Nuclear Collective Excitations within the UCOM Framework: RPA and beyond

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Overview

- Introduction
- Results within RPA models
  - Self-consistent Hartree-Fock + RPA calculations
  - Explicit RPA correlations within ”Extended” RPA
  - Second RPA: extended model space
- Summary

Introduction

Correlated realistic interactions V_{UCOM}

- Short-range central and tensor correlations (SRC) described by a unitary correlation operator $C = C_\Omega C_r$
- Introduce SRC to uncorrelated A-body state or an operator of interest

$$\langle\tilde{\Psi}|O|\tilde{\Psi}\rangle = \langle\Psi|C^\dagger O C|\Psi\rangle = \langle\Psi|\tilde{O}|\Psi\rangle$$

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

Introduction

Related talks

- P. Hedfeld, HK27.4:
  - Brueckner-Hartree-Fock
- H. Hergert, HK27.5:
  - Hartree-Fock-Bogoliubov and Quasiparticle-RPA
- A. Zapp, HK32.8:
  - Three-body interaction

This talk

- Collective excitations: **RPA, extended RPA, Second RPA**
- Correlated Argonne V18, no three-body term

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:

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

- RPA equations in $ph-$space:

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

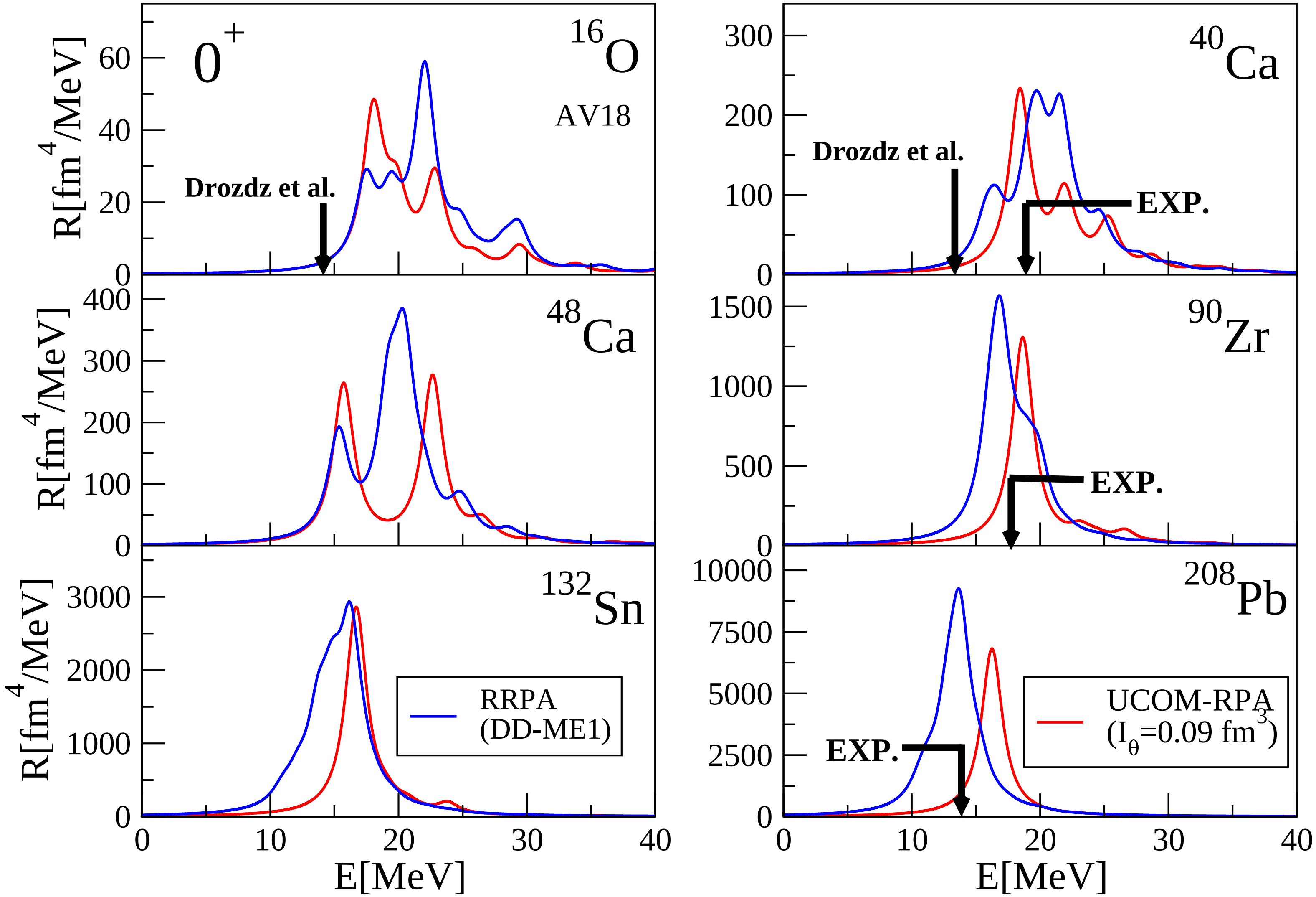
$$A_{ph,p'h'} = \delta_{pp'}\delta_{hh'}(e_p - e_h) + H_{hp',ph'} \;\; ; \;\; B_{ph,p'h'} = H_{hh',pp'} \;\; ; \;\; H = H_{\mathrm{int}} = T_{\mathrm{rel}} + V_{\mathrm{UCOM}}$$

