Recent applications of the subtracted second random-phase approximation

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Outline

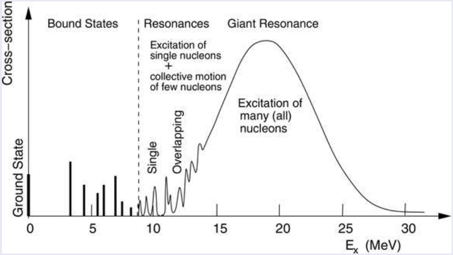
Microscopic description of the Giant Resonances

- The Random Phase Approximation (RPA)
- Beyond the RPA: The Second RPA
- The Subtraction method: Why and How

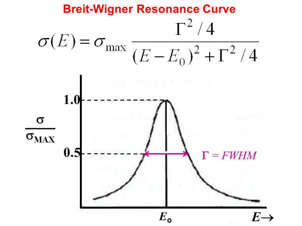
Recent Applications

- Monopole and Quadrupole response for ^{16}O
- Dipole response in ^{48}Ca: Low-Lying states (PDR) and GDR
- ISGQR systematic calculations for spherical nuclei

Total Strength



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



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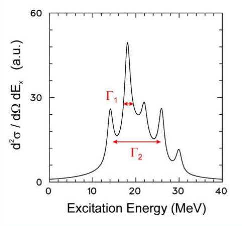
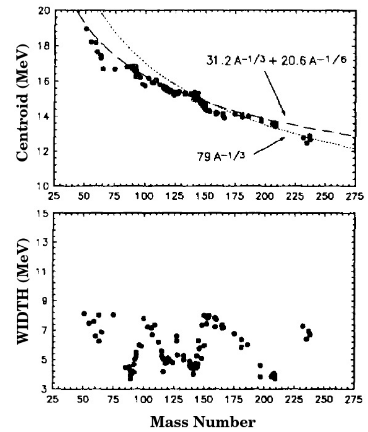


High precision studies

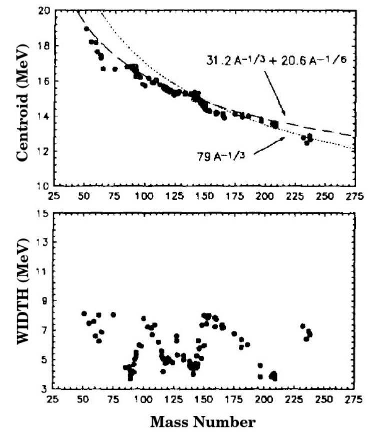
Centroid Energy and Width



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

Centroid Energy: Very smooth dependence on A
Width: Strongly dependent on A

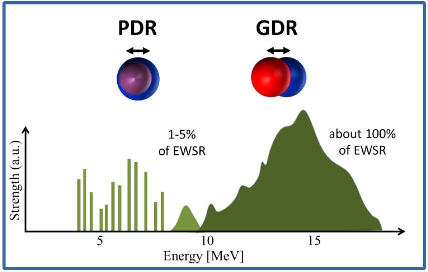
Centroid Energy and Width



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

Centroid Energy: Very smooth dependence on A
Width: Strongly dependent on A **Very Challenging !**

Future Investigations of the PDR and GDR @ ELI-NP



GDR: collective motion of the neutrons against the protons.

PDR: motion of neutrons skin against proton-neutron core

ELI-NP: high-intensity, mono-chromatic and linear-polarized gamma ray beam facility:

-**Separate measure of E1 and M1**: no need of model-dependent determination of M1 strength

-**Complementary studies**: strength below (NRF) and above (ELI-GANT) the neutron threshold

-**Mono-chromatic beam**: fine structure of the response

-**Model independent results:** pure electromagnetic excitation process

The Random Phase Approximation (RPA)

- The RPA is a widely used approximation for the description of GRs
- Very successful especially within the Energy Density Functional framework (interactions á la Skyrme or Gogny, or Covariant EDF)
- It provides global properties of the GRs

However, extensions of the RPA are also required for:

- Spreading Width
- Fine Structure
- Low Lying excitations in closed shell nuclei
- Double exctiations and Anharmonicities
- ...

