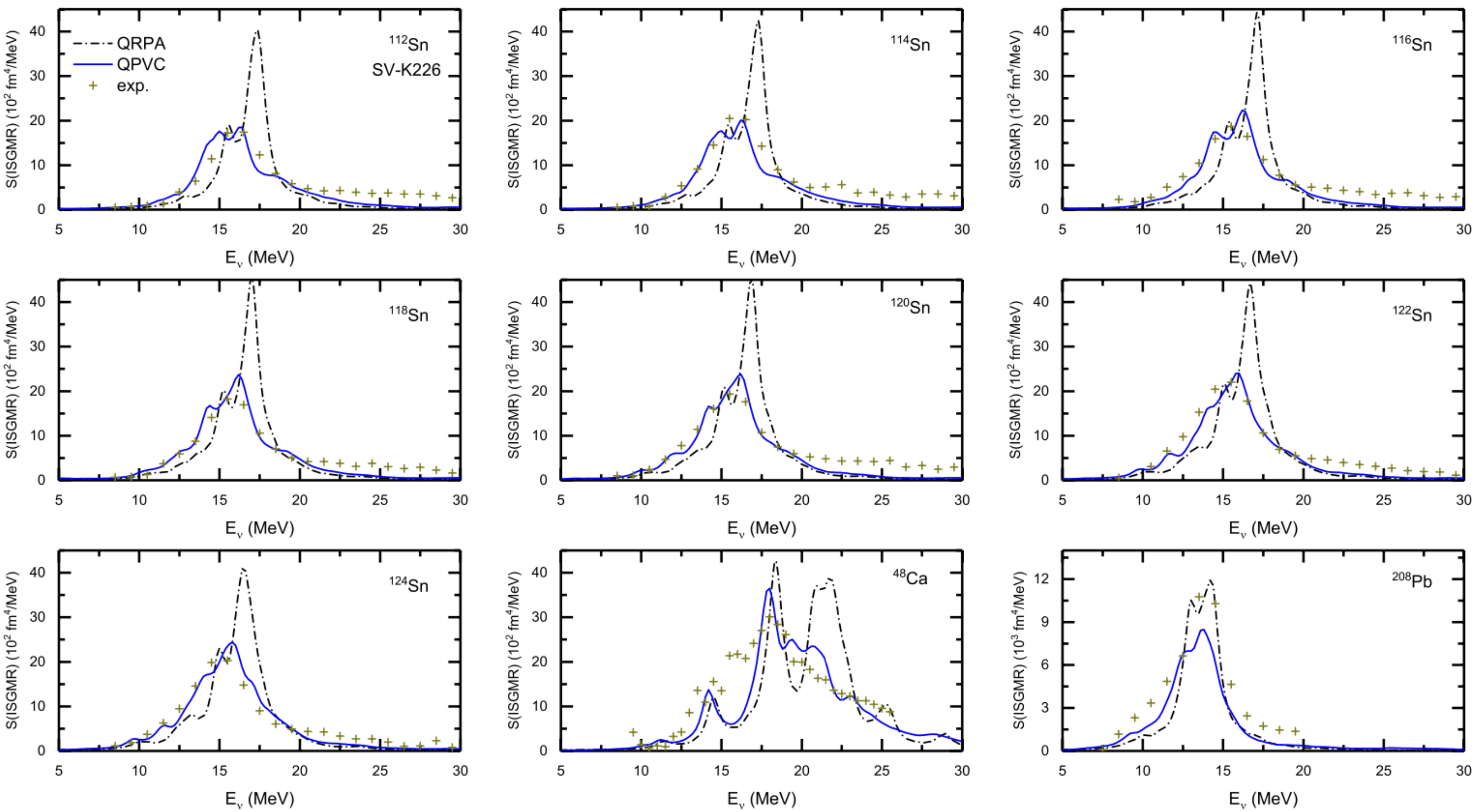
2 qp ⊗ phonons

2 quasiparticles(qp)



✓ Pairing effect

Unified description of giant monople resonances



SV-K226: $K_\infty = 226\,\text{MeV}$ Z. Z. Li, Y. F. Niu, and G. Colo, **PRL** 131, 082501 (2023)

