Problemi di struttura del nucleo atomico

Giampaolo Co'

INFN - Lecce

Lecce 20 Giugno 2008

Iniziativa specifica PI31

Titolo

Microscopic theories of strongly interacting many-body systems

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Sedi

Firenze, Genova, Lecce, Pisa, Roma 1, Trento, Torino, Trieste

15 Strutturati, 10 Dottorandi-Assegnisti

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A Lecce

Giampaolo Co', Viviana De Donno, Chiara Maieron
In collaborazione con
Marta Anguiano, Fernando Arias de Saavedra, Antonio M. Lallena, Miguel Moreno-Torres (Granada)

Ipotesi di lavoro

- Nucleoni come gradi di libertà fondamentali.
- Sistema a molticorpi non relativistico.

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- Nucleoni come gradi di libertà fondamentali.
- Sistema a molticorpi non relativistico.

Il sistema nucleare è descritto dall'equazione di Schrödinger, e l'interazione nucleone-nucleone da un potenziale.

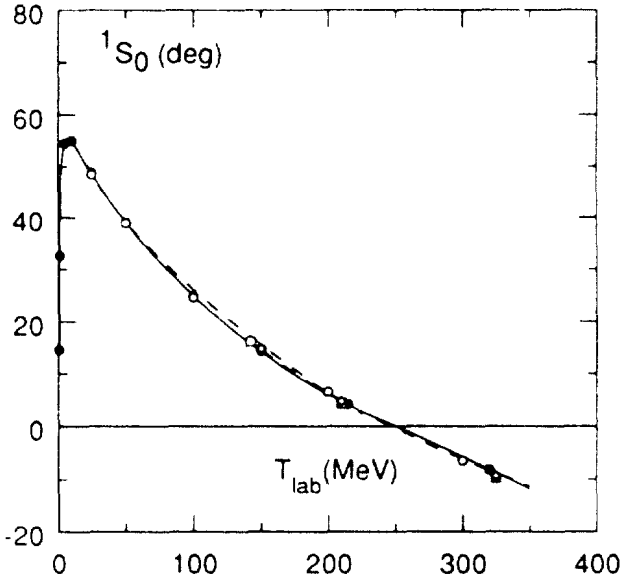
L'interazione

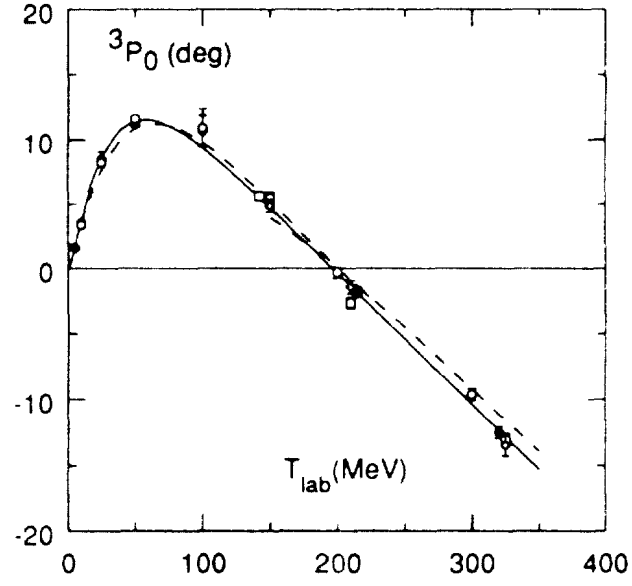
$$V(i,j) = \sum_{p=1,18} v_p(r_{ij}) O_{ij}^p$$

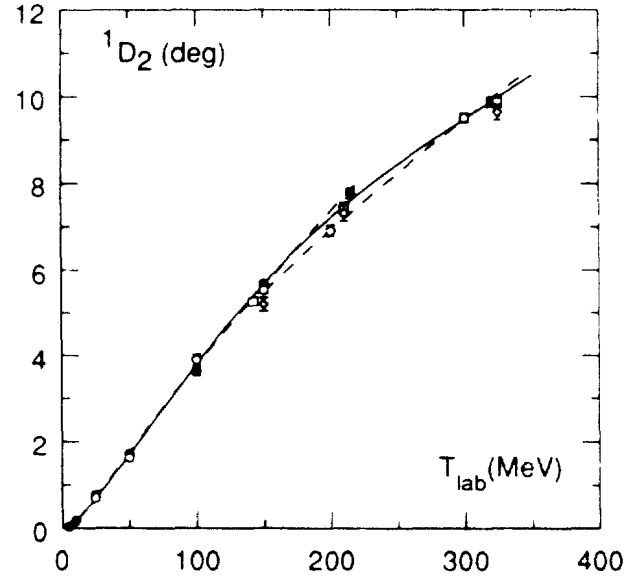
$$\begin{aligned} O_{ij}^{p=1,14} &= [1, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j, S_{ij}, (\mathbf{L}\cdot\mathbf{S}), \mathbf{L}^2, \mathbf{L}^2(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j), (\mathbf{L}\cdot\mathbf{S})^2] \\ &\otimes [1, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j] \end{aligned}$$

