Giant Resonances using Realistic Interactions and Second RPA

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Overview

- Introduction
  - Giant Resonances and the Mean-Field Picture of the Nucleus
  - The Unitary Correlation Operator Method (UCOM)
- Recent Applications
  - Hartree-Fock and Perturbation Theory, RPA
- Collective excitations and Second RPA
  - Effective Interactions for Second RPA?
- Summary - Perspectives

Introduction

- The mean-field picture of the nucleus can account for many basic nuclear properties
  - s.p. energies and wavefunctions, density
- ... and is the starting point for the microscopic description of giant resonances
  - Small amplitude oscillations of the density

HF(B) — A self-consistent description of the ground state - DFTs

(Q)RPA — The small-amplitude limit of time-dependent HF: oscillations of the density

SRPA,VCM,... — Collisional damping: fragment

Appropriate effective NN Interactions?

The Unitary Correlation Operator Method

Correlated realistic interactions V_{UCOM}

- Short-range central and tensor correlations (SRC) described by a unitary correlation operator $C = C_\Omega C_r$

realistic NN interaction $\longrightarrow$ correlated interaction

- Same for all nuclei
- Phase-shift equivalent to the original NN interaction
- Suitable for use within simple Hilbert spaces

a two-body UCOM Hamiltonian based on the Argonne V18 potential is used in what follows

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Ground-State Properties

UCOM-HF

Standard Hartree-Fock

- Ground state approximated by a single Slater determinant

$$|\mathrm{HF}\rangle = \mathcal{A}\{|\phi_1\rangle \otimes |\phi_2\rangle \otimes \cdots |\phi_A\rangle\}$$

→ no correlations

- Single-particle states are expanded in a H.O. basis

$$|\phi_i\rangle = \sum_\alpha D_{i\alpha}|\alpha\rangle \quad ; \quad |\alpha\rangle = |n, (\ell\tfrac{1}{2})jm, \tfrac{1}{2}m_t\rangle$$

- Expansion coeff's $D_{i\alpha}$ determined by minimizing the energy

$$E_{\mathrm{HF}} = \langle \mathrm{HF}|\hat{H}_{\mathrm{int}}|\mathrm{HF}\rangle = \tfrac{1}{2}\sum_{i,j=1}^{A}\langle \phi_i\phi_j|T_{\mathrm{rel}} + V_{\mathrm{UCOM}}|\phi_i\phi_j\rangle$$

↓ inclusion of SRC

UCOM-HF + PT

LRC: extending the model space

Second-order perturbation theory

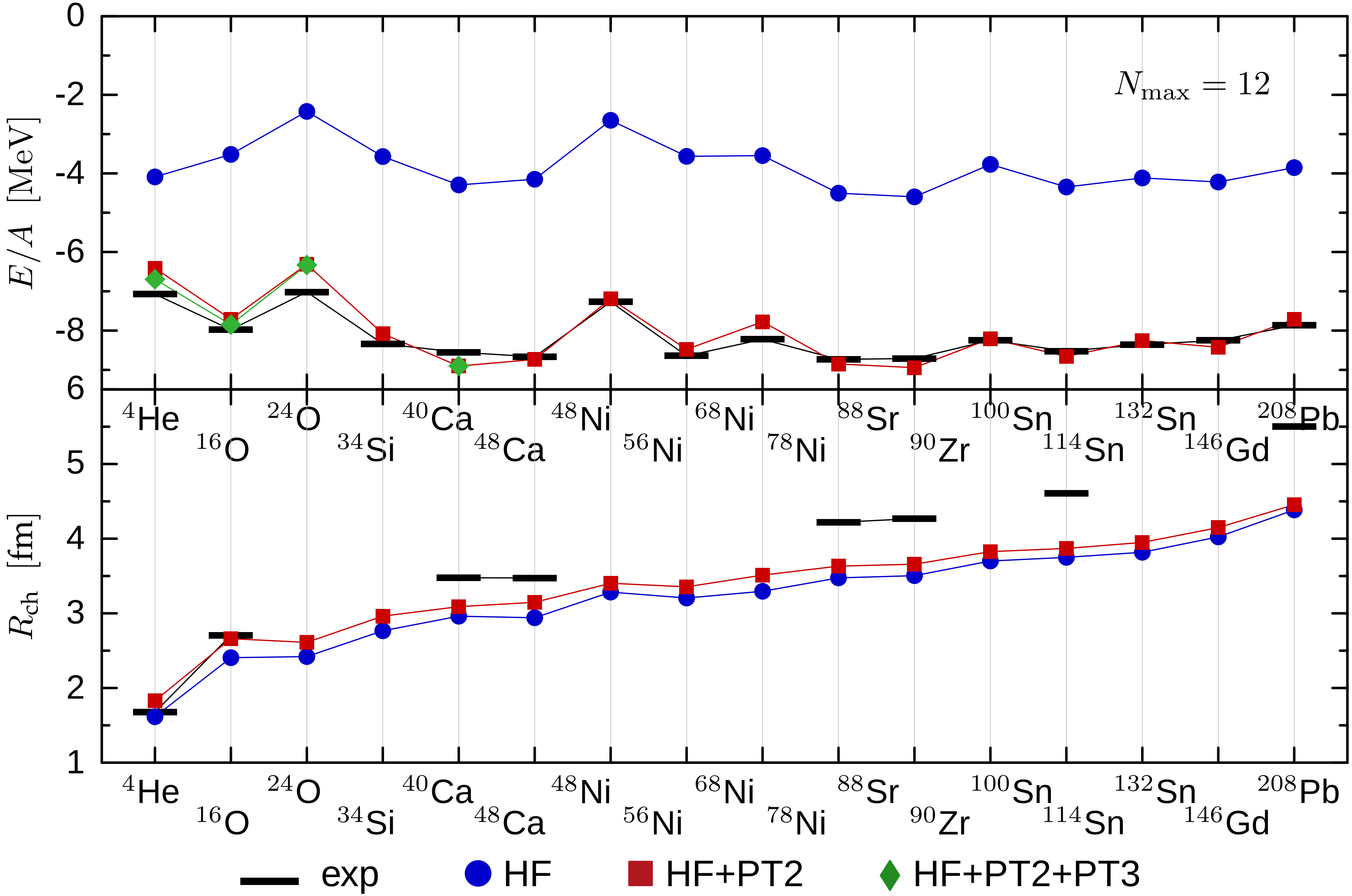
- Binding-energy correction:

$$E^{(2)} = -\frac{1}{4} \sum_{i,j}^{\text{occ}} \sum_{a,b}^{\text{unocc}} \frac{|\langle ij|H_{\text{int}}|ab\rangle|^2}{e_a + e_b - e_i - e_j} \quad ; \quad H_{\text{int}} = T_{\text{rel}} + V_{\text{UCOM}}$$

- Modified density matrix and occupation numbers

☞ Modified charge radii

UCOM-HF + PT



$N_{max} = 12$
E/A [MeV]
R_{ch} [fm]
^{4}He ^{16}O ^{24}O ^{34}Si ^{40}Ca ^{48}Ca ^{48}Ni ^{56}Ni ^{68}Ni ^{78}Ni ^{88}Sr ^{90}Zr ^{100}Sn ^{114}Sn ^{132}Sn ^{146}Gd ^{208}Pb
exp
HF
HF+PT2
HF+PT2+PT3

Collective Excitations

Standard RPA

- Vibration creation operator:

$$Q_\nu^\dagger = \sum_{ph} X_{ph}^\nu O_{ph}^\dagger - \sum_{ph} Y_{ph}^\nu O_{ph} \quad ; \quad Q_\nu |\mathrm{RPA}\rangle = 0 \quad ; \quad Q_\nu^\dagger |\mathrm{RPA}\rangle = |\nu\rangle$$