See Zhengzheng Li's talk

``Excitation of the isoscalar giant monopole resonance and incompressibility of nuclear matter: **resolution of a long-standing puzzle"** M. N. Harakeh, *Science Bulletin 68, 3081 (2023)*

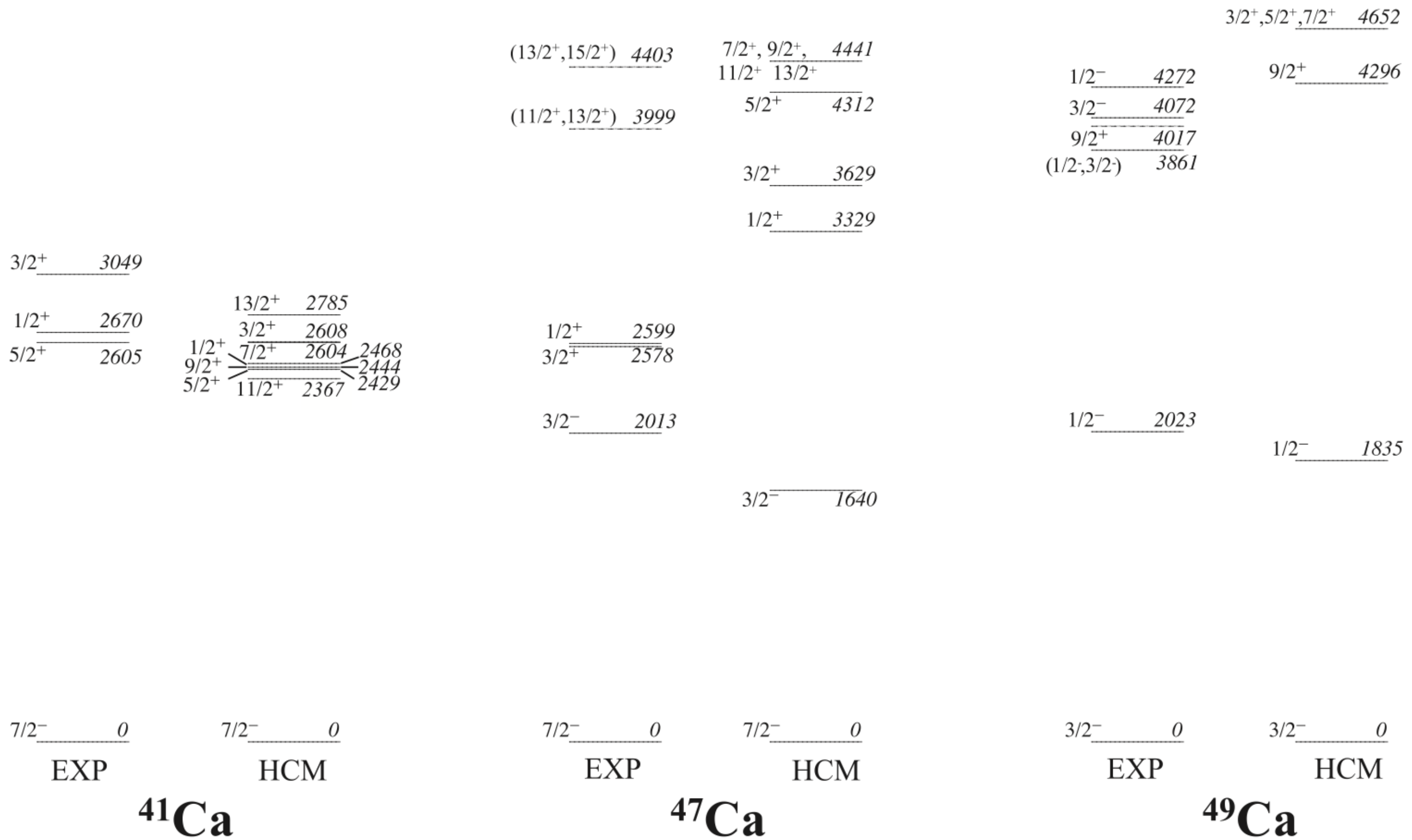
Low-spin particle(hole)-core excitations in odd-A nuclei