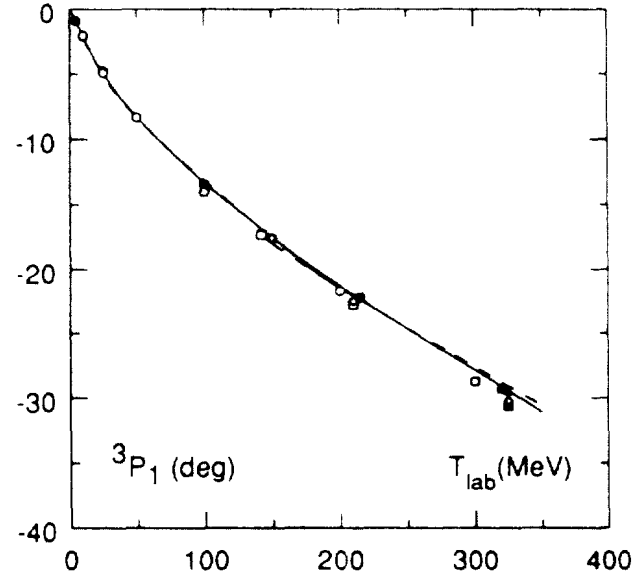
$$O_{ij}^{p=15,18} = [1, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j, S_{ij},] \otimes [T_{ij}, \tau_{zi} + \tau_{zj}]$$

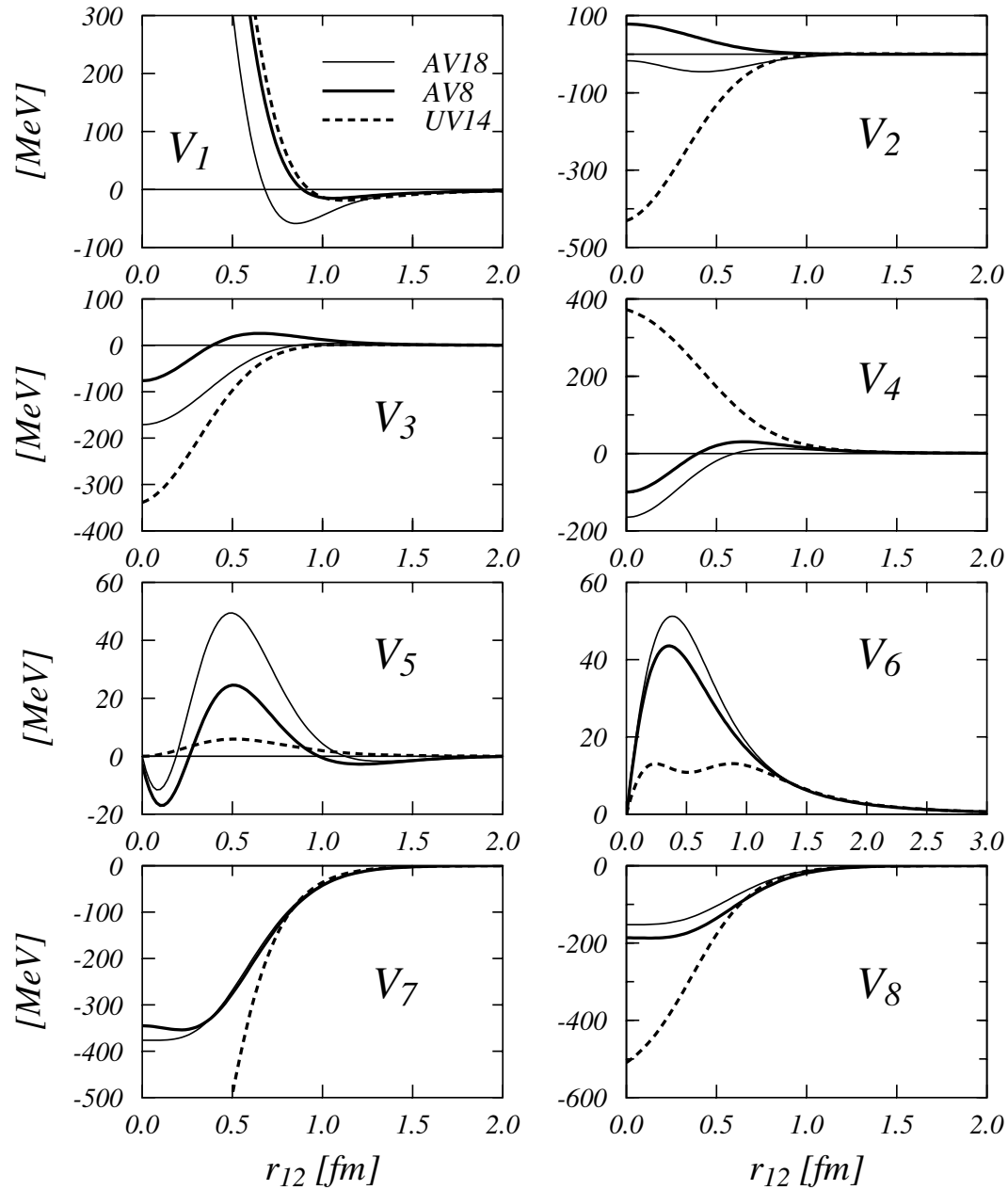
$$S_{ij} = 3\frac{(\boldsymbol{\sigma}_i \cdot \mathbf{r})(\boldsymbol{\sigma}_j \cdot \mathbf{r})}{r^2} - \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$


