Continuum Random Phase Approximation Theory

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Aim:

How can we give predictions about ground and excited states of unstable nuclei?

Outline

1. The problem: how can we study unstable nuclei?
2. RPA or MF?
3. Self consistent RPA approach
4. Continuum in RPA (new technique with Sturmian function basis)
5. Results: chain of Oxygen
6. Results: chain of Calcium

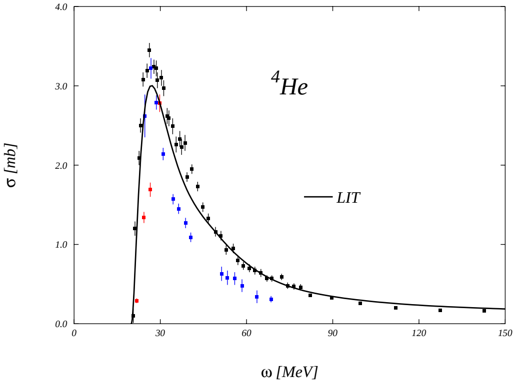
Facilities:

EUROPE
SPES, LNL - 2015
SPIRAL2, Caen -2015
FAIR,GSI $<$2020
ISOLDE, CERN - operating
HIE-ISOLDE,CERN $<$2020
EURISOL - 2020

JAPAN
RIBF, RIKEN - operating

AMERICA
HRIBF, Oak Ridge National Laboratory- operating
FRIB, Michigan State University $<$2020
RIBRAS, São Paulo Pelletron Laboratory- operating

Microscopic calculation: Helium



Data:
T. Shima et al., Phys. Rev. C 72 (2005) 044004
B. Nilsson et al., Phys. Lett. B 626 (2005) 65;Yu. M. Arkatov et al. Yad. Konst. 4 (1979) 55.

LIT: D. Gazit at al., Phys. Rev. Lett. 96 (2006) 112301; G. Orlandini, priv. comm.

Effective theory

$$H|\Psi> = E|\Psi> \qquad H^{\text{eff}}|\Psi^{\text{eff}}> = E|\Psi^{\text{eff}}>$$

$$H = H_0 + H_1 \qquad H_0 P|\Psi> = \omega P|\Psi> \qquad P^2 = P \qquad Q = I - P$$

$$\left[H_0 + P\left(H_1 + H_1 Q \frac{1}{E - H_0 - QH_1Q} QH_1\right) P\right] P|\Psi> = EP|\Psi>$$

$$\left[H_0 + V^{\text{eff}}(E)\right] P|\Psi> = EP|\Psi>$$

Effective hamiltonian depends on the choice of H_0
Effective hamiltonian depends on the energy E

Random Phase Approximation

$$|\nu>= Q_\nu^\dagger|0> \qquad Q_\nu|0>=0$$

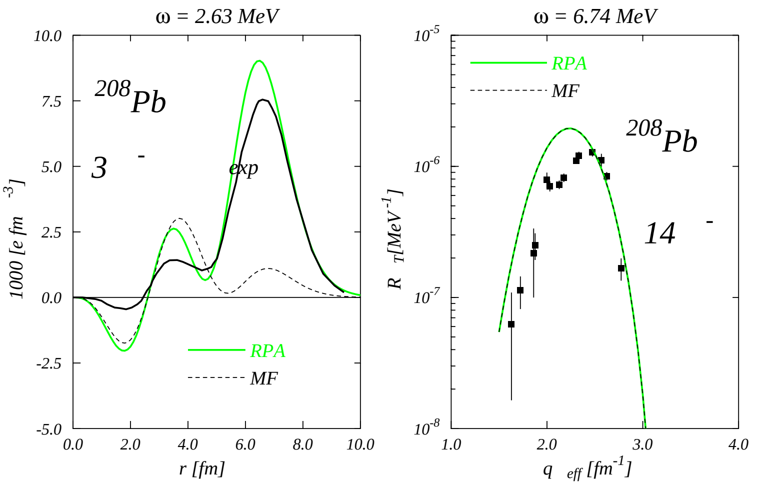
$$Q_\nu^\dagger = \sum_{ph} X_{ph} a_p^\dagger a_h - \sum_{ph} Y_{ph} a_h^\dagger a_p$$