- Hybrid configuration mixing model

describes the excited states made of 2p-1h and 1p-1phonon excitations

(1p-2h) (1h-1phonon)

G. Colo, P.F. Bortignon, and G. Bocchi, **PRC** 95, 034303 (2017)



S. Bottoni, N. Cieplicka-Orynczak, S. Leoni et al., **PRC** 103, 014320 (2021)

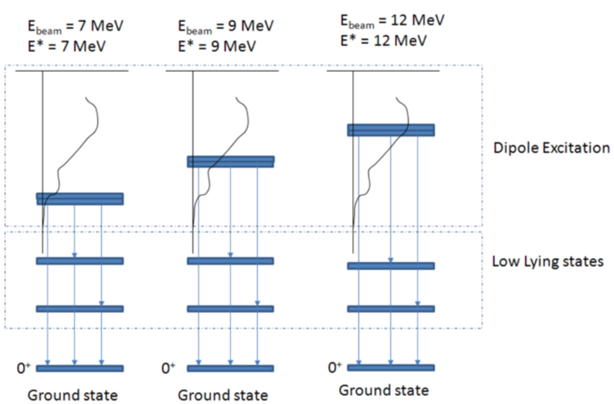
γ decay of Giant Resonances

PHYSICAL REVIEW C **85**, 014305 (2012)

Microscopic theory of the γ decay of nuclear giant resonances

Marco Brenna,[*] Gianluca Colò,[†] and Pier Francesco Bortignon[‡]
Dipartimento di Fisica, Università degli Studi di Milano and INFN, Sezione di Milano, via Celoria 16, I-20133 Milano, Italy
(Received 27 October 2011; published 6 January 2012)

- Gamma decay width of giant resonances to ground state and low-lying excited states



Romanian Reports in Physics, 68, Supplement, S539 (2016)

Nuclear Inst. and Methods in Physics Research, A 916 (2019) 257–274

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

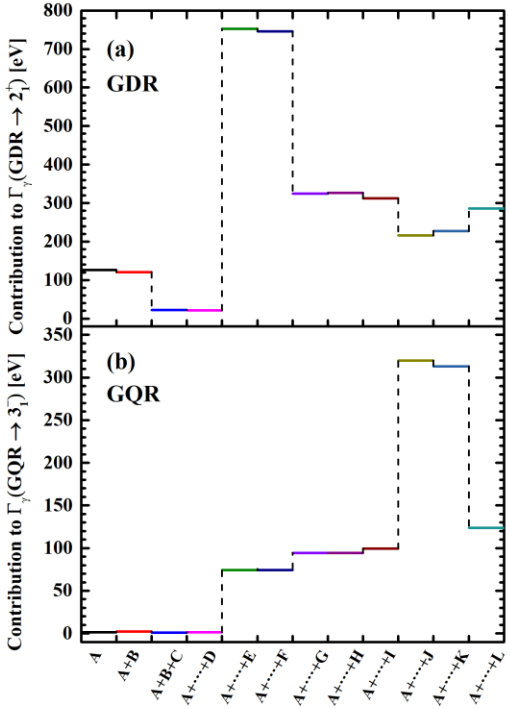
journal homepage: www.elsevier.com/locate/nima

Simulation of the ELIGANT-GN array performances at ELI-NP for gamma beam energies larger than neutron threshold

M. Krzysiek [a,b,*], F. Camera [c,d], D.M. Filipescu [a,e], H. Utsunomiya [f], G. Colò [c,d], I. Gheorghe [a], Y. Niu [a]