$^1S_0$ (deg)
T_{lab}(MeV)
80
60
40
20
0
-20
0
100
200
300
400


$^3P_0$ (deg)
T_{lab}(MeV)
20
10
0
-10
-20
0
100
200
300
400


$^1D_2$ (deg)
T_{lab}(MeV)
12
10
8
6
4
2
0
0
100
200
300
400


$^3P_1$ (deg)
T_{lab}(MeV)
0
-10
-20
-30
-40
0
100
200
300
400

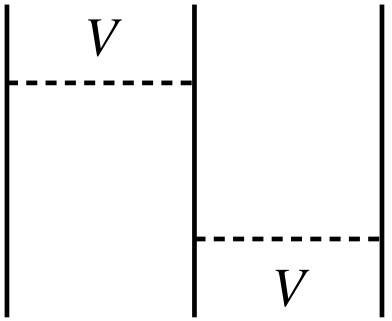

AV18
AV8
UV14
V1
V2
V3
V4
V5
V6
V7
V8
[MeV]
r12 [fm]

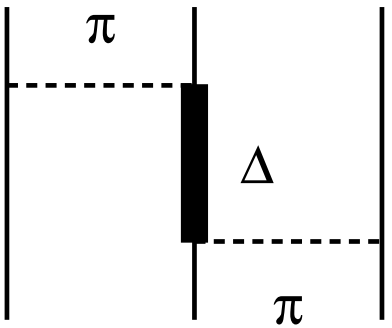
^{3}H Binding energy

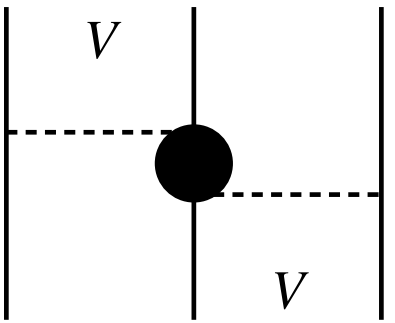
Exp 8.48 MeV

2 N potential	2N
CD Bonn	7.953
Nijm II	7.709
Nijm I	7.731
Nijm 93	7.664
Reid 93	7.648
AV14	7.683
AV18	7.576

Forza a 3 corpi







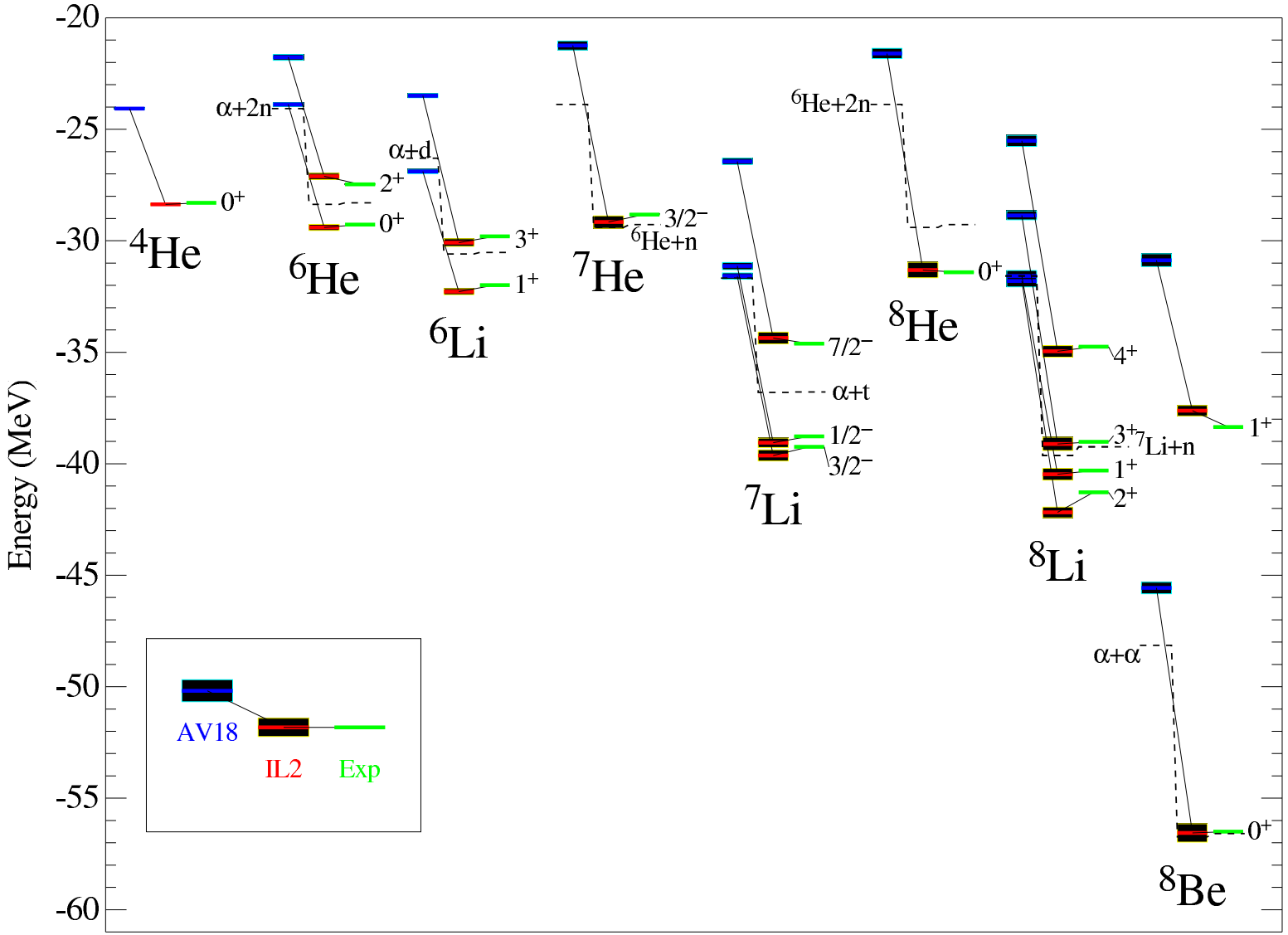
^{3}H Binding energy

Exp 8.48 MeV

2 N potential	2N	2N + 3N
CD Bonn	7.953	8.483
Nijm II	7.709	8.477
Nijm I	7.731	8.480
Nijm 93	7.664	8.480
Reid 93	7.648	8.480
AV14	7.683	8.480
AV18	7.576	8.479

Monte Carlo

S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci. 51 (2001) 53.