$$\begin{aligned}
(\epsilon_p - \epsilon_h - \omega) X_{ph} + \sum_{p'h'} [v_{ph,p'h'} X_{p'h'} + u_{ph,p'h'} Y_{p'h'}] &= 0 \\
(\epsilon_p - \epsilon_h + \omega) Y_{ph} + \sum_{p'h'} [u^*_{ph,p'h'} X_{p'h'} + v^*_{ph,p'h'} Y_{p'h'}] &= 0
\end{aligned}$$

$$\begin{aligned}
v_{ph,p'h'} &= < ph'|V|hp' > - < ph'|V|p'h > \\
u_{ph,p'h'} &= < pp'|V|hh' > - < pp'|V|h'h >
\end{aligned}$$

$$< \nu|T|0 >= \sum_{ph} [X_{ph} < p|T|h > - Y_{ph} < h|T|p >]$$

MF and RPA



ω = 2.63 MeV
^{208}Pb
3$^-$
exp
RPA
MF
1000 [e fm^{-3}]
r [fm]
ω = 6.74 MeV
RPA
MF
^{208}Pb
14$^-$
R_T[MeV^{-1}]
q_{eff} [fm^{-1}]

RPA calculations

Input

Single particle wavefunctions
Single particle energies
Effective nucleon-nucleon interaction

Phenomenological RPA calculations

Input

Single particle wavefunctions from Woods-Saxon potentials
Experimental single particle energies (when available)
Effective nucleon-nucleon interaction chosen to reproduce some empirical quantity.

The input changes for each nucleus.

Self-consistent RPA calculations

Input

Single particle bases taken from Hartree Fock (HF) calculations
The same interaction is used in HF and RPA

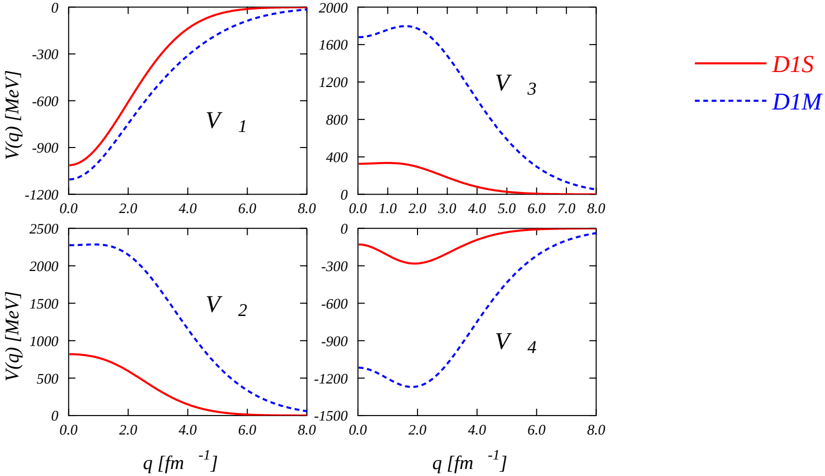
A unique interaction for all the nuclei

Our choice

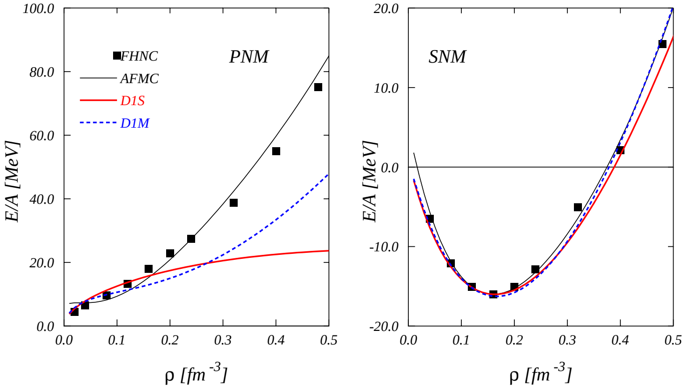
- Gogny-like interaction
- finite range
- zero-range Spin-Orbit term
- zero-range Density dependent term
- 14 parameters chosen with a fit of about 2000 nuclear binding energies and 700 charge radii.