The Second RPA (SRPA): more general excitation operators are introduced

Phonon Operators: RPA vs SRPA

Random Phase Approximation (RPA)

$$Q_\nu^\dagger = \underbrace{\sum_{ph} X_{ph}^{(\nu)} \underbrace{a_p^\dagger a_h}_{\text{1p-1h}} - \sum_{ph} Y_{ph}^{(\nu)} \underbrace{a_h^\dagger a_p}_{\text{1h-1p}}}_{\text{Only Landau Damping, Centroid Energy and Total Strength of GRs}}$$

Second Random Phase Approximation (SRPA)

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

$$+ \underbrace{\sum_{p_1<p_2, h_1<h_2} (X_{p_1 h_1 p_2 h_2}^{(\nu)} \underbrace{a_{p_1}^\dagger a_{h_1} a_{p_2}^\dagger a_{h_2}}_{\text{2p-2h}} - Y_{p_1 h_1 p_2 h_2}^{(\nu)} \underbrace{a_{h_1}^\dagger a_{p_1} a_{h_2}^\dagger a_{p_2}}_{\text{2h-2p}})}_{\text{Spreading Width, Fragmentation, Double GRs and Anharmonicites, Low-Lying States}}$$

Spreading Width, Fragmentation, Double GRs and Anharmonicites, Low-Lying States

RPA 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)

$$\left(\begin{array}{cc} \mathcal{A}_{11} & \mathcal{B}_{11} \\ -\mathcal{B}_{11}^* & -\mathcal{A}_{11}^* \end{array} \right) \left(\begin{array}{c} \mathcal{X}_1^\nu \\ \mathcal{Y}_1^\nu \end{array} \right) = \omega_\nu \left(\begin{array}{c} \mathcal{X}_1^\nu \\ \mathcal{Y}_1^\nu \end{array} \right)$$

SRPA Excitation Operators and Equations

SRPA Phonon Operators

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

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

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

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

SRPA Excitation Operators and Equations

SRPA 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 calculations

- Computationally very demanding
- Realistic studies were done using strong truncations in the s.p space and/or approximations in the evaluation of the SRPA matrices
- Only recently full SRPA calculations have been performed: [a]

[a] P. Papakonstantinou and R. Roth PLB 671, 356 (2009) ; D. G. *et al.* PRC 81, 054312 (2010)

Large scale SRPA calculations have shown that:

- The SRPA strength distribution is sistematically shifted towards lower energies compared to the RPA one
- This shift is very strong ($\simeq$ 5 MeV), RPA description often spoiled

Origins and Causes:

1. Quasi Boson Approximation and stability problems in SRPA
2. Use of effective interactions in beyond-mean field methods

The Subtraction procedure (I. Tselyaev Phys. Rev. C 75, 024306 (2007))

- Designed for beyond RPA approaches
- It restores the Thouless theorem, e.g. instabilities are removed
- Static ($\omega = 0$) limit of the SRPA imposed to be equal to the RPA one

The Subtraction procedure

From SRPA to an Energy dependent RPA-like problem

- The SRPA problem as an energy-dependent RPA problem

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

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The Subtraction procedure is SRPA (SSRPA)