- Standard RPA - the RPA vacuum is approximated by the HF ground state:

$$\langle \mathrm{RPA}| \ldots |\mathrm{RPA}\rangle \rightarrow \langle \mathrm{HF}| \ldots |\mathrm{HF}\rangle \quad ; \quad O_{ph} \rightarrow a_p^\dagger a_h$$

- RPA equations in $ph-$space:

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} = \hbar\omega_\nu \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix}$$

$$A_{ph,p'h'} = \delta_{pp'}\delta_{hh'}(e_p - e_h) + H_{hp',ph'} \;\; ; \;\; B_{ph,p'h'} = H_{hh',pp'} \;\; ; \;\; H = H_{\mathrm{int}} = T_{\mathrm{rel}} + V_{\mathrm{UCOM}}$$

☞ Self-consistent HF+RPA: spurious state and sum rules

Second RPA

- Vibration creation operator: Includes $2p2h$ configurations

$$Q_\nu^\dagger = \sum_{ph} X_{ph}^\nu O_{ph}^\dagger - \sum_{ph} Y_{ph}^\nu O_{ph} + \sum_{p_1h_1p_2h_2} \mathcal{X}^\nu_{p_1h_1p_2h_2} O^\dagger_{p_1h_1p_2h_2} - \sum_{p_1h_1p_2h_2} \mathcal{Y}^\nu_{p_1h_1p_2h_2} O_{p_1h_1p_2h_2}$$

- The SRPA vacuum is approximated by the HF ground state:

$$\langle \mathrm{SRPA}|\ldots|\mathrm{SRPA}\rangle \rightarrow \langle \mathrm{HF}|\ldots|\mathrm{HF}\rangle$$

- SRPA equations in $ph \oplus 2p2h-$space:

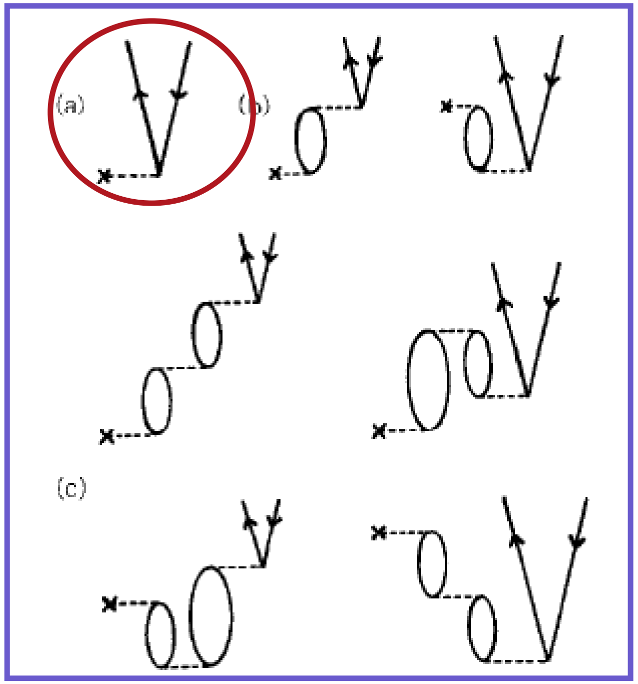
$$\left(\begin{array}{cc|cc} A & \mathcal{A}_{12} & B & 0 \\ \mathcal{A}_{21} & \mathcal{A}_{22} & 0 & 0 \\ \hline -B^* & 0 & -A^* & -\mathcal{A}_{12}^* \\ 0 & 0 & -\mathcal{A}_{21}^* & -\mathcal{A}_{22}^* \end{array}\right) \left(\begin{array}{c} X^\nu \\ \mathcal{X}^\nu \\ \hline Y^\nu \\ \mathcal{Y}^\nu \end{array}\right) = \hbar\omega_\nu \left(\begin{array}{c} X^\nu \\ \mathcal{X}^\nu \\ \hline Y^\nu \\ \mathcal{Y}^\nu \end{array}\right)$$

$A_{ph,p'h'} = \delta_{pp'}\delta_{hh'}(e_p - e_h) + H_{hp',ph'}$; $B_{ph,p'h'} = H_{hh',pp'}$; $H = H_{\mathrm{int}} = T_{\mathrm{rel}} + V_{\mathrm{UCOM}}$

$\mathcal{A}_{12}$: interactions between ph and $2p2h$ states

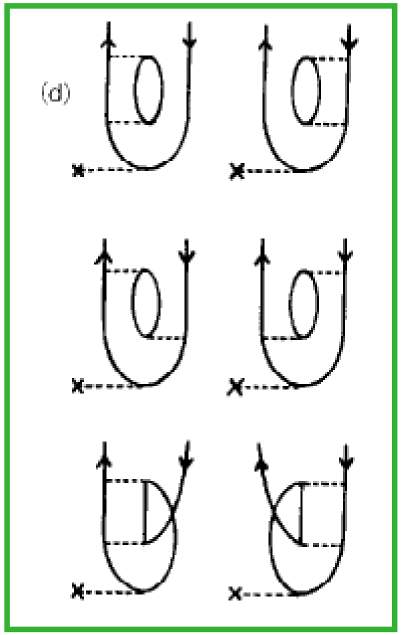
$\mathcal{A}_{22}$: $\delta_{p_1p_1'}\delta_{h_1h_1'}\delta_{p_1p_1'}\delta_{h_1h_1'}(e_{p_1} + e_{p_2} - e_{h_1} - e_{h_2})$ + interactions among $2p2h$ states