Two parametrizations

-D1S: J. F. Berger et al., Comp. Phys. Comm. 63 (1991) 365
-D1M: S. Goriely et al,: Phys. Rev. Lett. 102 (2009) 252501

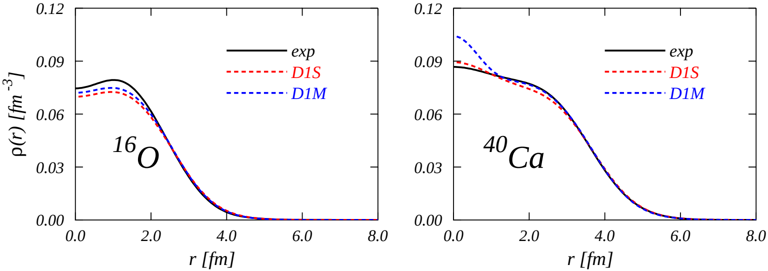

V 1
V 3
V 2
V 4
V(q) [MeV]
q [fm -1]
D1S
D1M
0
-300
-600
-900
-1200
2000
1600
1200
800
400
2500
1500
1000
500
-1500
0.0
2.0
4.0
6.0
8.0
1.0
3.0
5.0
7.0

Equations of state



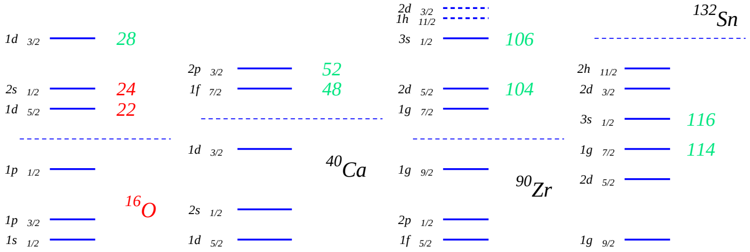
FHNC: A. Akmal et al., Phys Rev C 58 (1998) 1804

AFMC: S. Gandolfi et al., Mon. Not. Roy. Astron. Soc. 404 (2010) L35

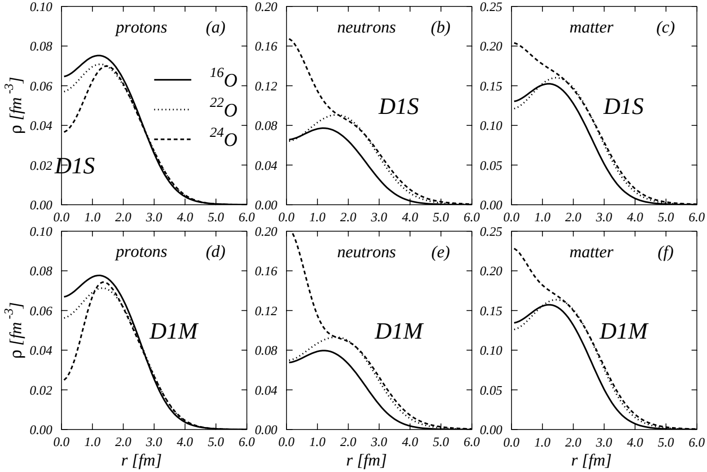


Data: C.W.D.Jager et al., Nucl. Data Tables 36 (1987) 495.