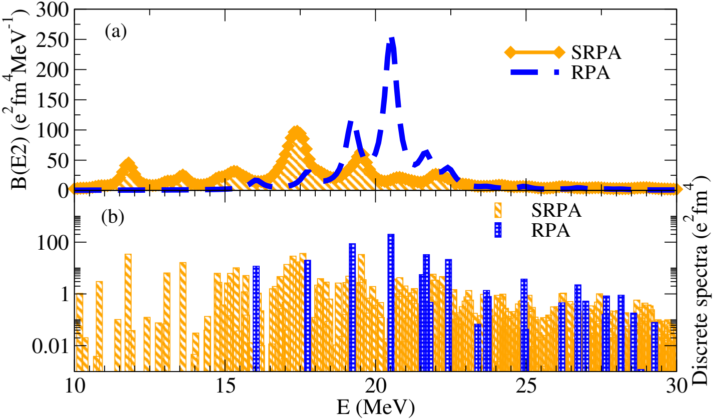
- Subtraction of the zero–frequency limit of the SRPA correction

$$A^{Cor}_{1,1'} \mapsto \tilde{A}^{Cor}_{1,1'}(\omega) = A_{1,1'}(\omega) - A_{1,1'}(\omega = 0) \Rightarrow$$

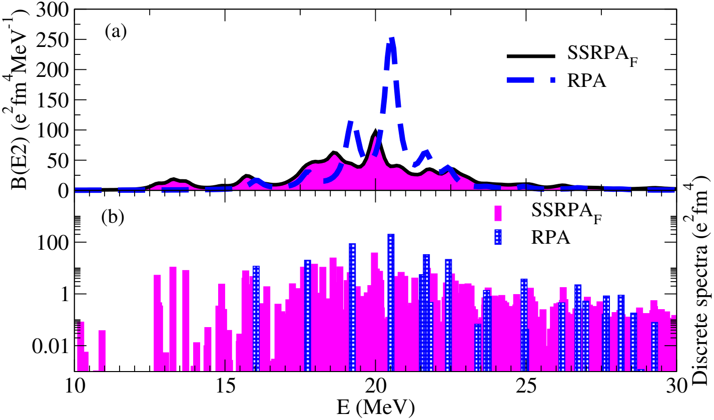
$$\tilde{A}_{1,1'}(\omega = 0) = A^{RPA}_{1,1'}$$