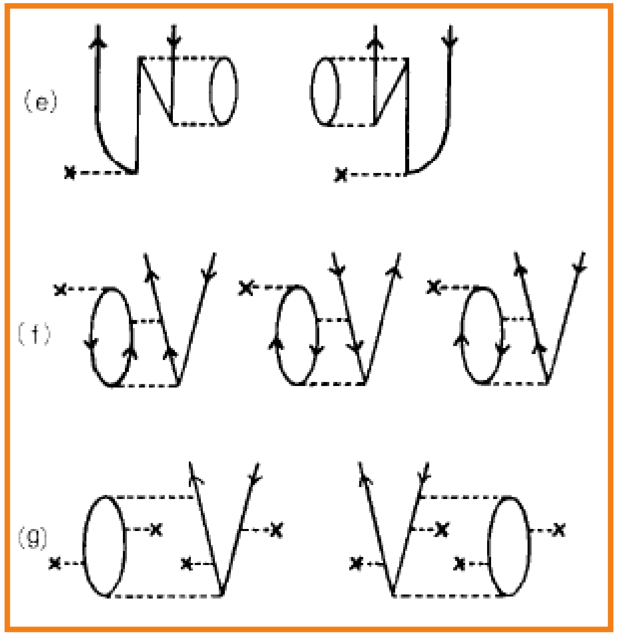
RPA, SRPA, and extensions



RPA

SRPA





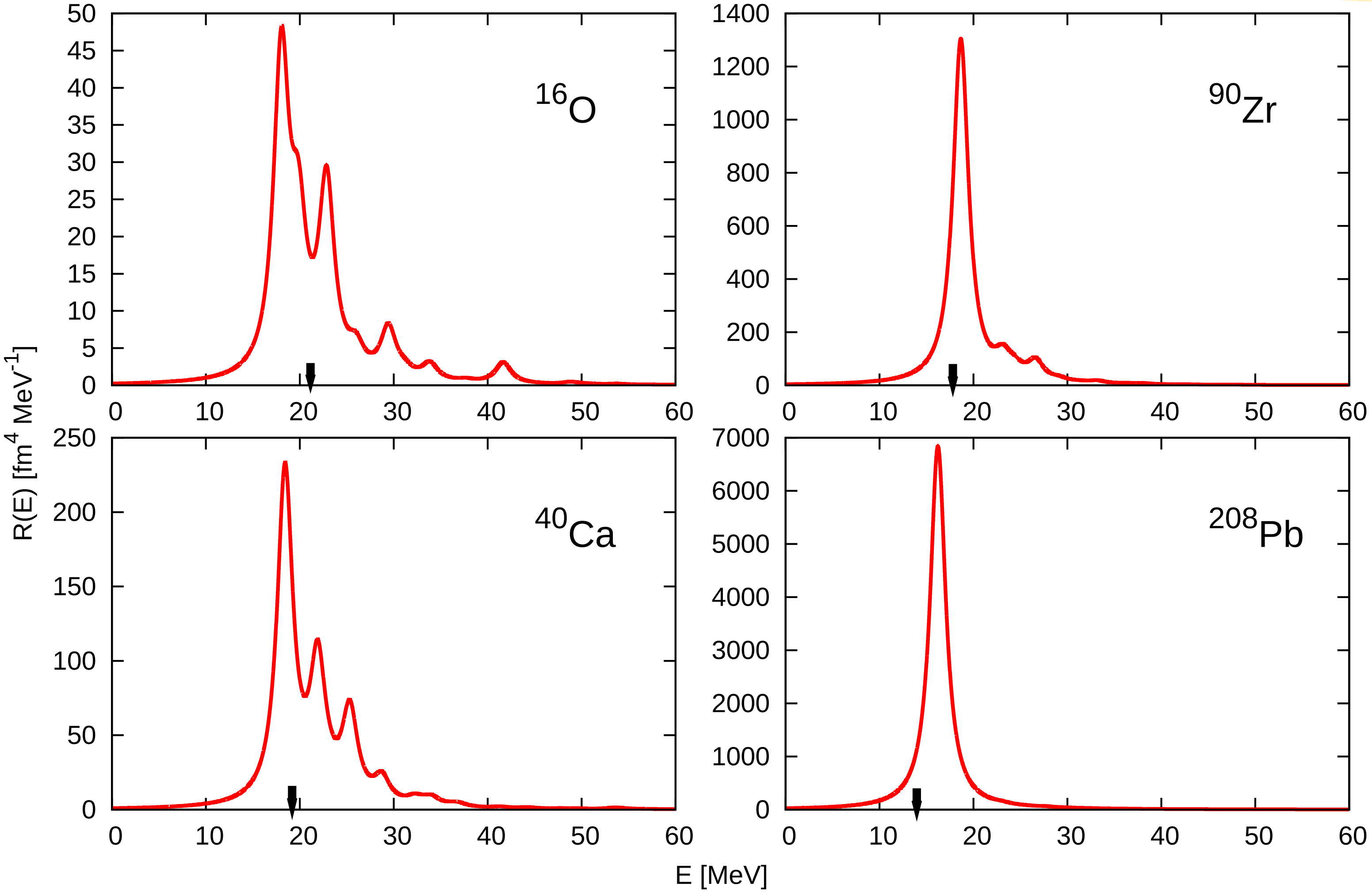
additional 2nd-order diagrams

Nucl.Phys.A477(88)205 etc

Standard RPA

Isoscalar monopole response