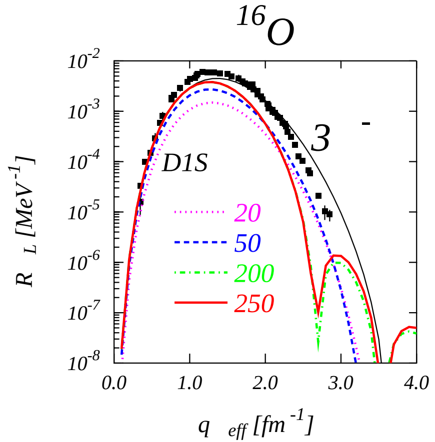
Isotope Chains



Distributions of Oxygen



Sensitivity to configuration space in the continuum



$\epsilon_{ph}^{\max}$ [MeV]	ω [MeV]
20.0	9.11
50.0	8.55
200.0	7.87
250.0	7.85
exp	6.13

Data: R. Buti et al., Phys. Rev. C 33 (1986) 755

Continuum in RPA

(A pedagogical and simplified presentation)

$$(\epsilon_p - \epsilon_h - \omega) X_{ph}(\epsilon_p) + \sum_{p'h'} \int d\epsilon_{p'} \, v_{ph,p'h'}(\epsilon_p, \epsilon_{p'}) X_{ph}(\epsilon'_p) = 0$$

Definition of a new unknown

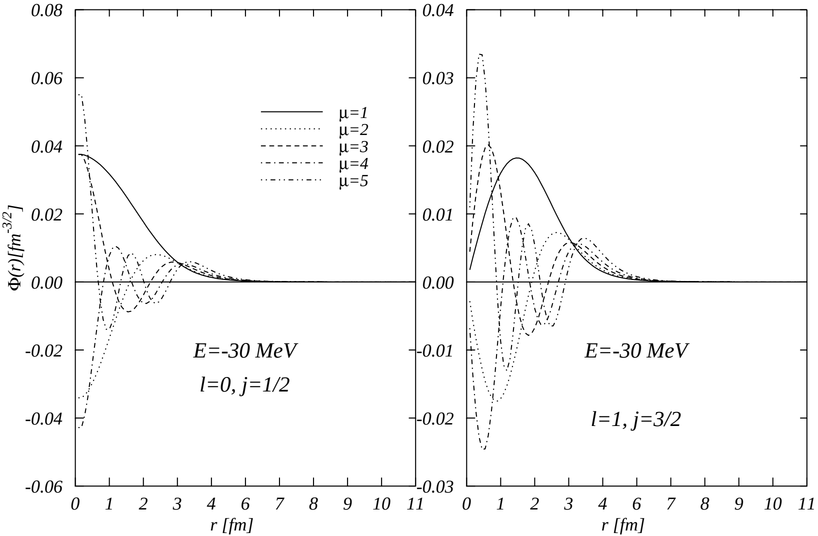
$$f_{ph}(r) = \int d\epsilon_p X_{ph}(\epsilon_p) R_p(r, \epsilon_p)$$

A new equation to be solved

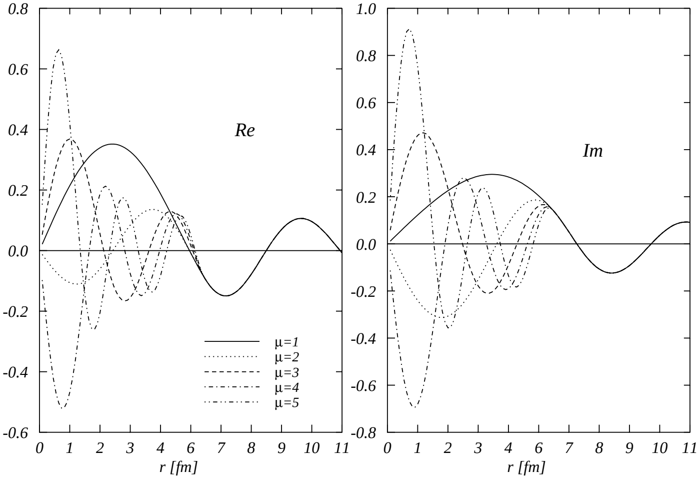
$$0 = -\frac{\hbar^2}{2m}\nabla^2 f_{ph}(r) + U(r) f_{ph}(r) - \int dr' \, r'^2 \, W(r, r') f_{ph}(r') - (\epsilon_h + \omega) f_{ph}(r)$$
$$- \sum_{p'h'} \int dr' \, r'^2 \left[R^*_{h'}(r') v^{\mathrm{dir}}(r, r') R^*_h(r) f_{p'h'}(r') - R^*_{h'}(r') v^{\mathrm{exc}}(r, r') R^*_h(r') f_{p'h'}(r) \right]$$