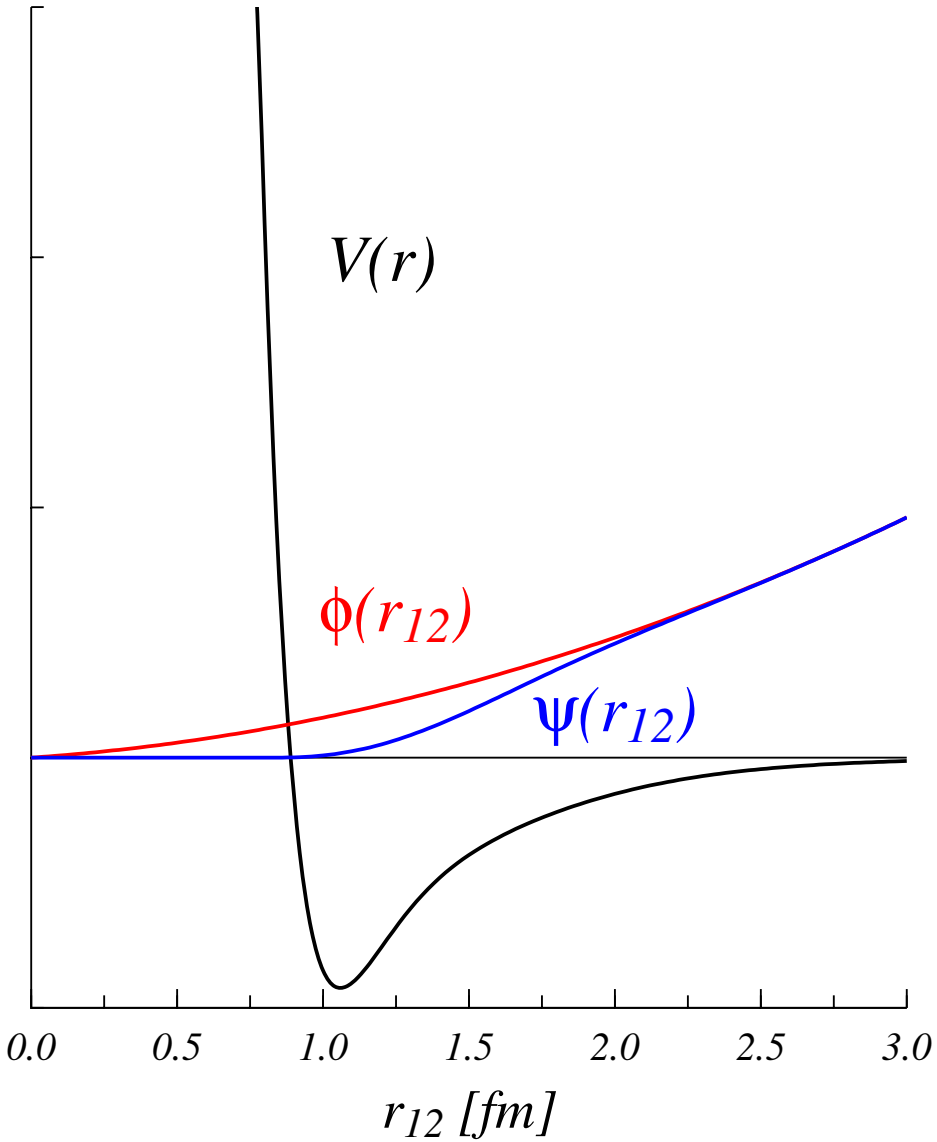
Teoria perturbativa

$$H = H_0 + H_1$$

$$H_0|\Phi_0\rangle = E_0|\Phi_0\rangle$$

$$H_0|\Phi_0\rangle = \sum_i h_i \prod_{k=1,A} |\phi_k\rangle = \sum_i \epsilon_i \prod_{k=1,A} |\phi_k\rangle$$

$$\begin{aligned} E &= \langle\Phi_0|H_0|\Phi_0\rangle + \langle\Phi_0|H_1 \sum_{n=0}^{\infty} \left(\frac{1}{E_0 - H_0} H_1\right)^n |\Phi_0\rangle_c \\ &= E_0 + \langle\Phi_0|H_1|\Phi_0\rangle + \langle\Phi_0|H_1 \frac{1}{E_0 - H_0} H_1|\Phi_0\rangle_c + \cdots \end{aligned}$$


V(r)
ϕ(r12)
ψ(r12)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
r12 [fm]