$$\Rightarrow \Pi^{SSRPA}(\omega = 0) = \Pi^{RPA}$$

Quadrupole Strength Distribution in ^{16}O: RPA, SRPA and SSRPA

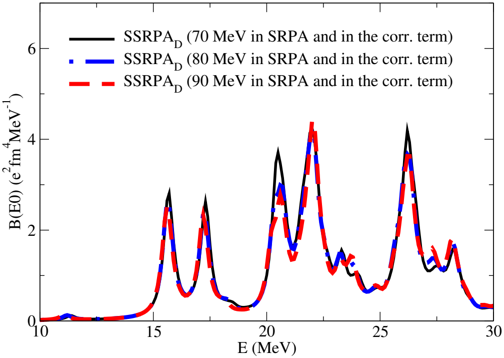


D. G., M. Grasso and J.Engel, Phys. Rev. C 92 , 034303 (2015)

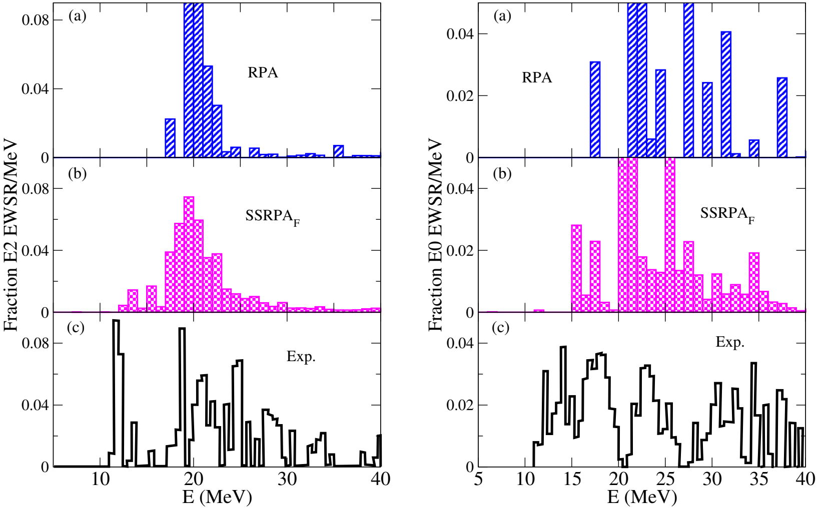


D. G., M. Grasso and J.Engel, Phys. Rev. C 92 , 034303 (2015)

Monopole Strength Distribution ^{16}O: cutoff dependence



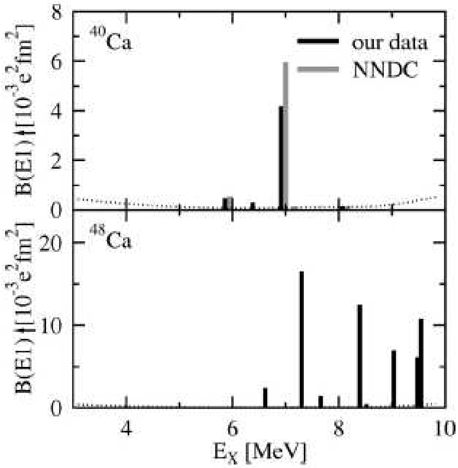
Comparison with experimental data for ^{16}O



Low-lying dipole response in ^{48}Ca: Motivation

- Experimental low-lying dipole (from 5 to 10 MeV) response in ^{48}Ca
- Pygmy Dipole Resonance (PDR) type?
- Not described in relativistic and non-relativistic RPA models
- What happens in SRPA [a] ?
- and in the SSRPA [b] ?

[a] D. G. , M. Grasso, and F. Catara, Phys. Rev. C 84, 034301 (2011)
[b] D. G., M. Grasso and O. Vasseur, Physics Letters B 777 (2018) 163168



$\sum$ B(E1)=5.1 $\pm$ 0.8 ($10^{-3}e^2fm^2$),

$\sum$ B(E1)=68.7 $\pm$ 7.5 ($10^{-3}e^2fm^2$),

From T. Hartmann *et al.*, PRC 65, 034301, (2002)

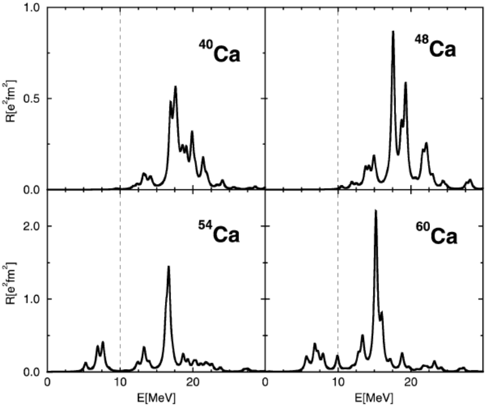
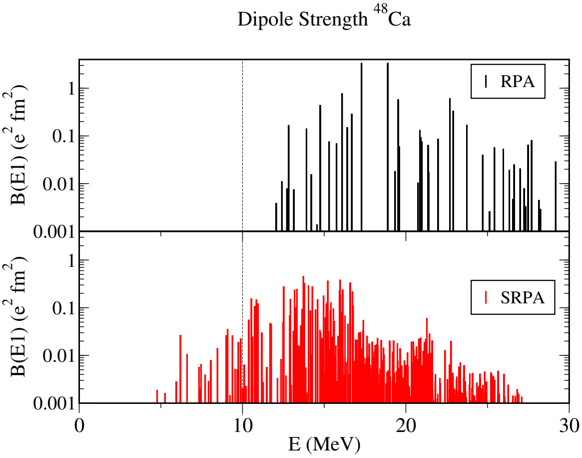
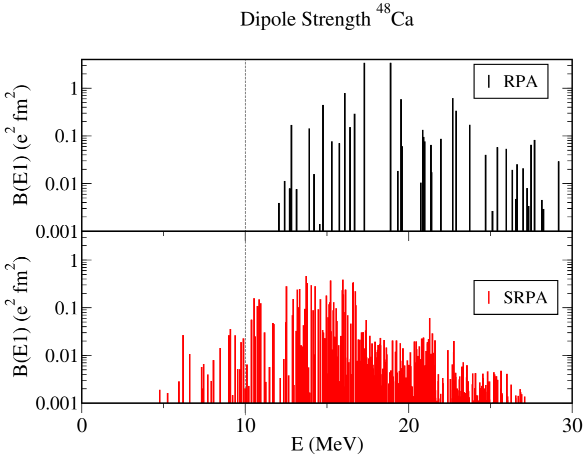