Expansion of $f_{ph}(r)$ on a Sturm-Bessel functions basis

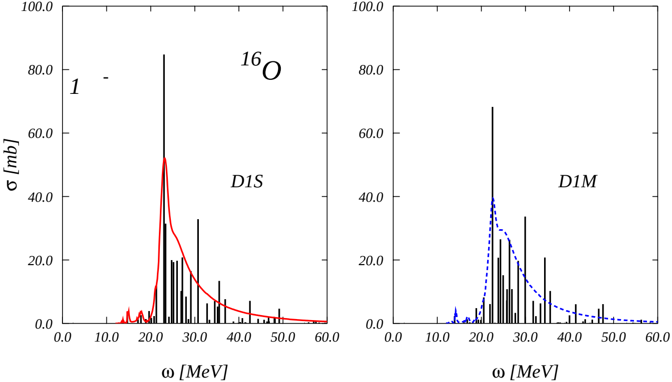
Sturmian functions



Sturmian functions



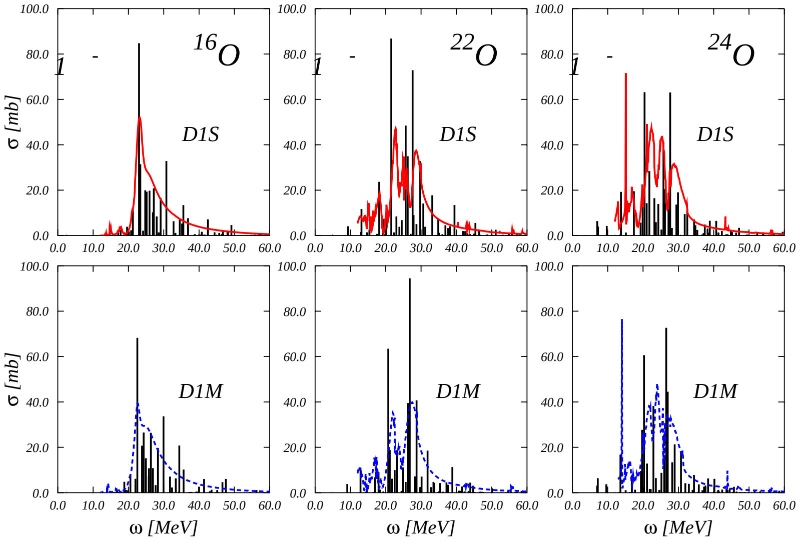
ϵ=30 MeV, $l = 1$, $j = 3/2$, ^{16}O



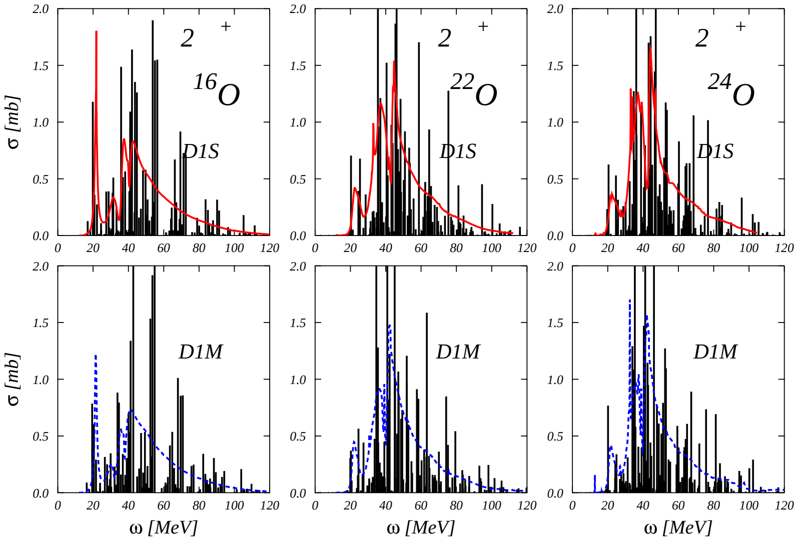
Centroid energies in MeV

$\epsilon_{ph}^{\max}$	20	50	200	250	cont.
D1S	24.06	27.80	28.27	28.25	28.58
D1M	24.74	27.82	28.25	28.23	28.57

Continuum versus Discrete RPA: 1^- Oxygen chain