CBF - Teoria della Funzione della Base Correlata

Principio Variazionale

$$\Psi(1,2,...,A) = F(1,2,...,A)\Phi(1,2,....,A)$$

$$F = \prod_{i<j} f(r_{ij})$$

$$\delta E[\Psi] = \delta\left[\frac{<\Psi|H|\Psi>}{<\Psi|\Psi>}\right] = \delta\left[\frac{<\Phi|F^{\dagger}HF|\Phi>}{<\Psi|\Psi>}\right] = 0$$

Correlazioni scalari

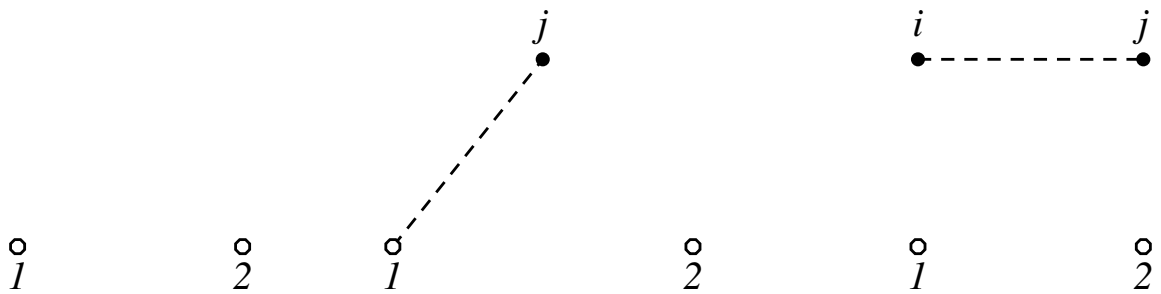
$$\frac{<\Phi|F^{\dagger}VF|\Phi>}{<\Phi|F^{2}|\Phi>} = \frac{<\Phi|VF^{2}|\Phi>}{<\Phi|F^{2}|\Phi>} = \int dx_1 dx_2 V(x_1,x_2) g(x_1,x_2)$$

$$g(x_1,x_2) = \frac{A(A-1)\int dx_3 \dots dx_A \Phi^*(x_1,\dots,x_A) F^* F\Phi(x_1,\dots,x_A)}{\rho^2 \int dx_1 dx_2 \dots dx_A \Phi^*(x_1,\dots,x_A) F^* F\Phi(x_1,\dots,x_A)}$$