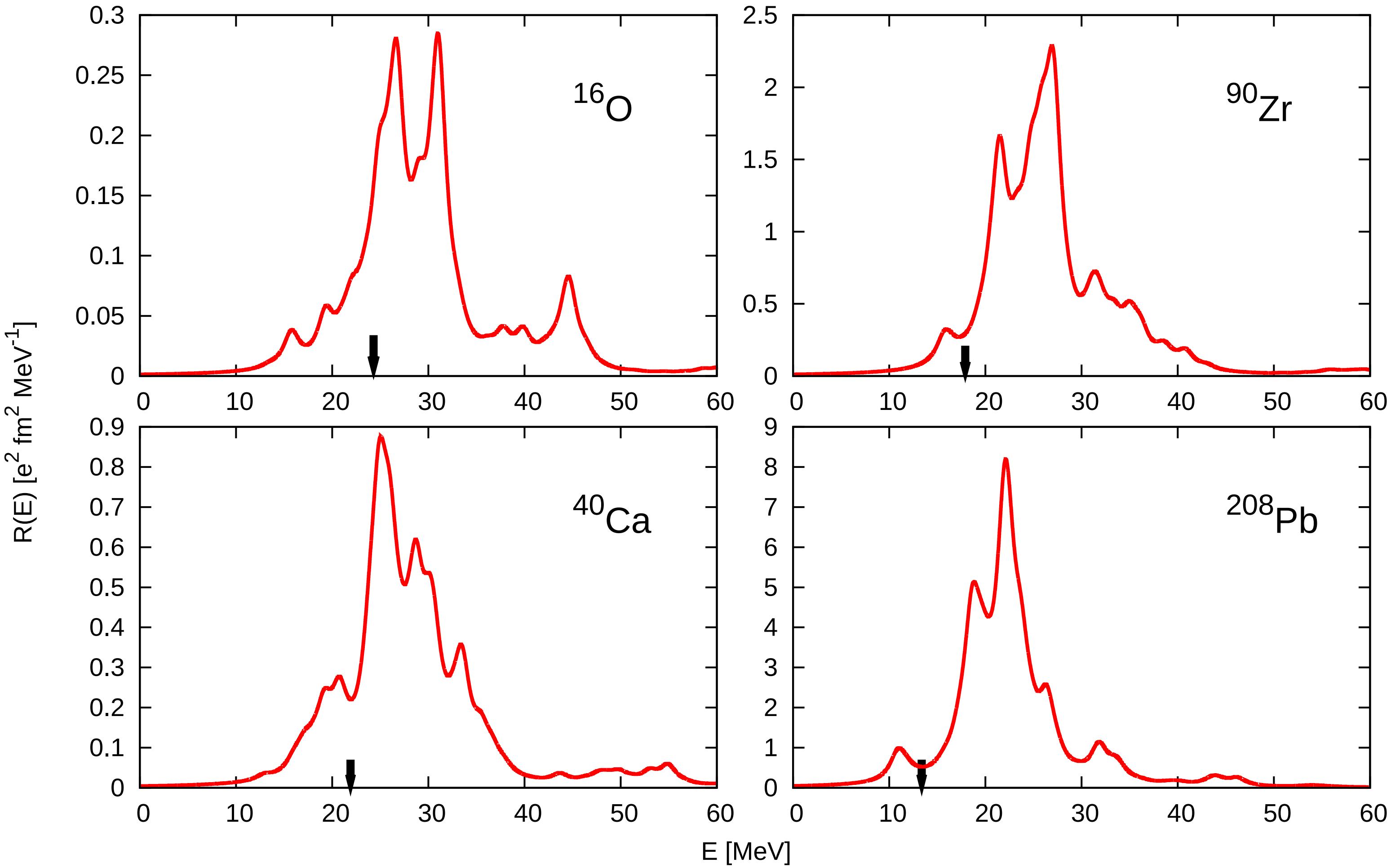
$N_{\text{max}} = 12$



Standard RPA

Isovector dipole response

$N_{\text{max}} = 12$



Standard RPA

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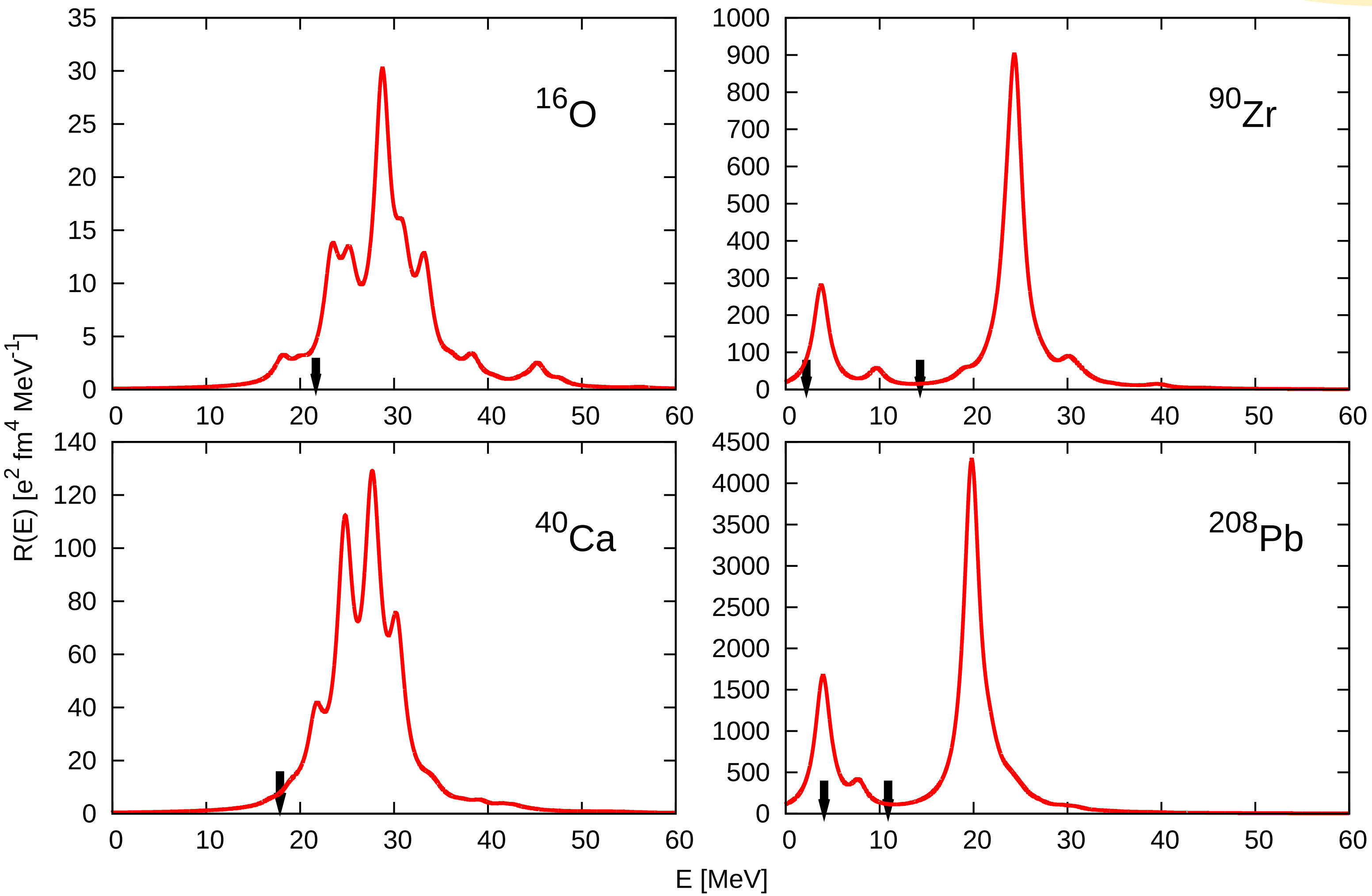