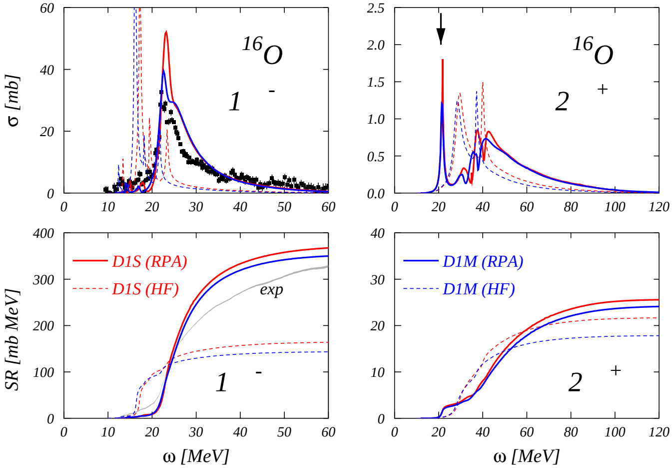
Continuum versus Discrete RPA: 2^+ Oxygen chain



Centroid energies in MeV

	D1S(dis)	D1S(con)	D1M(dis)	D1M(con)
1^-				
^{16}O	28.27	28.58	28.24	28.56
^{22}O	27.34	27.43	27.09	27.50
^{24}O	26.08	26.18	25.99	26.31
2^+				
^{16}O	67.99	45.45	69.04	45.76
^{22}O	68.77	44.87	67.50	45.00
^{24}O	67.54	44.21	60.07	43.74

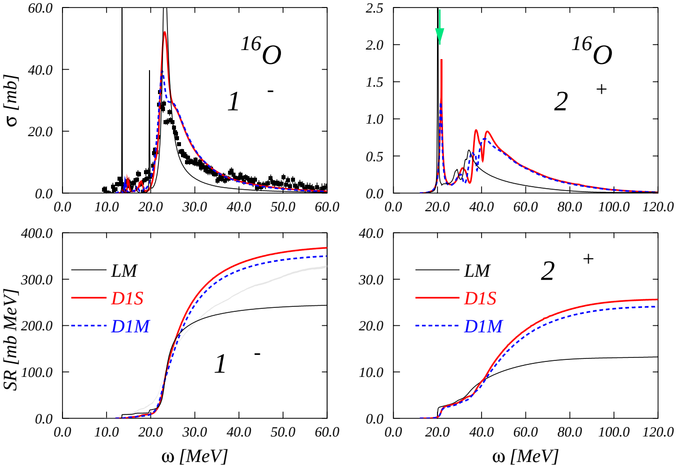
RPA versus MF



1^- data: J. Ahrens et al., Nucl. Phys. A 251 (1975) 479.