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

Standard RPA

Isoscalar monopole response

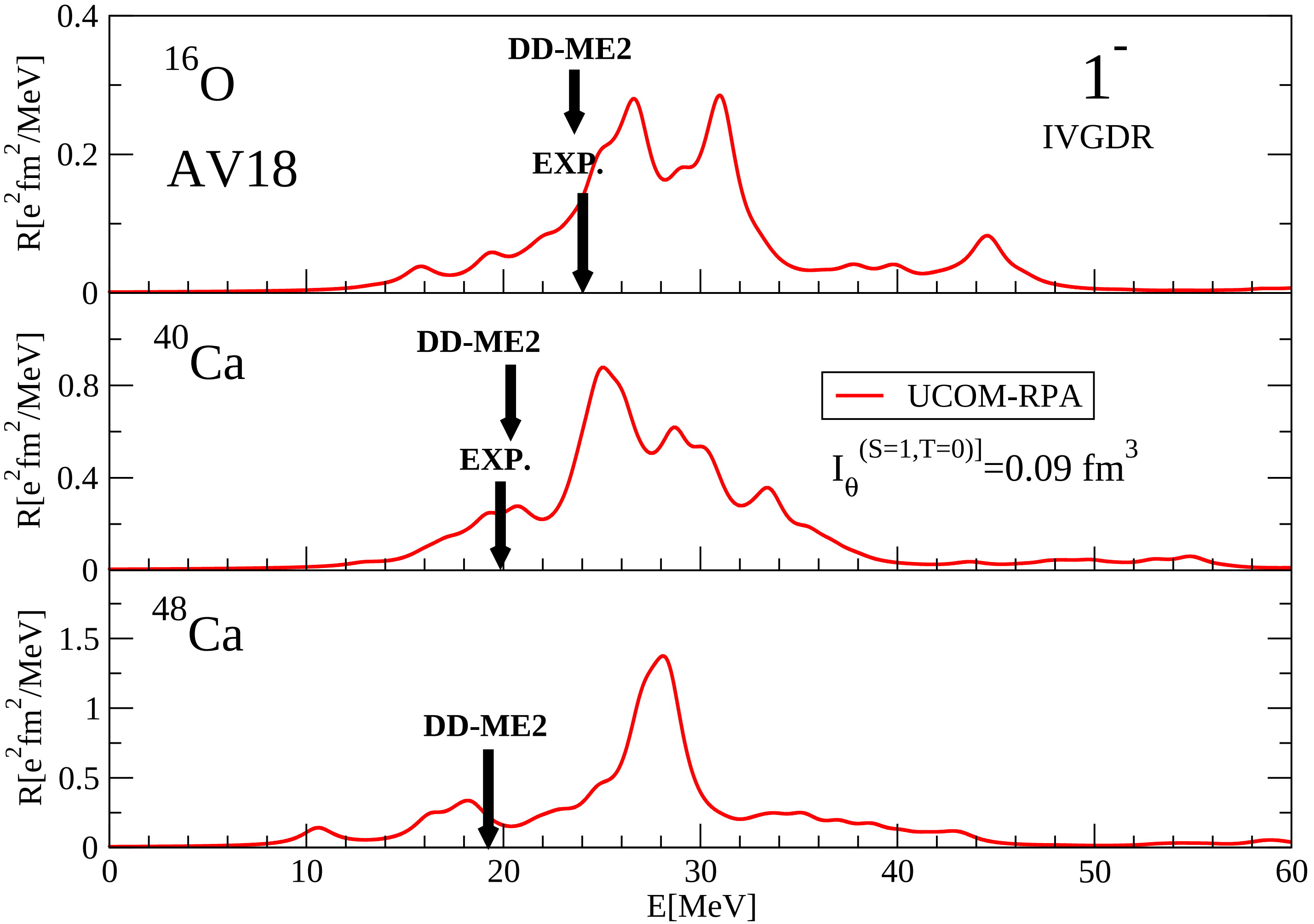
$N_{\text{max}} = 12$



Standard RPA

Isovector dipole response

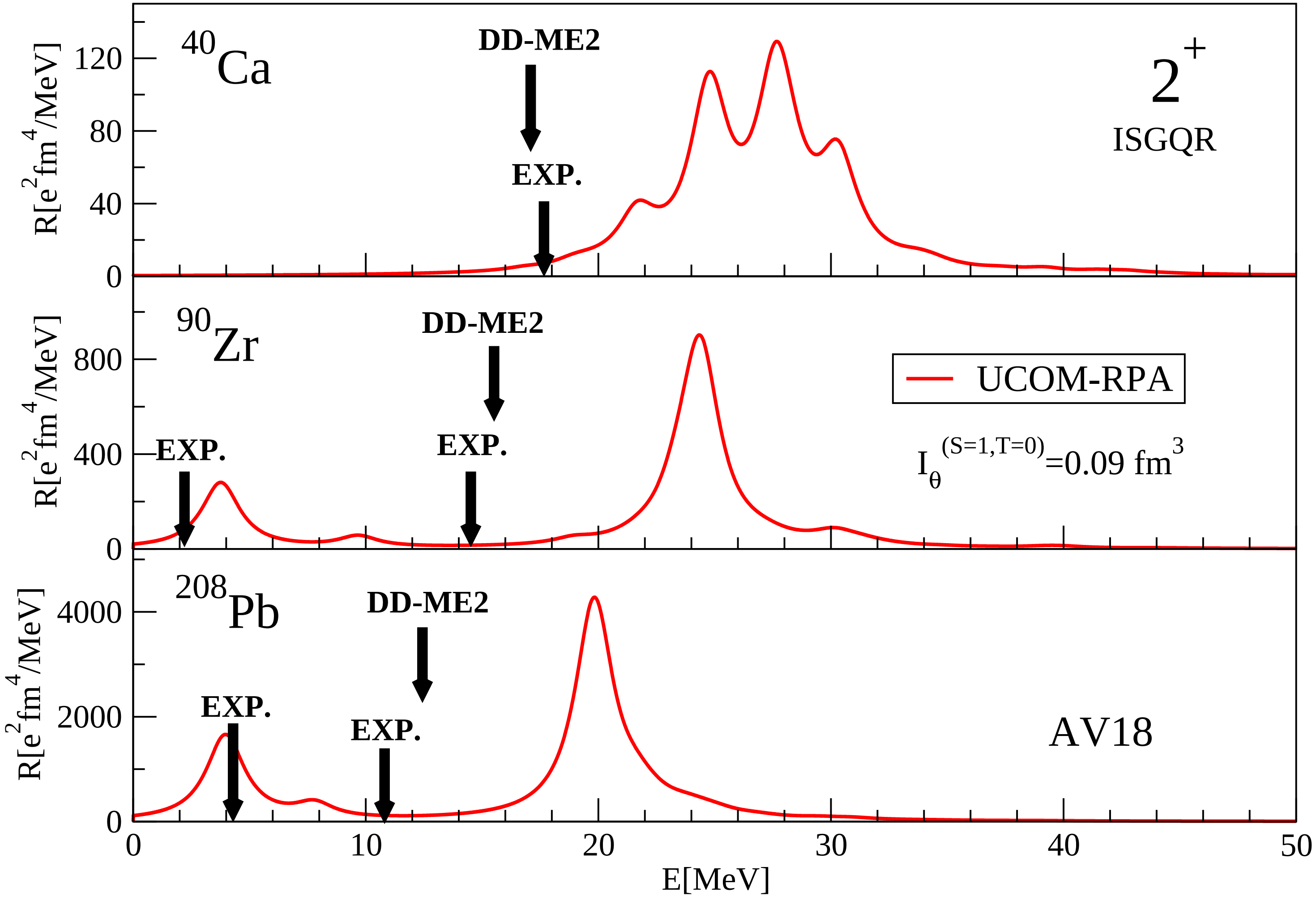
$N_{\mathrm{max}} = 12$



Standard RPA

Isoscalar quadrupole response

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



Beyond Standard RPA

The HF+RPA method is based mainly on the following approximations:

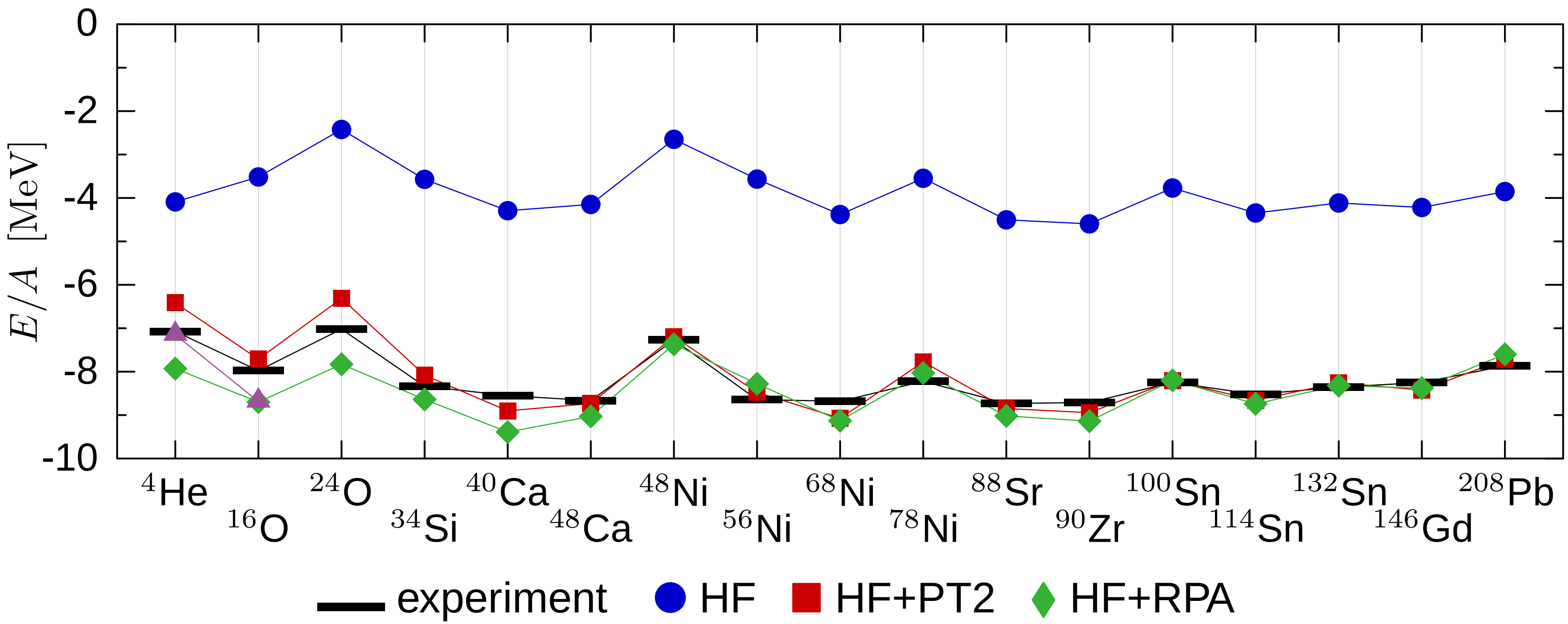
- ☞ Coupling to higher order excitations ($np-nh$) is neglected → Second RPA

- ☞ The ground state does not deviate much from the HF ground state → Renormalized RPA, “Extended” RPA, ...

RPA Ground State Correlations

- evaluate correlation energy beyond Hartree-Fock via **ring summation** using RPA amplitudes
- include all parities and charge exchange and correct for double-counting of 2nd order term

[C.Barbieri et al., nucl-th/0608011]



Extended RPA

[Catara et al.: PRB58(98)16070;
Voronov et. al.: Phys.Part.Nucl.31(00)904]

- Vibration creation operator:

$$Q^\dagger_\nu = \sum_{ph} X^\nu_{ph} O^\dagger_{ph} - \sum_{ph} Y^\nu_{ph} O_{ph} \quad ; \quad Q_\nu|\mathrm{RPA}\rangle = 0 \quad ; \quad Q^\dagger_\nu|\mathrm{RPA}\rangle = |\nu\rangle$$

- Excitations are built on the RPA vacuum. In general,

$$O_{ph} = \sum_{p'h'} N_{ph,p'h'} a^\dagger_{p'} a_{h'}$$

- ERPA is formulated in the natural-orbital basis:

$$O_{ph} \to D^{-1/2}_{ph} a^\dagger_p a_h \quad ; \quad D_{ph} \equiv n_h - n_p$$