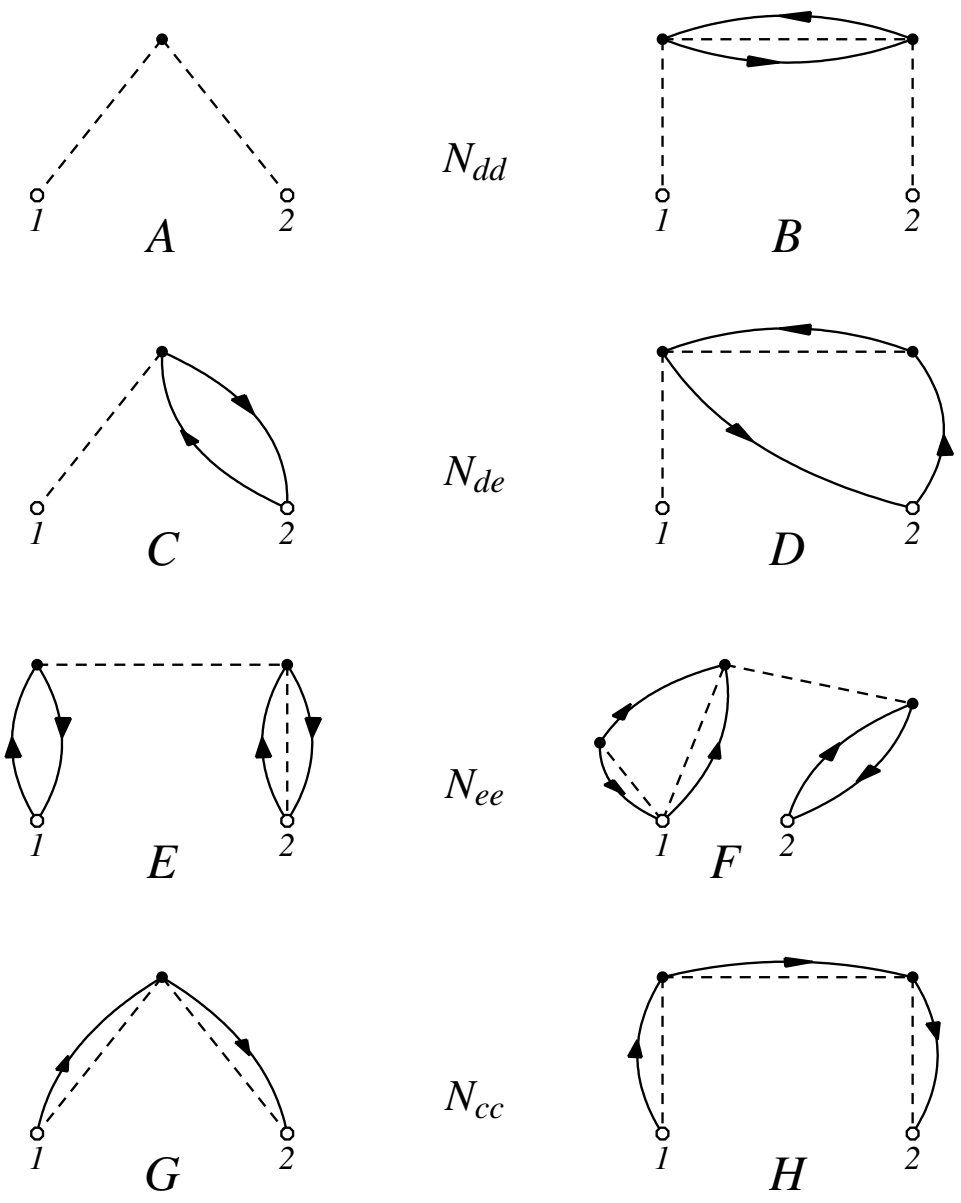
$$F^2 = \prod_{i<j} f^2(r_{ij})$$

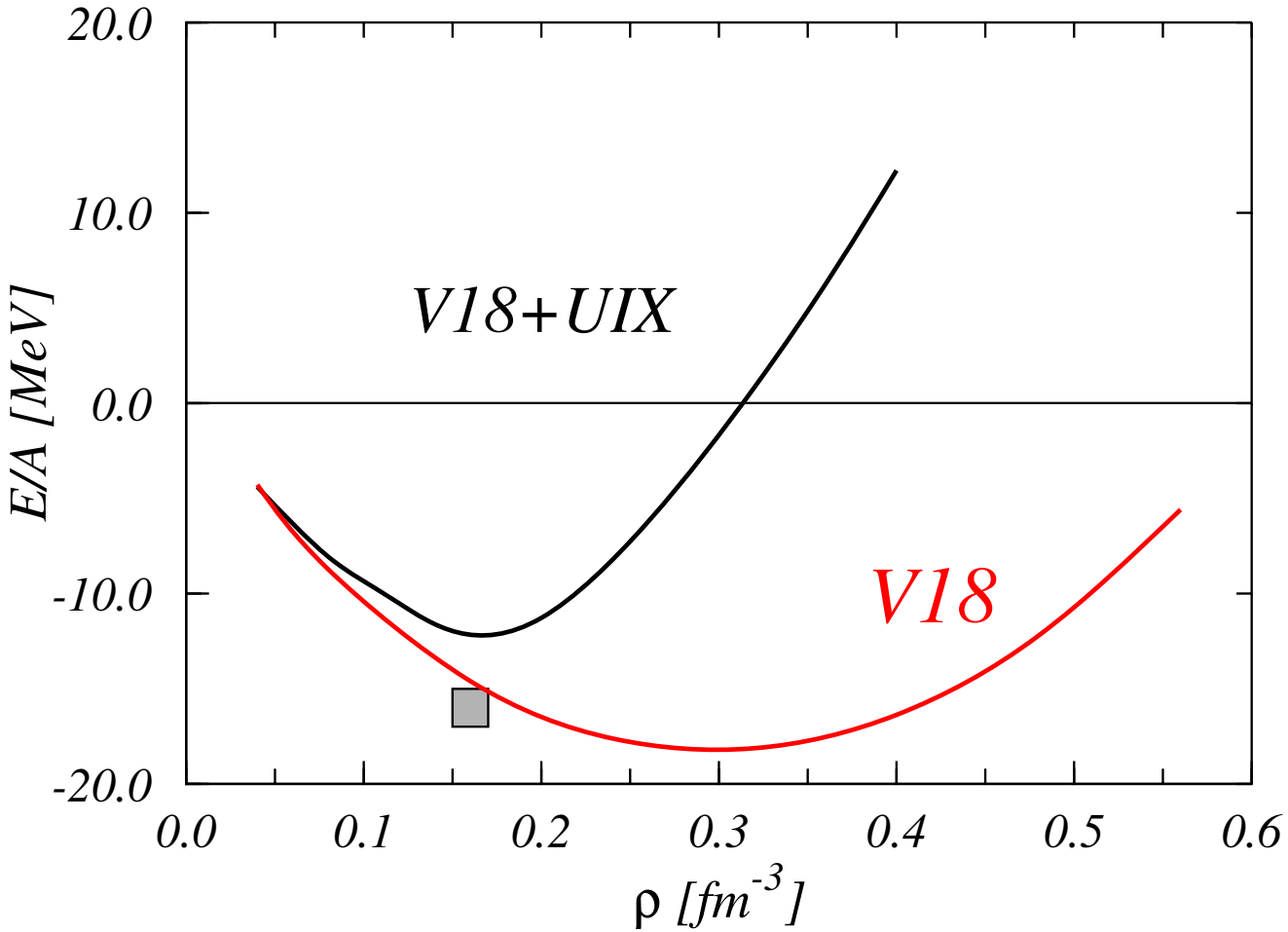
$$f^2(r_{ij}) = 1 + h(r_{ij})$$

$$\prod_{i<j} f^2(r_{ij}) = f^2(r_{12})[1 + h(r_{13})][1 + h(r_{14})]....[1 + h(r_{34})]....$$