2^+ data: K. T. Knöpfke et al., Phys. Rev. Lett. 35 (1975) 779

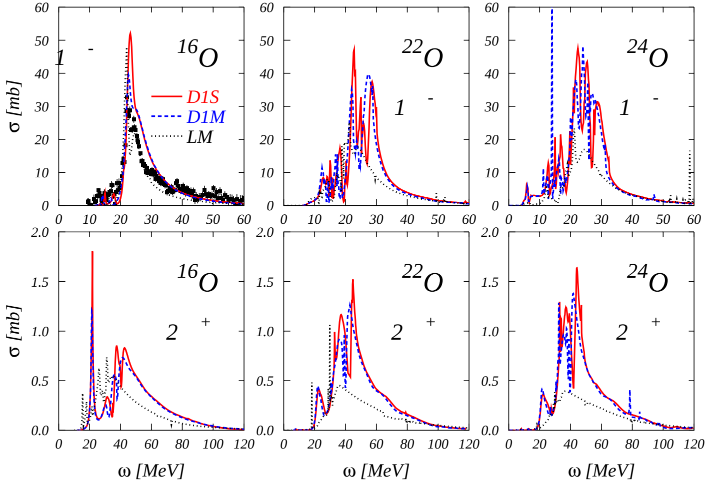
Self consistent versus Phenomenological approach



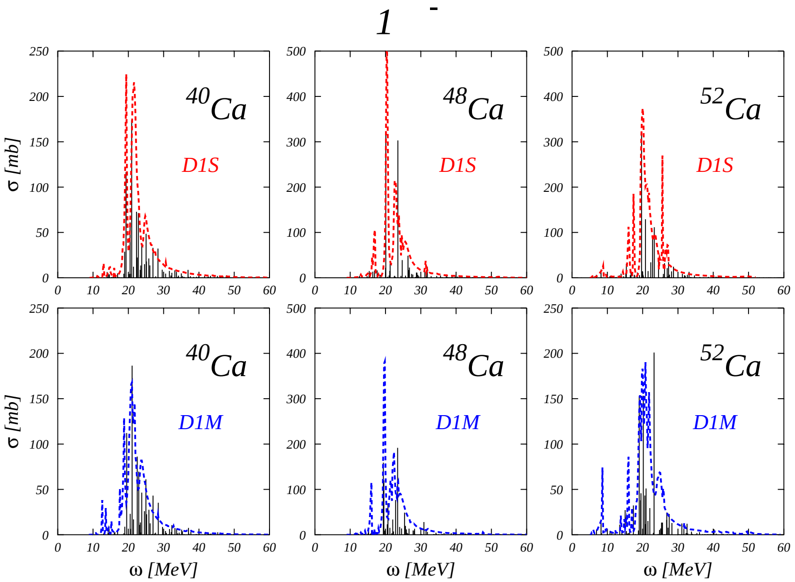
1^- data: J. Ahrens et al., Nucl. Phys. A 251 (1975) 479.