Isoscalar quadrupole response

$N_{\rm max} = 12$



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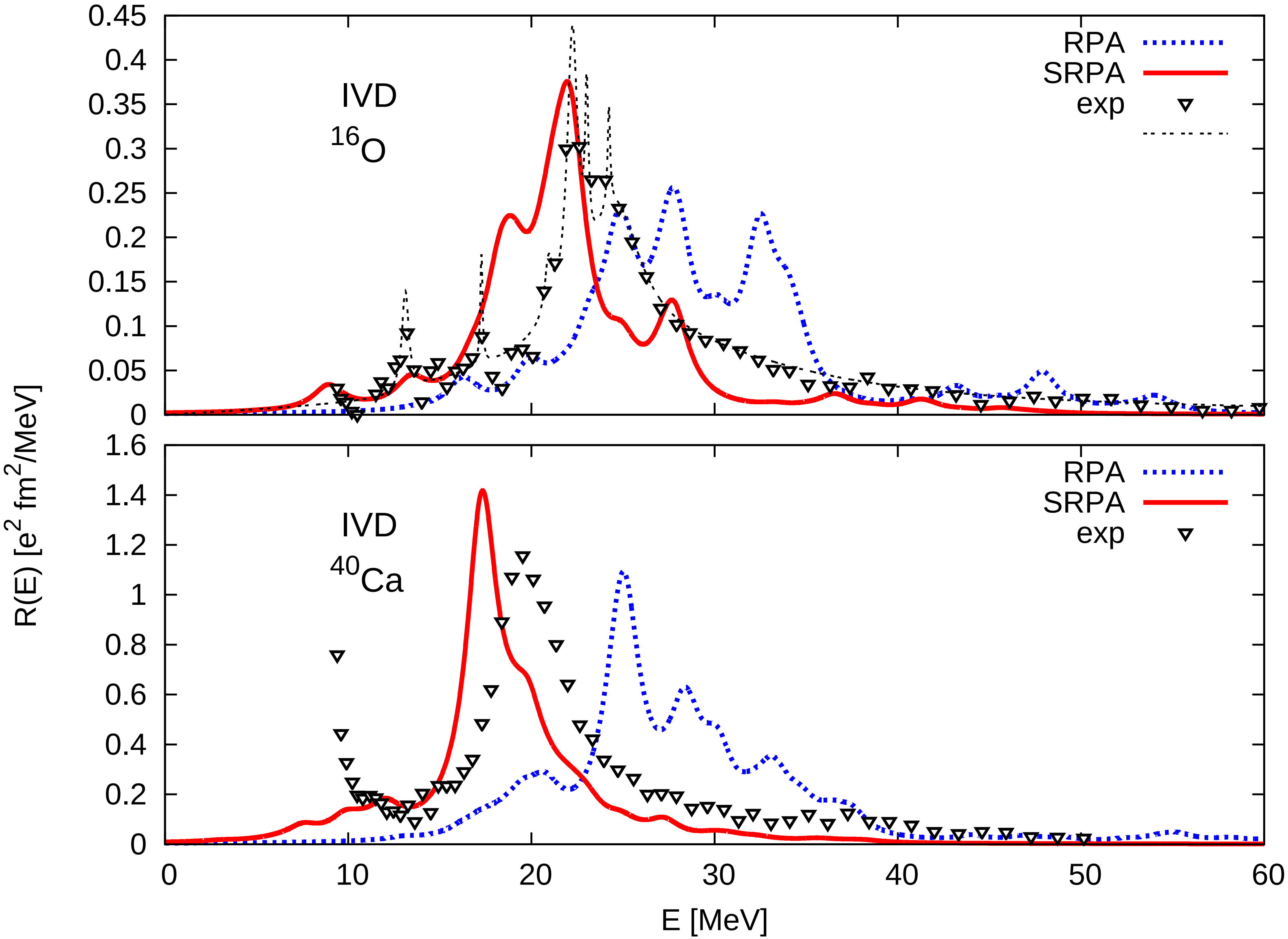
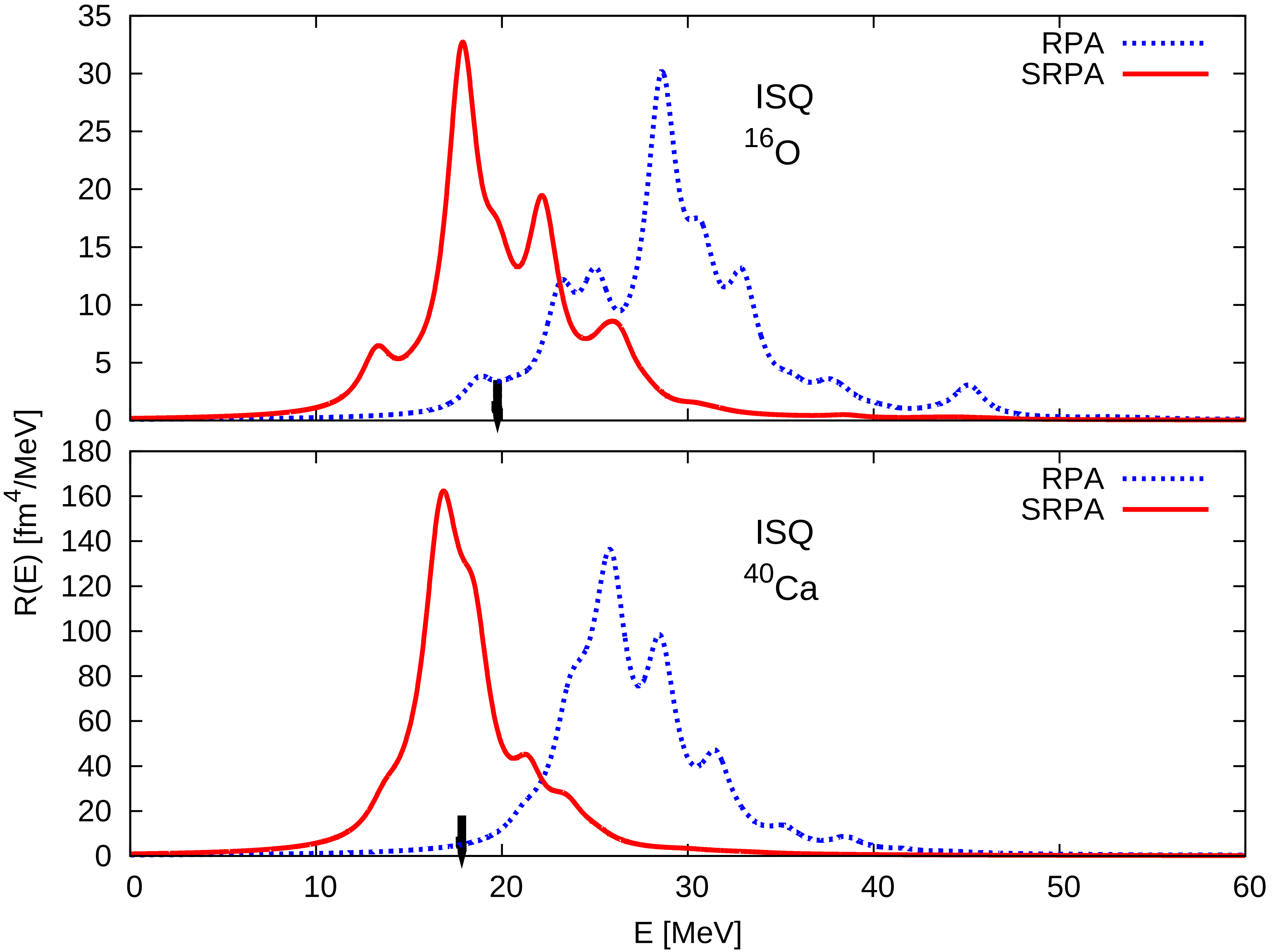
Second RPA