Fig. 5. RRPA isovector dipole strength distributions in Ca isotopes. The thin dashed line tentatively separates the region of giant resonances from the low-energy region below 10 MeV.

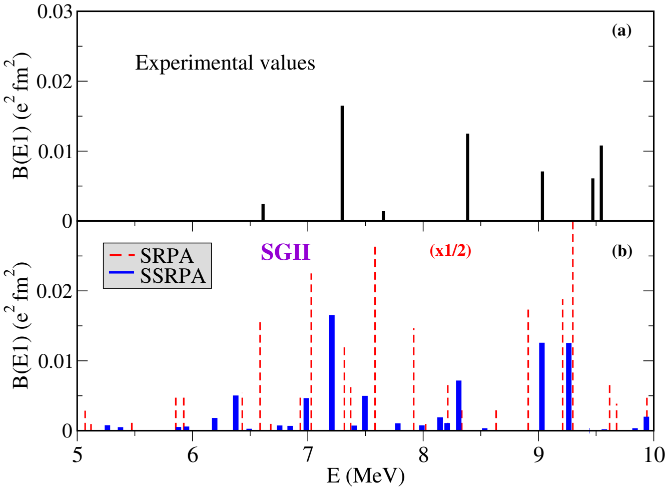
From D. Vretenar *et al.*, Nucl. Phys. A 692, 496 (2001)


Dipole Strength ^{48}Ca
RPA
SRPA
B(E1) (e^2 fm^2)
B(E1) (e^2 fm^2)
1
0.1
0.01
0.001
1
0.1
0.01
0.001
0
10
20
30
E (MeV)

RPA and SRPA Dipole Strength



SRPA provides the strength below 10 MeV, but total strength is overestimated.



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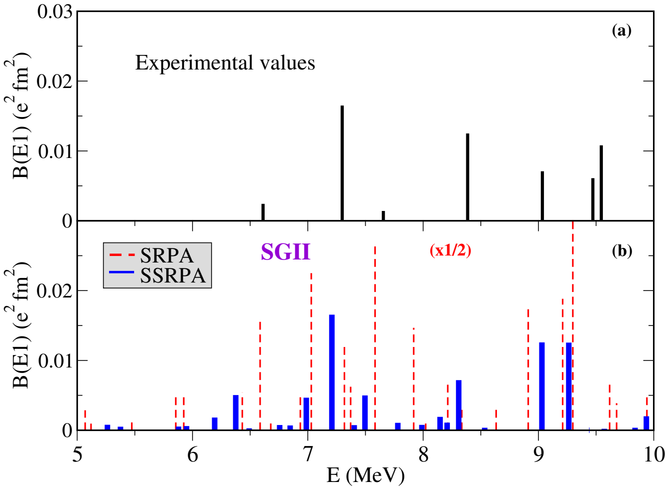
SRPA, SSRPA vs Data



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Interaction is the only input, e.g. no parameters are adjusted.