ERPA equations: solved iteratively

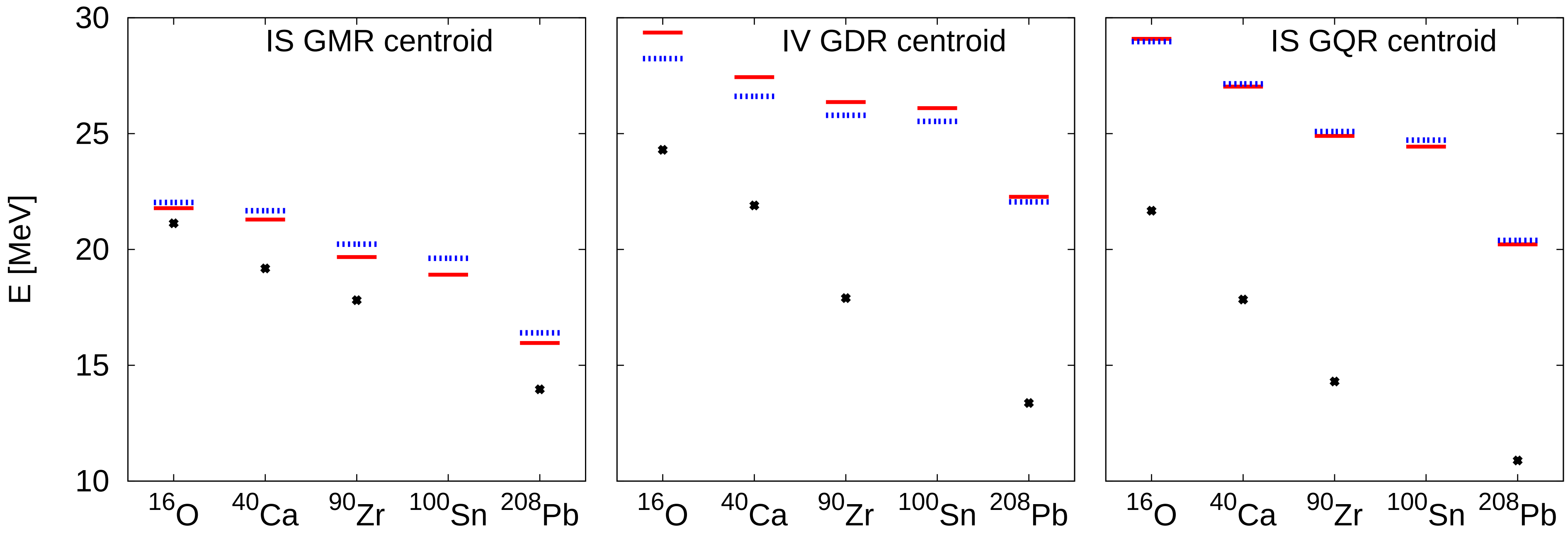
$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} = \hbar\omega_\nu \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix}$$

$$A_{ph,p'h'} = \delta_{hh'} e_{pp'} - \delta_{pp'} e_{hh'} + D^{1/2}_{ph} D^{1/2}_{p'h'} H_{hp',ph'} \quad ; \quad B_{ph,p'h'} = D^{1/2}_{ph} D^{1/2}_{p'h'} H_{hh',pp'}$$