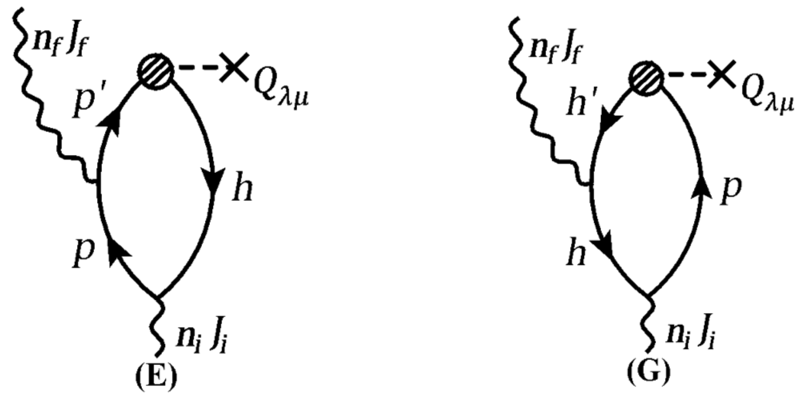
γ decay of Giant Resonances: Wave functions of GRs

- Contributions to $\boldsymbol{\gamma}$-decay width from different diagrams



✓ Diagrams E and G - PVC level

$\Gamma_\gamma(\mathrm{GDR}\to 2_1^+)$ 76% $\qquad$ $\Gamma_\gamma(\mathrm{GQR}\to 3_1^-)$ 95%



$$|J_i\rangle \sim |((1p1h)\otimes J_f)_{J_i}\rangle$$

W. L. Lv, Y. F. Niu, and G. Colo, Phys. Rev. C 103, 064321 (2021)

$$B^{\overline{\pi\nu}}(\mathrm{GDR}\to 2_1^+) < \frac{1}{2}\cdot B^{\overline{\pi\nu}}(\mathrm{GQR}\to 3_1^-)$$

$\left|\left[(ph)_J \otimes 2_1^+\right]_{\mathrm{GDR}}\right\rangle$ component in $|\mathrm{GDR}\rangle$ < $\left|\left[(ph)_J \otimes 3_1^-\right]_{\mathrm{GQR}}\right\rangle$ component in $|\mathrm{GQR}\rangle$

- In agreement with damping mechanism from wavelet analysis:

  GDR: 1p-1h configurations (Landau damping)

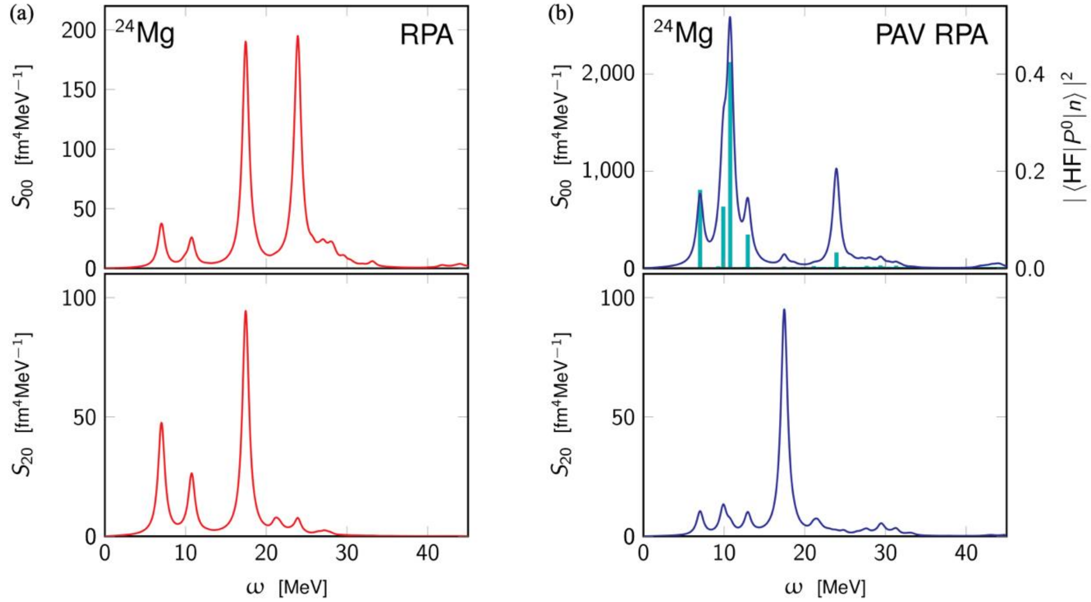
  GQR: 1p-1h coupled with phonons (spreading width)