Total $B(E1)$ and EWSRs (From 5 to 10 MeV)

	Exp	SRPA SGII	SSRPA SGII	SRPA SLy4	SSRPA SLy4
$\sum B(E1)$	0.068 $\pm$ 0.008	0.563	0.078	1.012	0.126
$\sum_i E_i B_i(E1)$	0.570 $\pm$ 0.062	4.618	0.621	8.795	1.062

Experimental and theoretical $\sum B(E1)$ in (e^2 fm^2) and $\sum_i E_i B_i(E1)$ in (MeV e^2 fm^2) summed between 5 and 10 MeV.
From D. G., M. Grasso , O. Vasseur, Physics Letters B 777 (2018) 163168

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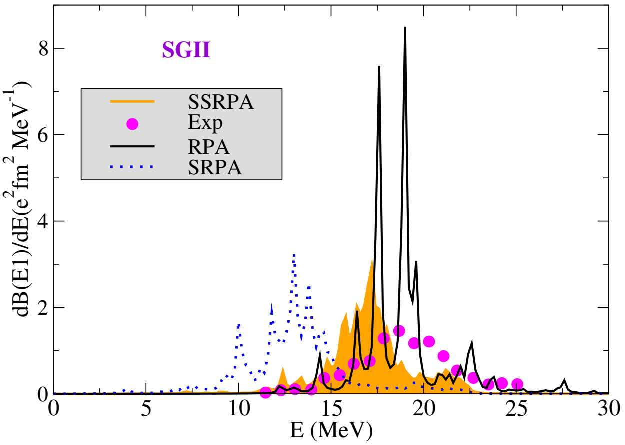
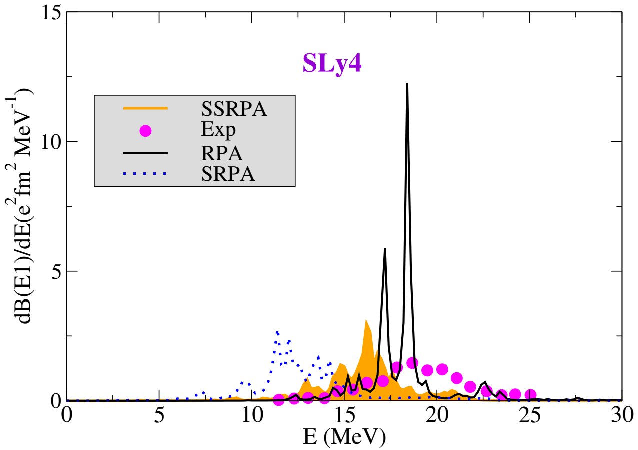


Data From J. Birkhan *et al.*, Phys. Rev. Lett. 118, 252501 (2017);
Theoretical results folded with a Lorentzian having a width of 0.25 MeV
D. G., M. Grasso , O. Vasseur, Physics Letters B 777 (2018) 163168



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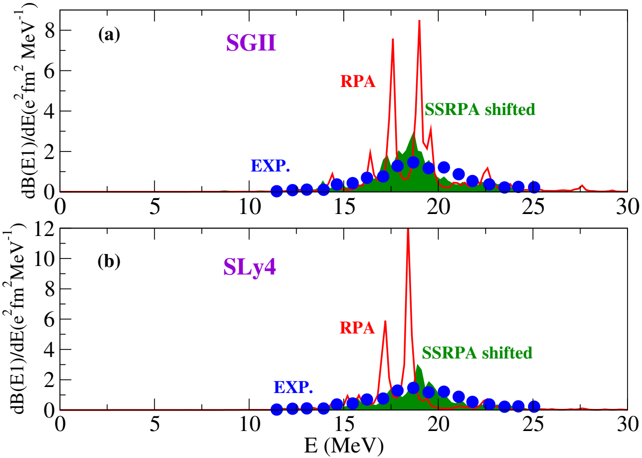
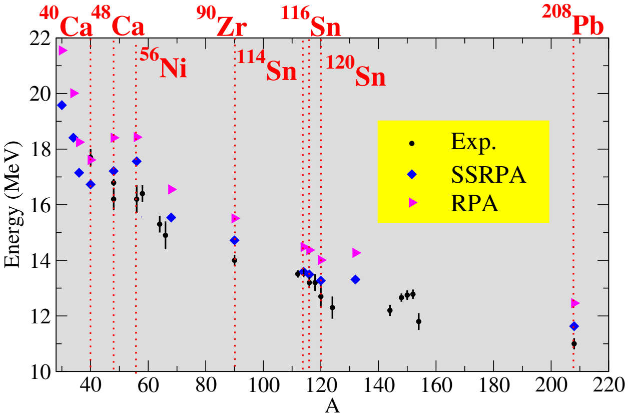
D. G., M. Grasso , O. Vasseur, Physics Letters B 777 (2018) 163168