$$e_{ij} = \sum_k n_k H_{ik,jk}$$

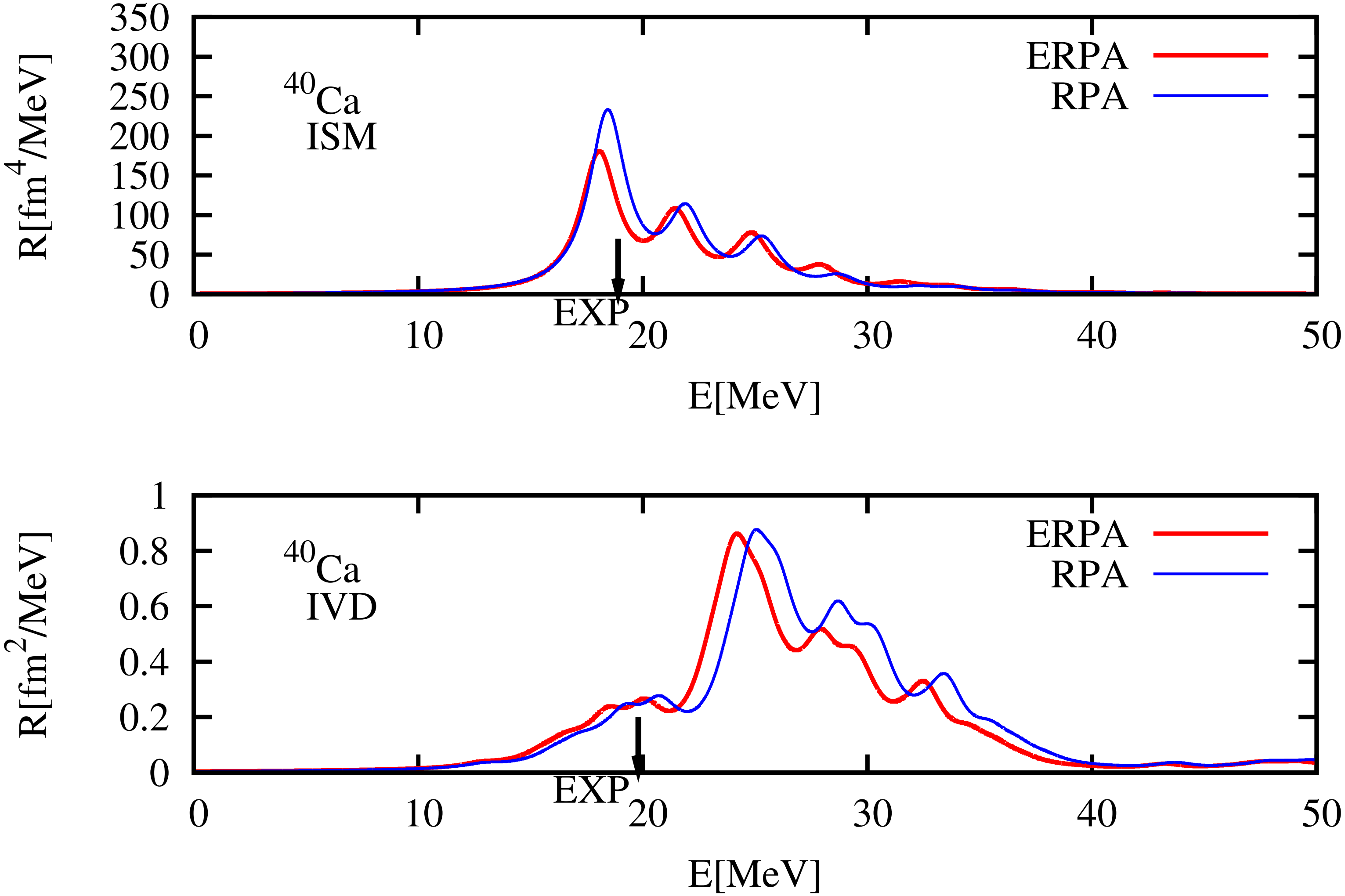
Extended RPA

Centroid energies — RPA ···· ERPA ▪ exp



Fermi-sea depletion: 2.6-5.0%

Extended RPA



Second RPA

- Vibration creation operator: Includes $2p2h$ configurations

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

- 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:

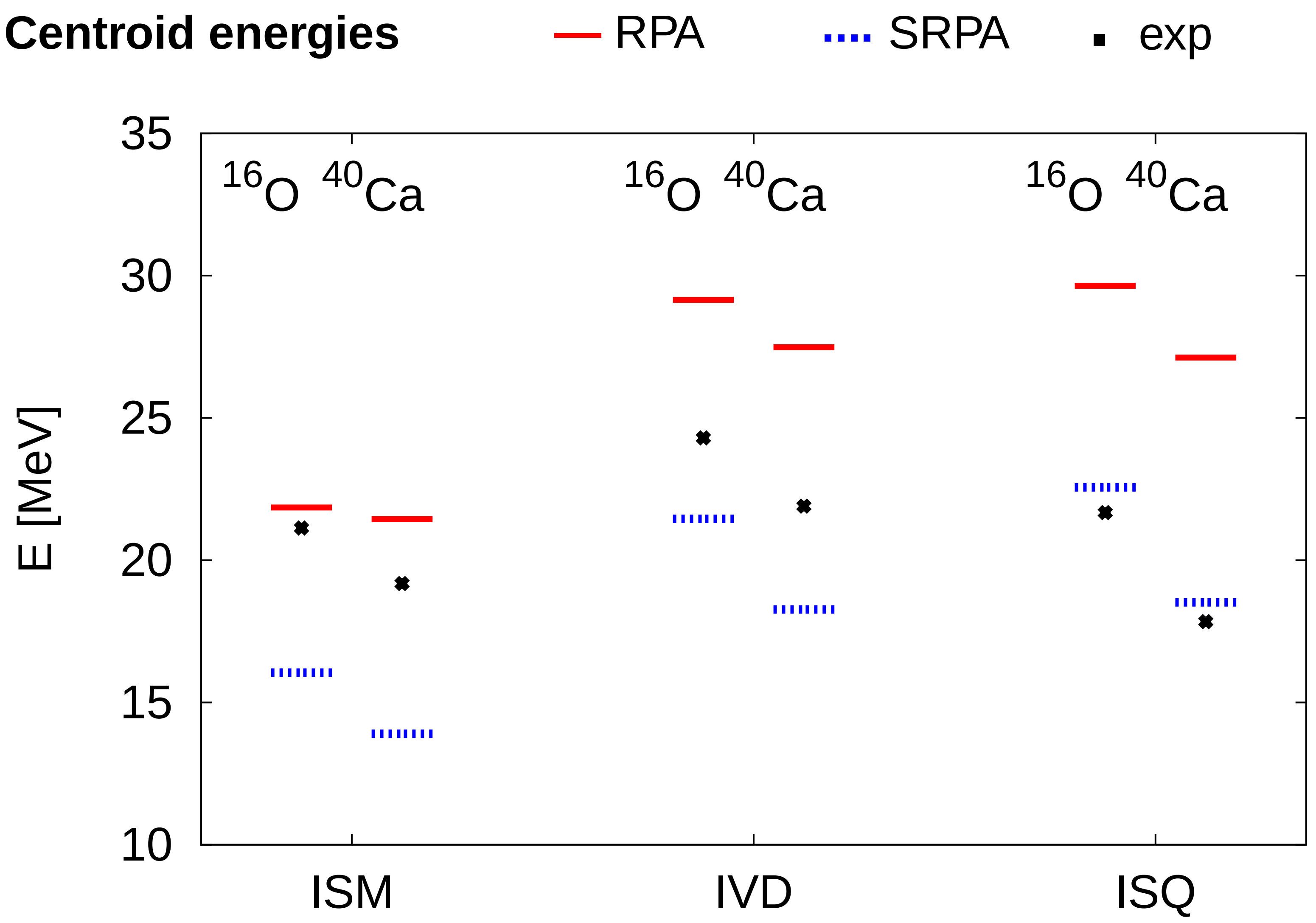
$$\left(\begin{array}{cc|cc} A & \mathcal{A}_{12} & B & 0 \\ \mathcal{A}_{21} & \mathcal{A}_{22} & 0 & 0 \\ \hline -B^* & 0 & -A^* & -\mathcal{A}_{12}^* \\ 0 & 0 & -\mathcal{A}_{21}^* & -\mathcal{A}_{22}^* \end{array}\right) \left(\begin{array}{c} X^\nu \\ \mathcal{X}^\nu \\ \hline Y^\nu \\ \mathcal{Y}^\nu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