More exciting collaborations are coming…

- **To include the deformation degree of freedom**

✓ Projected QRPA

Projection after Variation



➢ To develop Variation after Projection based on QFAM

A. Porro, G. Colo et al., **PRC** 109, 044315 (2024)

✓ Deformed QRPA+QPVC

More exciting collaborations are coming…

- **To include the temperature degree of freedom**

For astrophysical environment, temperature effect is important

✓ Finite temperature QRPA+QPVC

To study the electron-capture and beta-decay rates in stellar environment

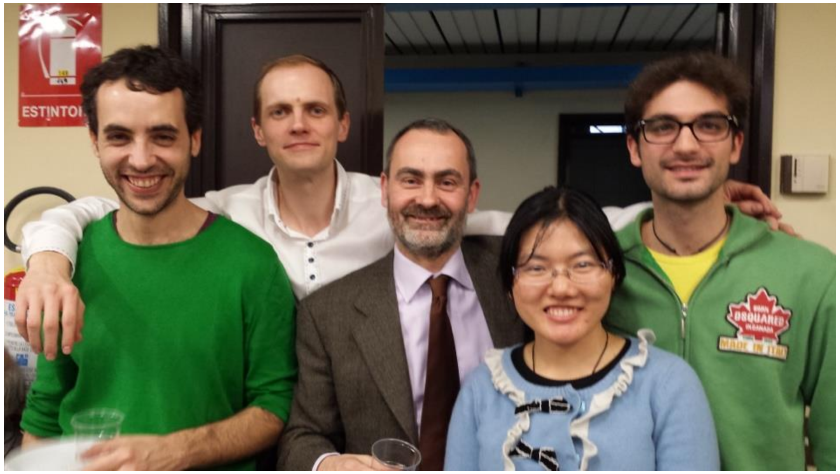
- **To include the pairing correlations**

✓ Gamma decay of giant resonances from superfluid nuclei

✓ Quasiparticle-core excitations of superfluid odd-A nuclei

More excellent young students will be trained during this collaboration

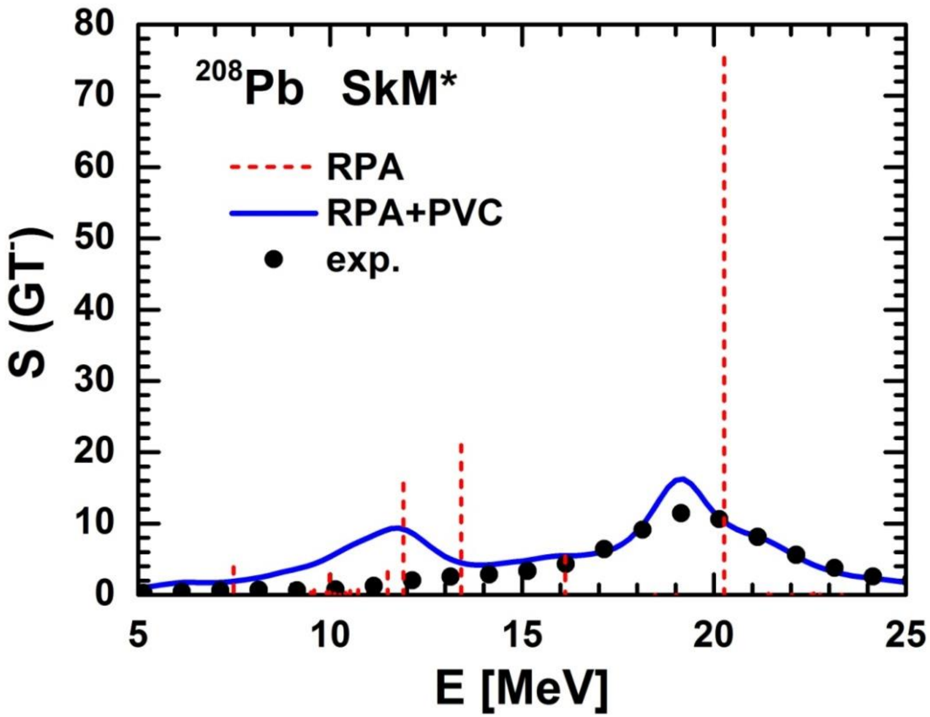
Tanti Auguri, Gianluca, Silvia, and Franco!