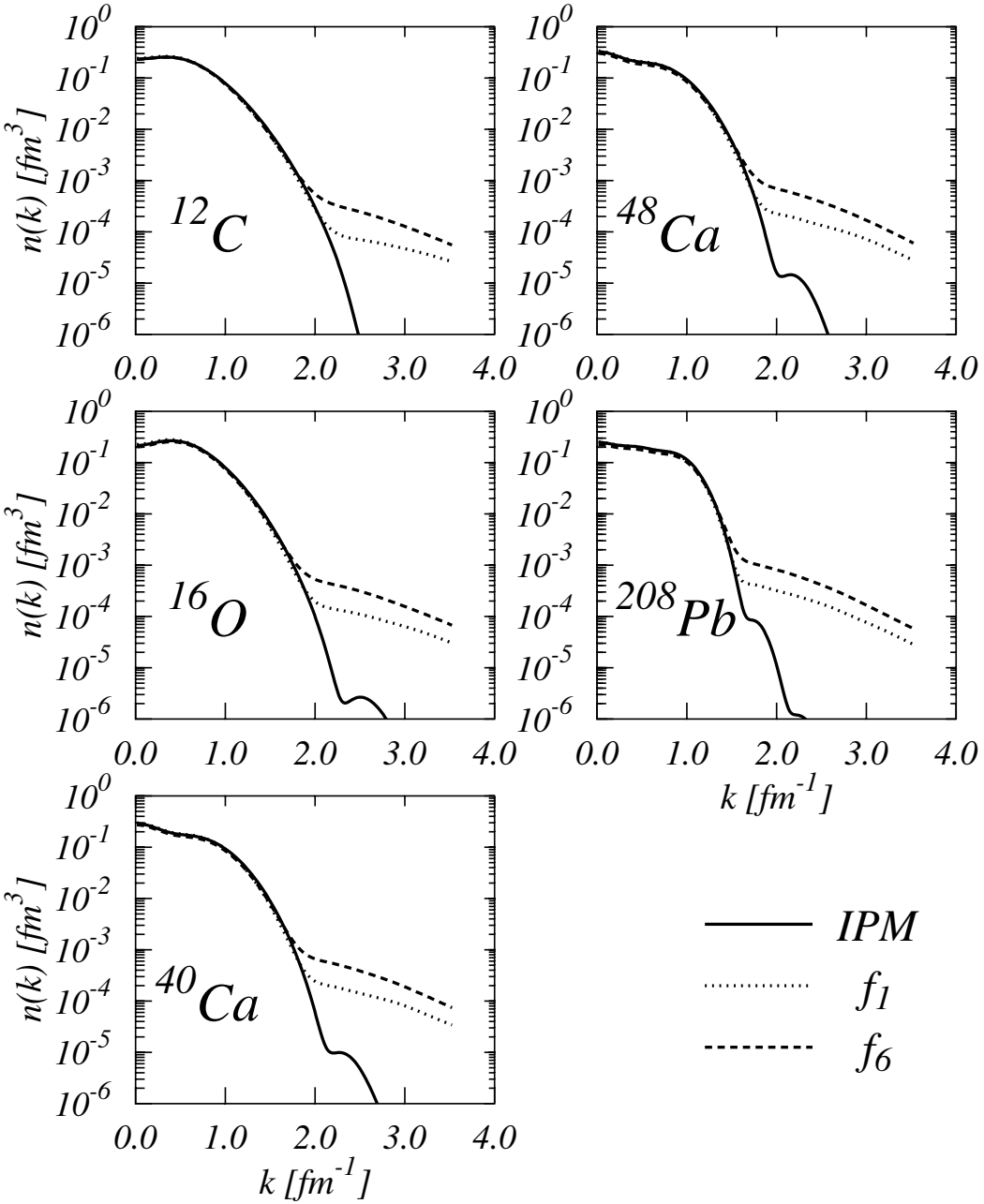
Fermi HyperNetted Chains

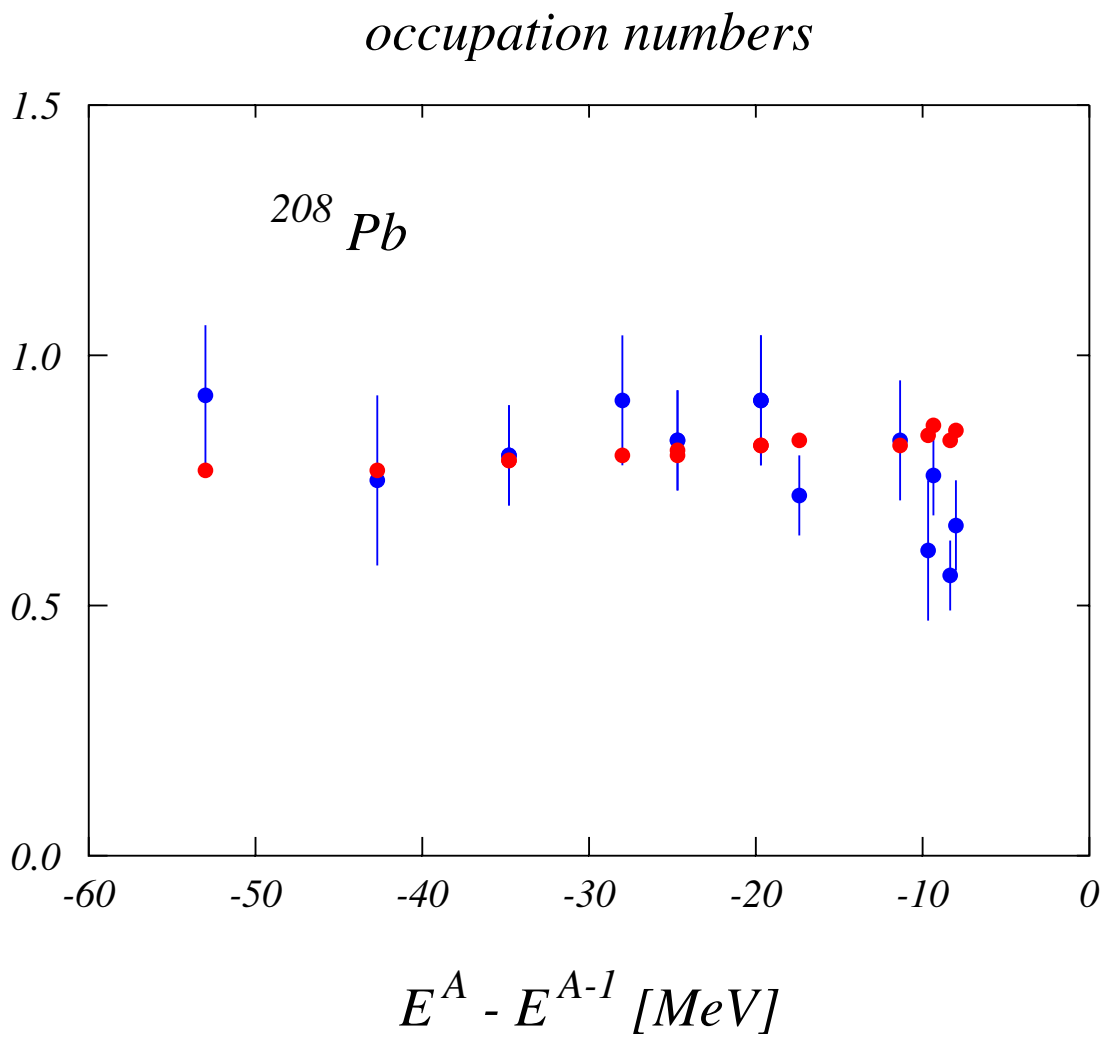



20.0
10.0
0.0
-10.0
-20.0
E/A [MeV]
V18+UIX
V18
0.0
0.1
0.2
0.3
0.4
0.5
0.6
ρ [fm^-3]

Risultati

		^{12}C	^{16}O	^{40}Ca	^{48}Ca	^{208}Pb
$v_8' + UIX$	T	27.13	32.33	41.06	39.64	39.56
	V^6_{2-body}	-29.13	-38.15	-48.97	-46.60	-48.43
	V_{LS}	-0.51	-0.70	-0.85	-0.79	-0.80
	V_{Coul}	0.67	0.86	1.96	1.57	3.97
	$T + V(2)$	-1.84	-5.66	-6.83	-6.24	-5.80
	V_{3-body}	0.66	0.86	1.76	1.61	1.91
	E	-1.17	-4.80	-5.05	-4.62	-3.78