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

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

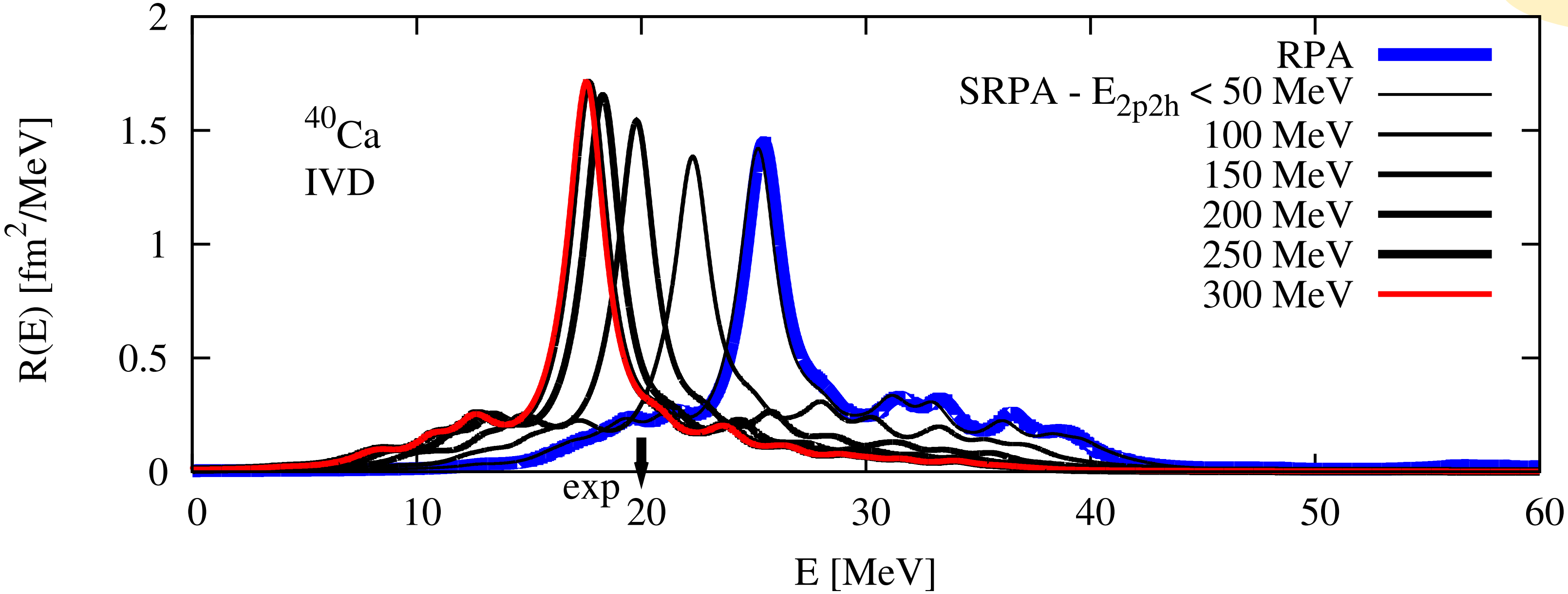
$\mathcal{A}_{22}$: $\delta_{p_1p_1'}\delta_{h_1h_1'}\delta_{p_1p_1'}\delta_{h_1h_1'}(e_{p_1} + e_{p_2} - e_{h_1} - e_{h_2})$ + interactions among $2p2h$ states

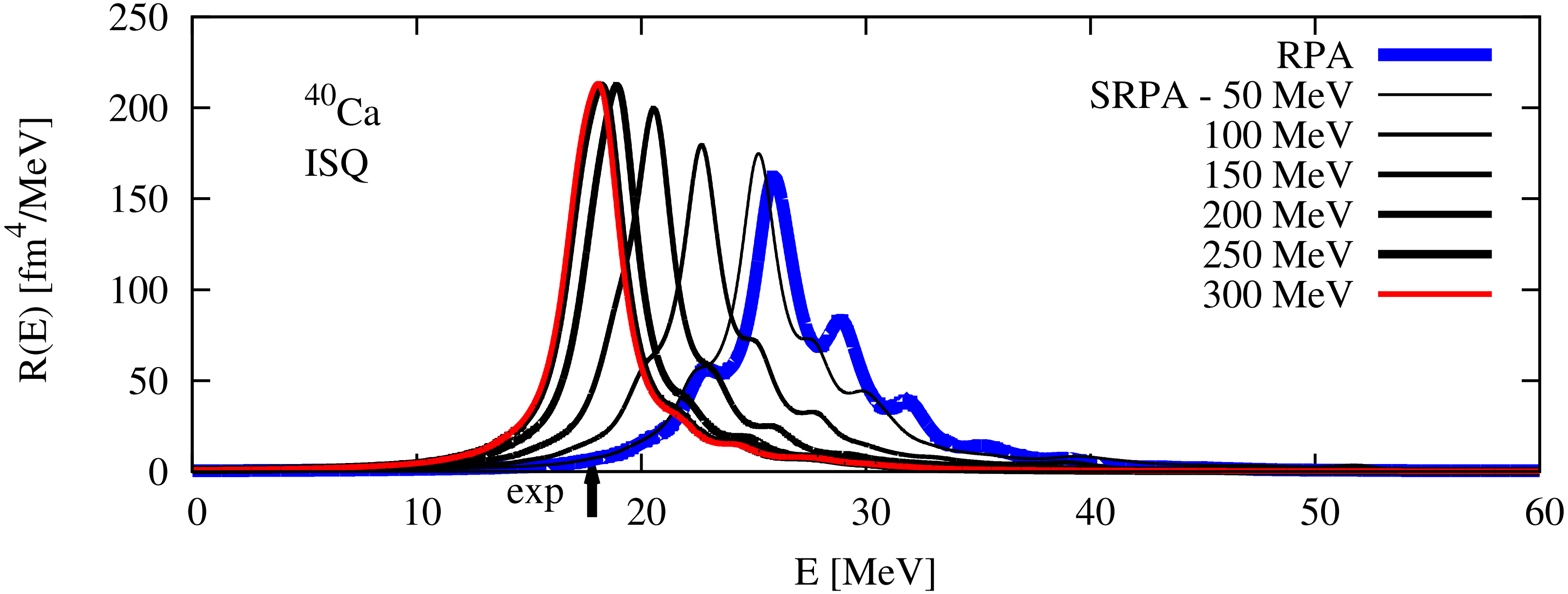
Second RPA


Centroid energies
RPA
SRPA
exp
16O 40Ca
16O 40Ca
16O 40Ca
E [MeV]
35
30
25
20
15
10
ISM
IVD
ISQ