Isovector dipole response



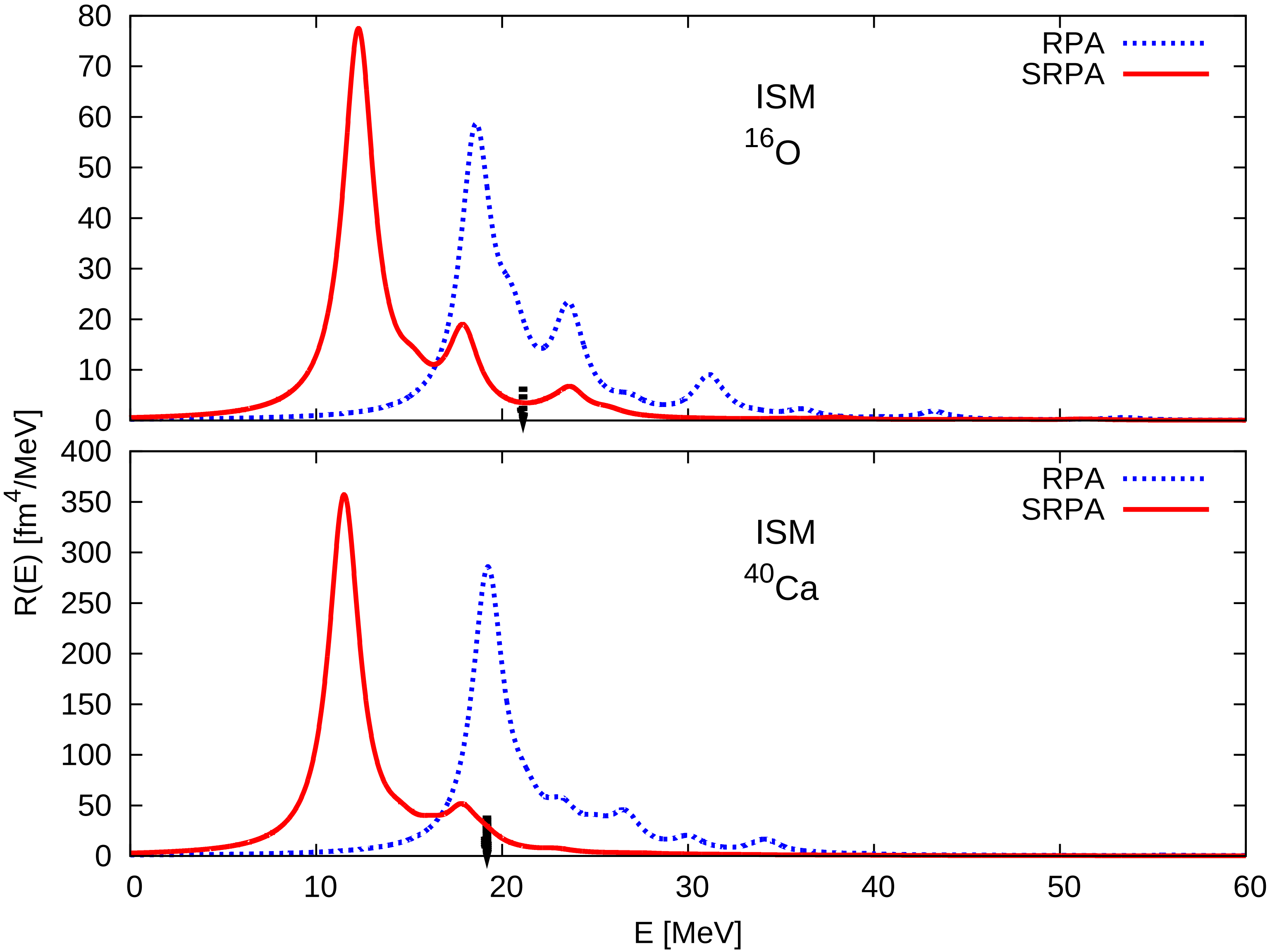
Second RPA

Isoscalar quadrupole response

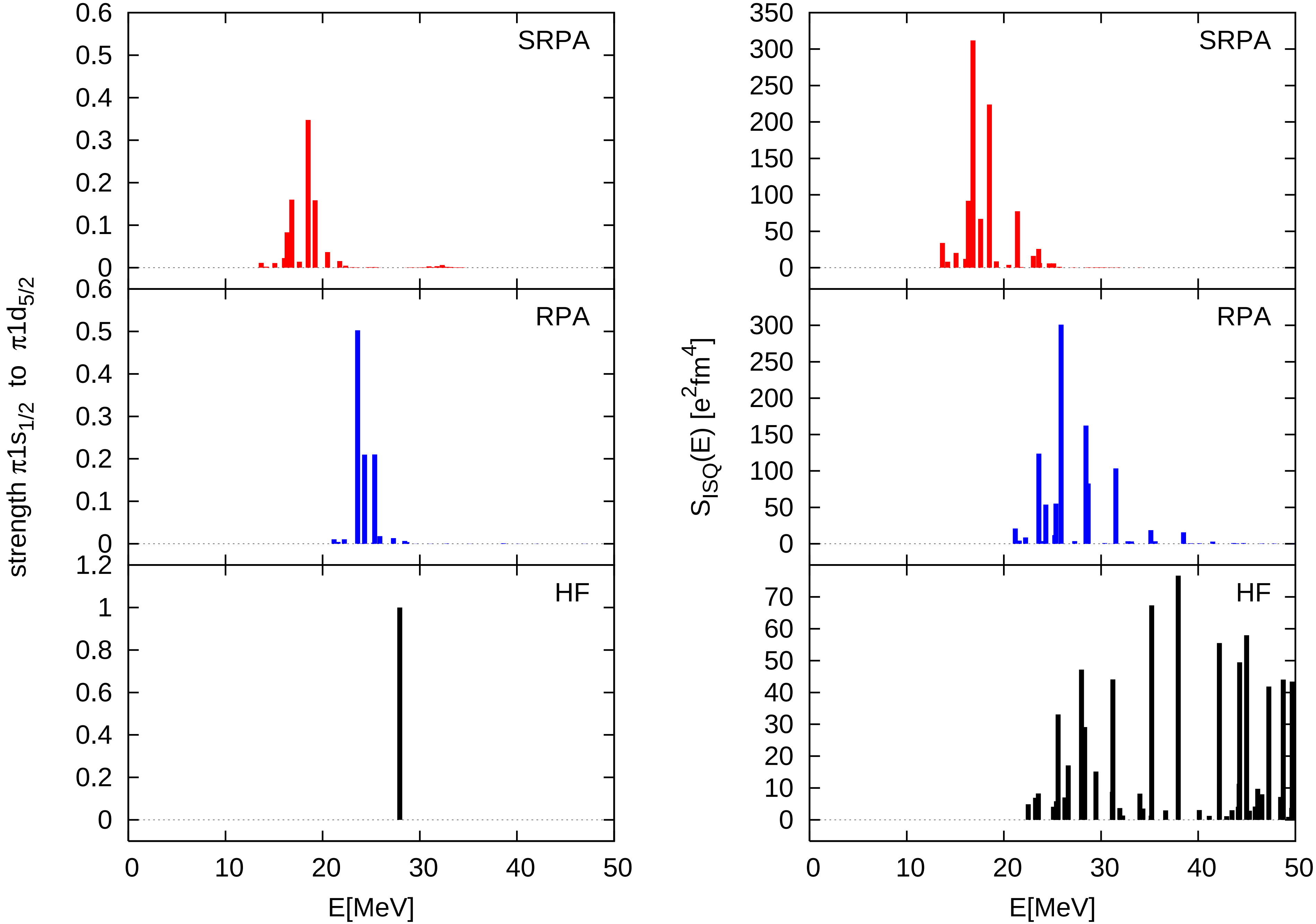


Second RPA

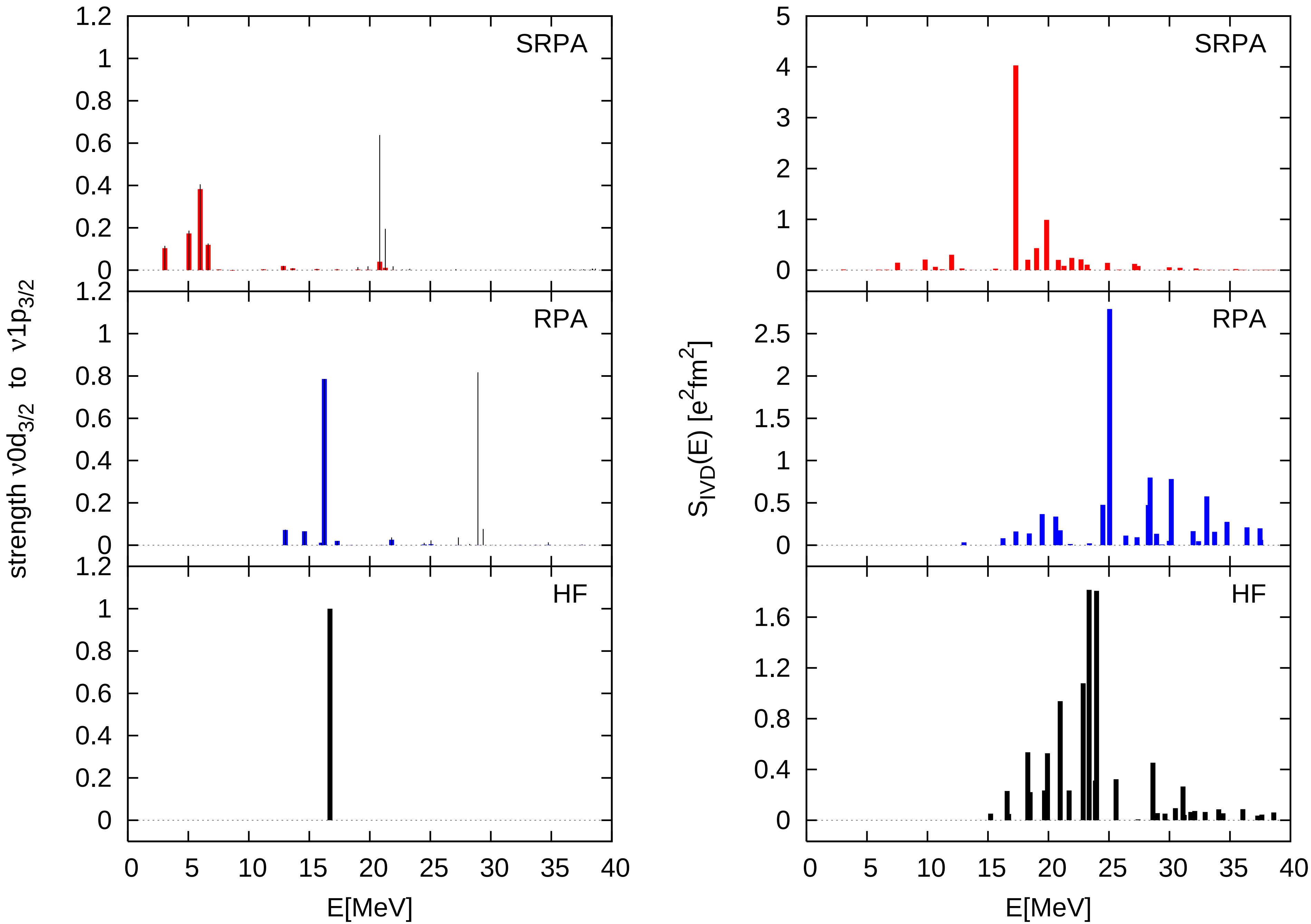
Isoscalar monopole response



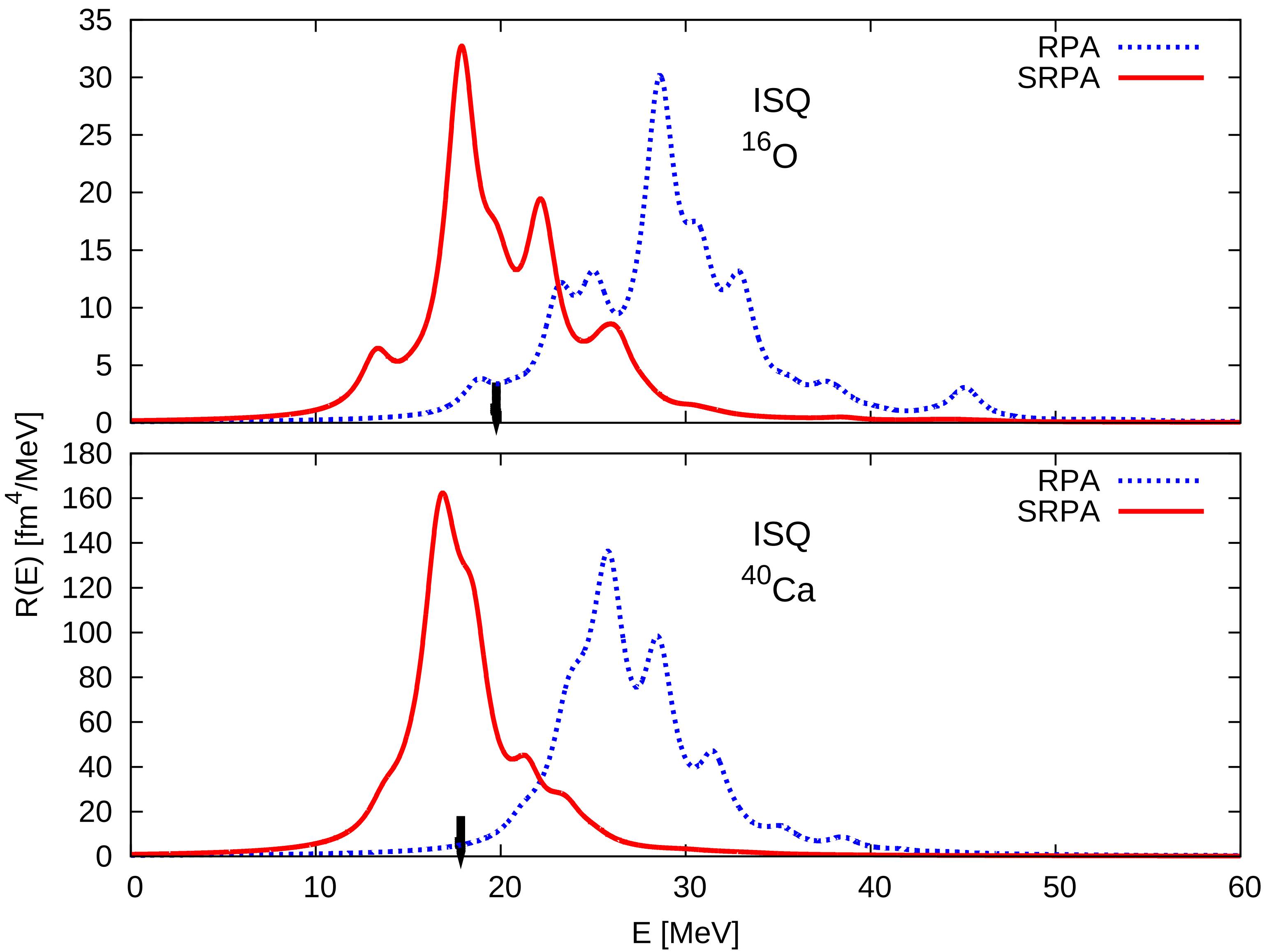
Fragmentation of ph states



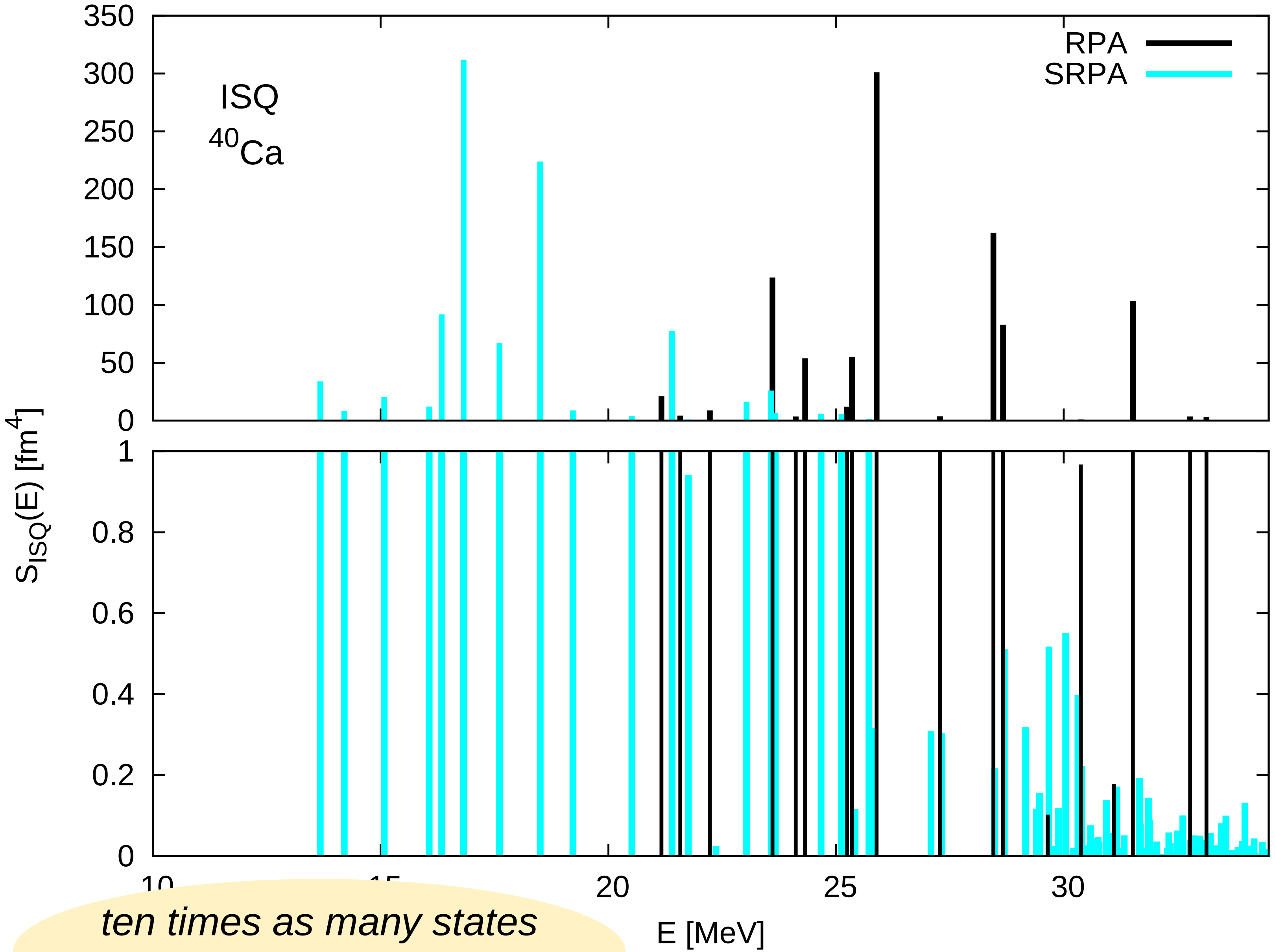
Fragmentation of ph states



Isoscalar quadrupole response

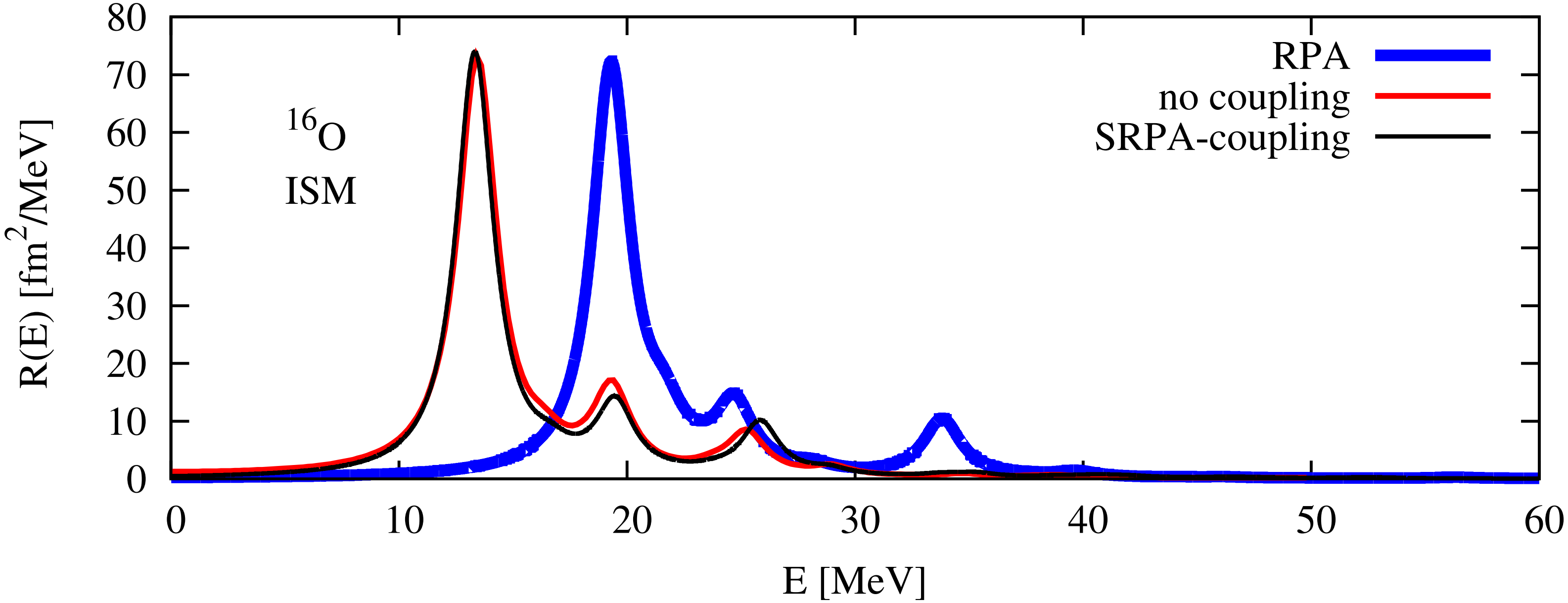


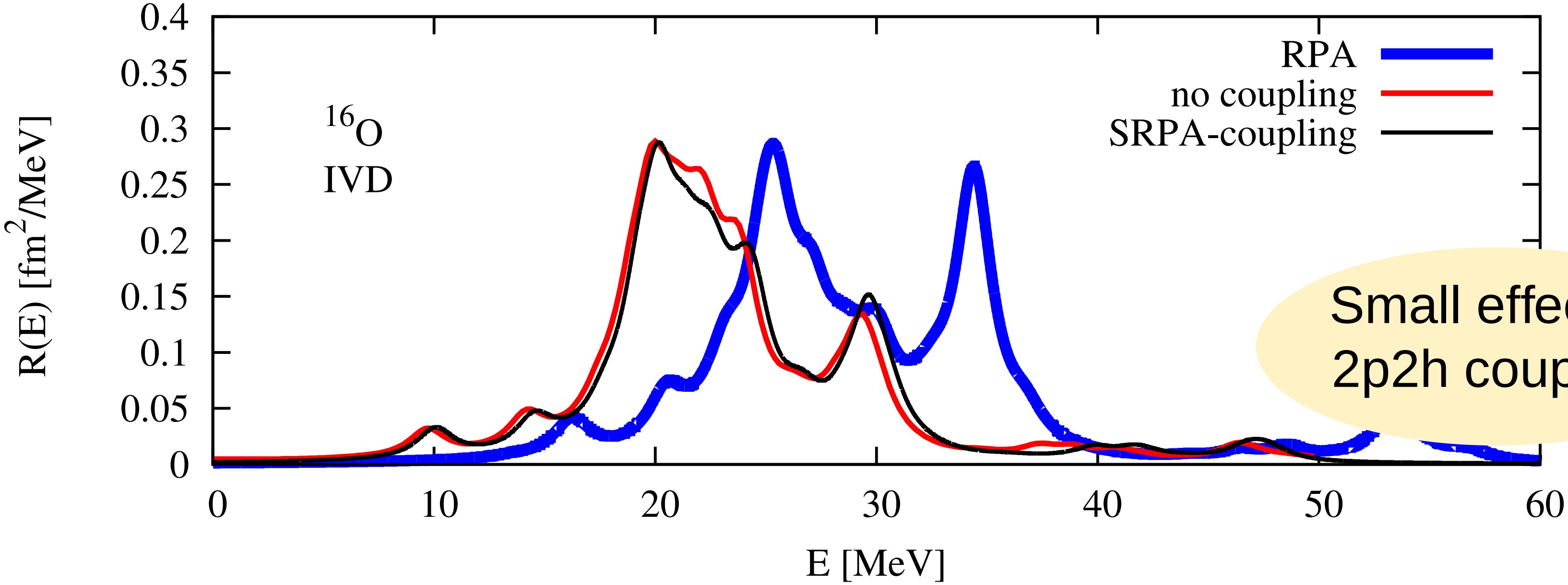
Fragmentation of resonances



ten times as many states below 35 MeV

Second RPA with 2p2h coupling





Small effect of 2p2h coupling

Summary and Outlook

Marrying Second RPA and the V_{UCOM}:

- Beyond RPA: fragmentation of collective modes
- Possibility for "self-consistent" SRPA calculations
- More fundamental treatment of nucleon self energy and effective mass (IVD, ISQ)

Effective interactions for SRPA?

Summary and Outlook

Use of V_{UCOM} in nuclear response calculations across the nuclear chart:

- First-order RPA: Properties of the V_{UCOM} as a traditional effective interaction
  - Centroid energies overestimated (IVD, ISQ)
  - Good compressibility, low effective mass
- Second RPA: Sizable effect of coupling with 2p2h configurations
  - Important role of residual correlations
  - Discrepancies due to residual three body effects?
  - Self-consistency issues of the SRPA formalism

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Thank you!

Work in collaboration with:

- R.Roth, H.Hergert, J. Wambach, A. Zapp, S. Reinhardt
  Institut für Kernphysik, TU Darmstadt, Germany
- C. Barbieri, H. Feldmeier, K. Langanke, G. Martinez-Pinedo, T. Neff
  GSI, Darmstadt, Germany

Recent References

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- P. Papakonstantinou, R. Roth, N.Paar, Phys. Rev. C**75**, 014310 (2007)
- N.Paar, P. Papakonstantinou, H.Hergert, R. Roth, Phys. Rev. C**74**, 014318 (2006)
- and many more: **http://crunch.ikp.physik.tu-darmstadt.de/tnp/**

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