Thank you!

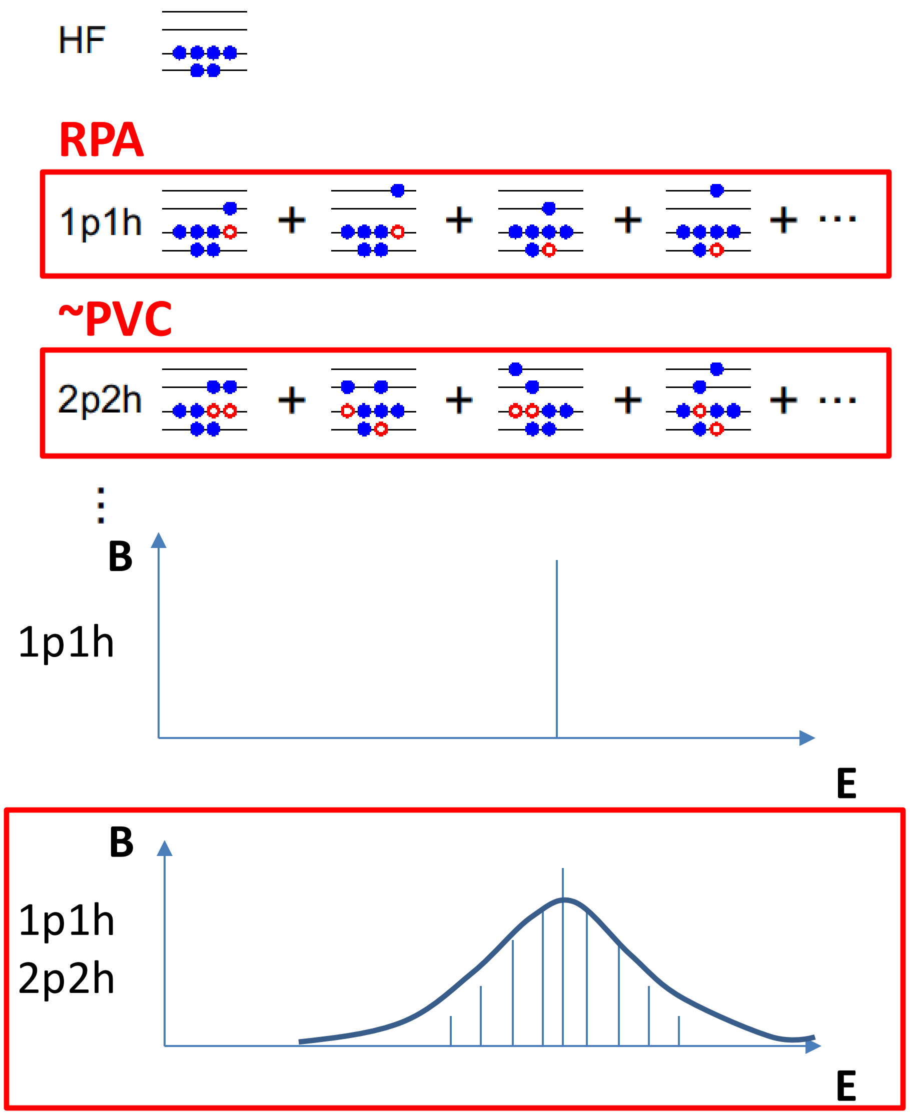
Solution: (Q)RPA + (Q)PVC

- **Particle Vibration Coupling (PVC) effect**



✓ **Develop a spreading width**
✓ **Reproduce resonance lineshape**

- **Correlations beyond RPA**



Y. F. Niu, G. Colo, and E. Vigezzi, **PRC** 90, 054328 (2014)