Second RPA - No 2p2h-2p2h coupling

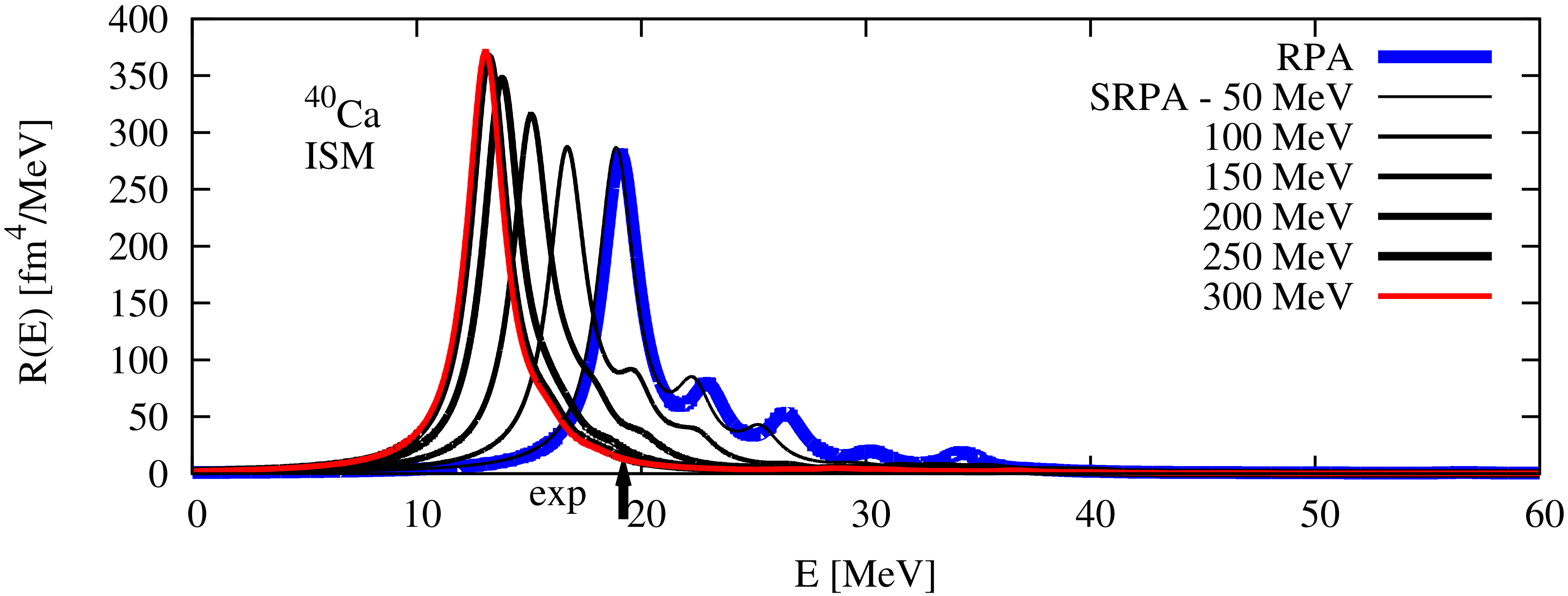
$N_{\max} = 10$





Second RPA - No 2p2h-2p2h coupling

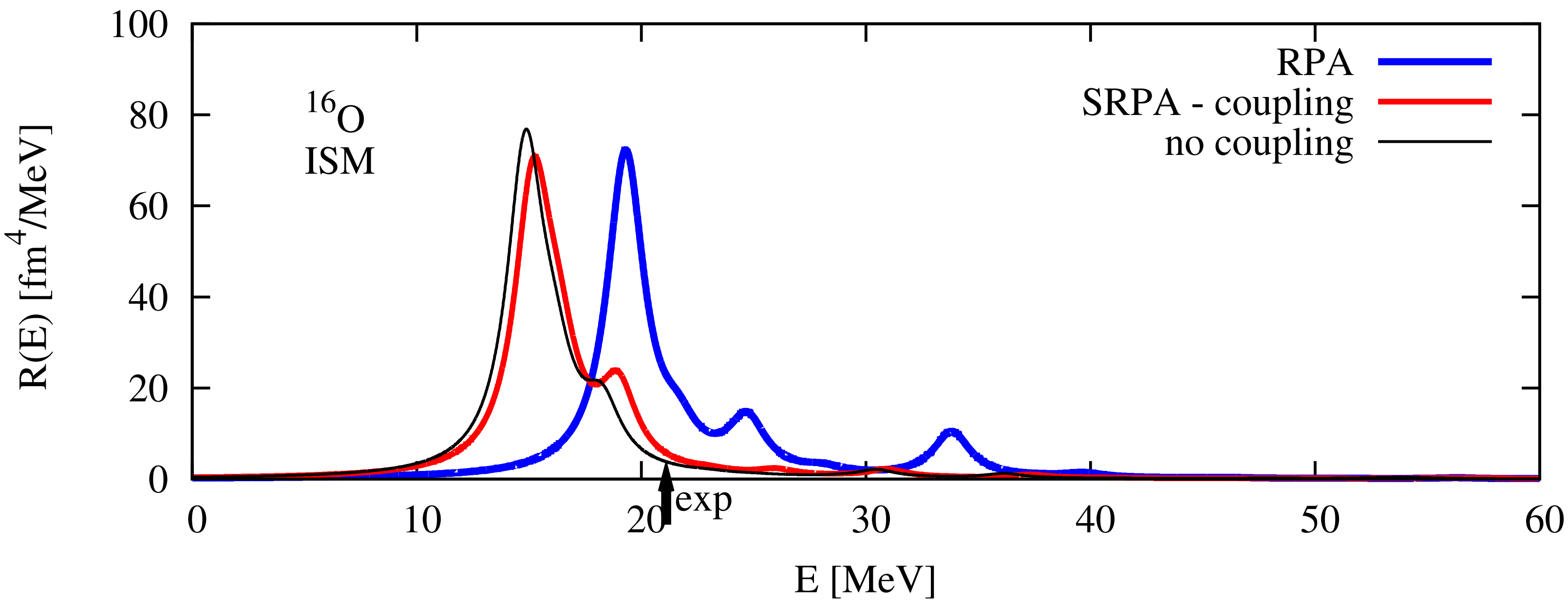
$N_{\rm max} = 10$



- Effects of three-body interactions?
- Full 2p2h-2p2h coupling?

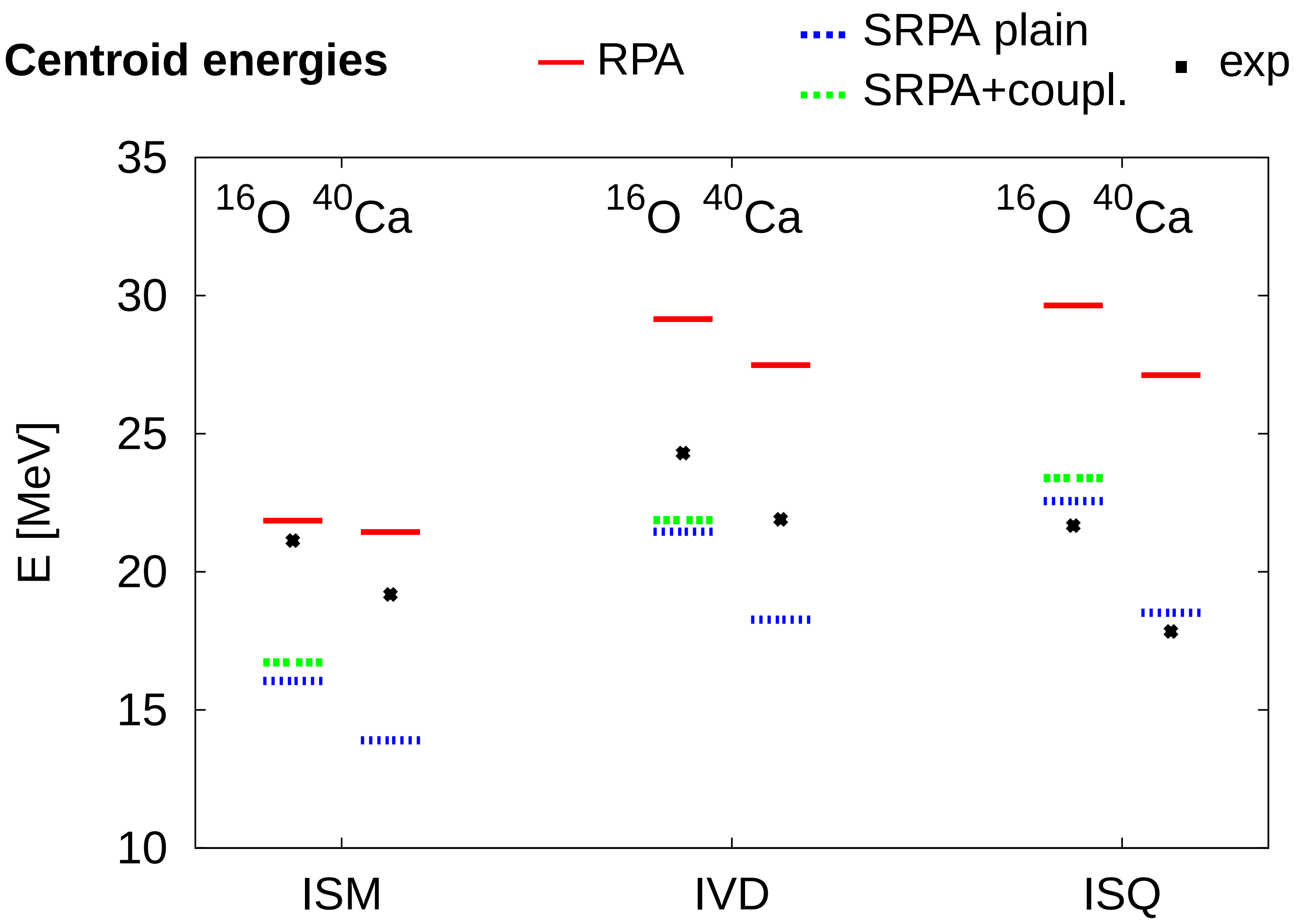
Second RPA

$N_{\mathrm{max}} = 10$



- Small effect of 2p2h-2p2h coupling

Second RPA



Centroid energies
RPA
SRPA plain
SRPA+coupl.
exp
35
30
25
20
15
10
E [MeV]
16O 40Ca
16O 40Ca
16O 40Ca
ISM
IVD
ISQ

Summary

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

- RPA: Properties of the V_{UCOM} as an effective interaction
  - Centroid energies overestimated (IVD, ISQ)
- Extended RPA: The role of RPA ground-state correlations
  - Weak effect on the properties of collective excitations
- SRPA: Sizable effect of coupling with 2p2h configurations
  - Discrepancies due to residual three body effects?

Thank you!

Work in collaboration with:

- R. Roth, H. Hergert, A. Zapp, P. Hedfeld

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  University of Zagreb, Croatia

Recent References

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