SSRPA vs Data, GDR case



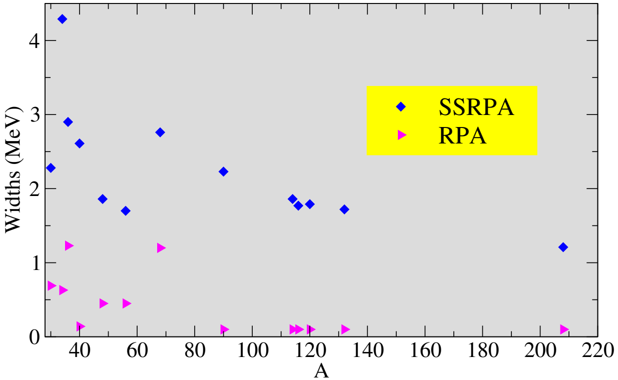
Data From J. Birkhan *et al.*, Phys. Rev. Lett. 118, 252501 (2017);
Theoretical results folded with a Lorentzian having a width of 0.25 MeV

Systematic calculations for Isoscalar GQRs: from 30Si to 208Pb
Centroid energy

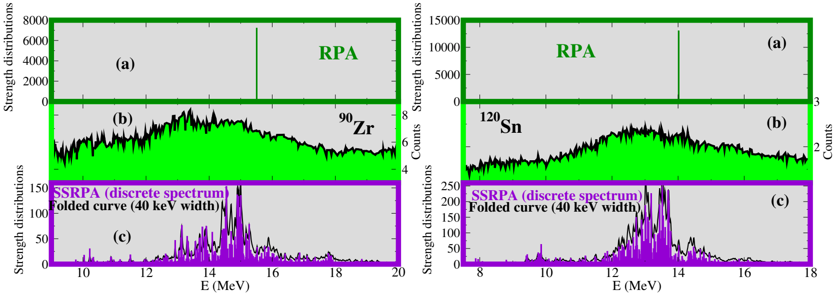


Globally: better agreement with the experimental data compared to RPA
Vasseur, Gambacurta, Grasso, PRC 98, 044313 (2018)

Systematic calculations for Isoscalar GQRs: from 30Si to 208Pb Width



General trend, found both in RPA and in SSRPA: the width is systematically reduced going from lighter to heavier nuclei (Landau damping)
Vasseur, Gambacurta, Grasso, PRC 98, 044313 (2018)



Exp. data: Shevchenko et al, PRL 93, 122501 (2004)

From : Vasseur, Gambacurta, Grasso, PRC 98, 044313 (2018)

Conclusions:

Microscopic description on the nuclear response

- Microscopic description based on the RPA and SRPA
- SRPA: coupling between $1p-1h$ and $2p-2h$ is fully taken into account
- Subtraction procedure in SRPA (SSRPA) cures SRPA issues

SSRPA Applications and Results

- Monopole and Quadrupole response for ^{16}O:
  improvement with respect to the RPA (especially the fragmentation)
- Dipole response in ^{48}Ca:
  i) Good description of PDR states and GDR width (Not in RPA),
  ii) Centroid of the GDR is underestimated in SSRPA
- ISGQR systematic calculations for spherical nuclei:
  overall improvement of the centroids and fine structure (missing in RPA)