2^+ data: K. T. Knöpfke et al., Phys. Rev. Lett. 35 (1975) 779

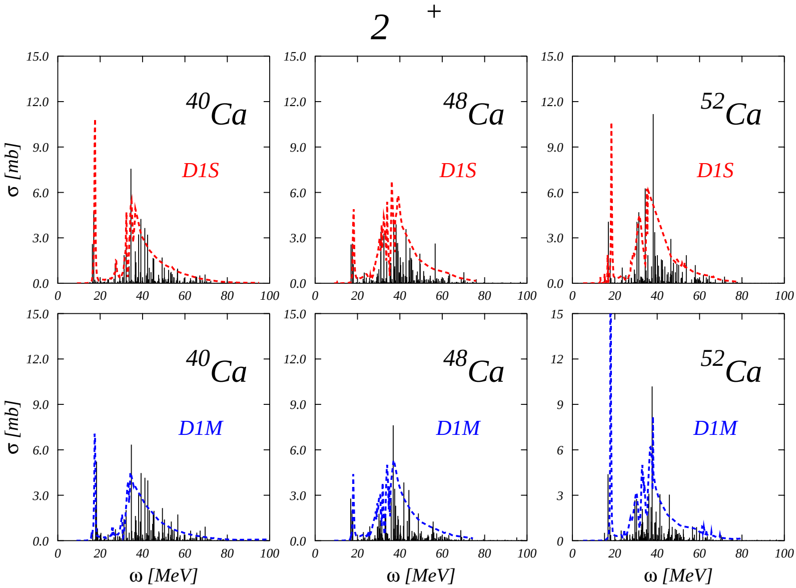
Self consistent versus Phenomenological approach: Oxygen chain

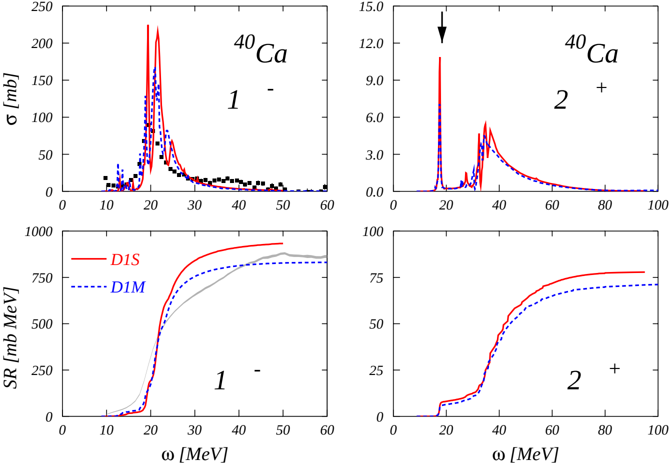


Continuum versus Discretuum: 1^- Calcium chain



Continuum versus Discretuum: 2^+ Calcium chain

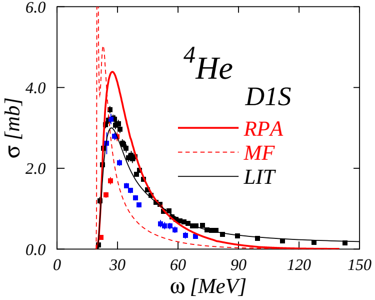




1^- data: J. Ahrens et al., Nucl. Phys. A 251 (1975) 479.

2^+ data: empirical expression 63.0 $A^{-1/3}$

Self-consistent Continuum RPA versus Microscopic Calculations



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Yu. M. Arkatov et al. Yad. Konst. 4 (1979) 55.
LIT:
D. Gazit at al., Phys. Rev. Lett. 96 (2006) 112301

G. Orlandini, priv. comm.

Conclusions

1. Our continuum RPA technique allows us to do calculations with interactions with finite range and tensor channel.
2. The D1S and D1M forces produce very similar results.
3. Comparison with MF calculations: MF does not predict the presence of giant resonances.
4. Comparison with discrete RPA: need of a correct treatment of the continuum in self-consistent calculations.
5. Comparison with phenomenological CRPA: inadequacy of the phenomenological approach in the study of nuclei lying in experimentally unexplored parts of the nuclear isotope chart.

Conclusions

1. Self-consistent CRPA calculations describe rather well the experimental positions of the giant resonances peaks, both for the 1^- and 2^+ excitations.
2. On the other hand, the strengths distibutions are incorrect, and the problem could be solved by considering the excitation of two particles-two holes pairs. This is confirmed by the results obtained in ^{4}He. In this case, the description of the ground state is much worse than that of heavier nuclei. However, the description of the total photoabsorption cross section is much better because in this system the contribution of more complex excitation modes is very small.