$v_{14} + UVII$	T	24.63	29.25	37.70	36.47	36.48
	V^6_{2-body}	-27.08	-35.84	-47.16	-44.86	-46.87
	V_{LS}	-0.06	-0.10	-0.10	-0.09	-0.08
	V_{Coul}	0.68	0.88	2.02	1.59	4.03
	$T + V(2)$	-1.83	-5.81	-7.54	-6.89	-6.44
	V_{3-body}	0.54	0.69	1.28	1.15	1.41
	E	-1.29	-5.12	-6.26	-5.74	-5.03
	E_{exp}	-7.68	-7.97	-8.55	-8.66	-7.86


^{12}C
^{48}Ca
^{16}O
^{208}Pb
^{40}Ca
$n(k)$ [fm^3]
k [fm^{-1}]
IPM
f_1
f_6

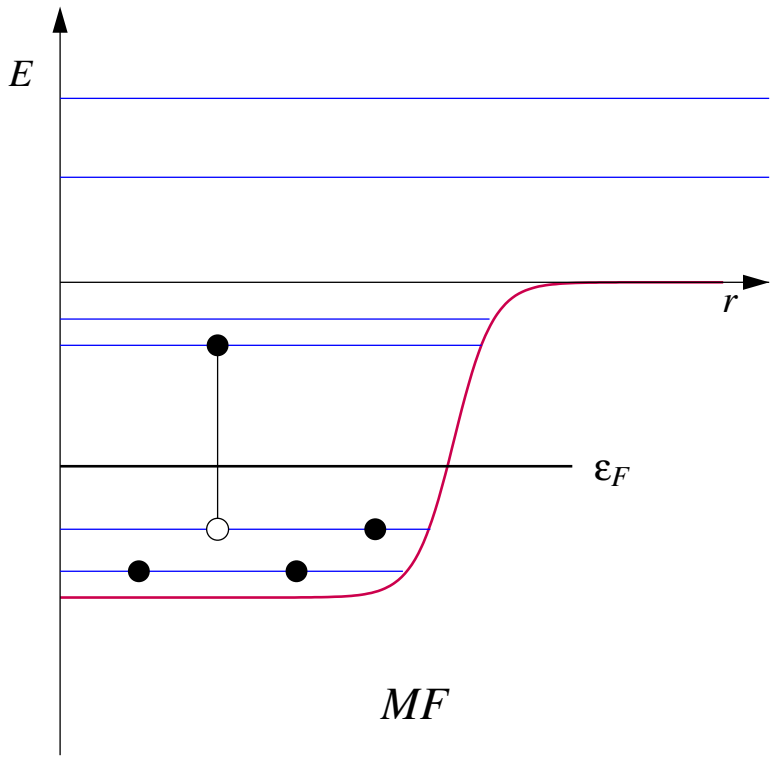


Data: M. F. van Batenburg, Ph.D. Thesis Utrecht (Nederlands) (2001)

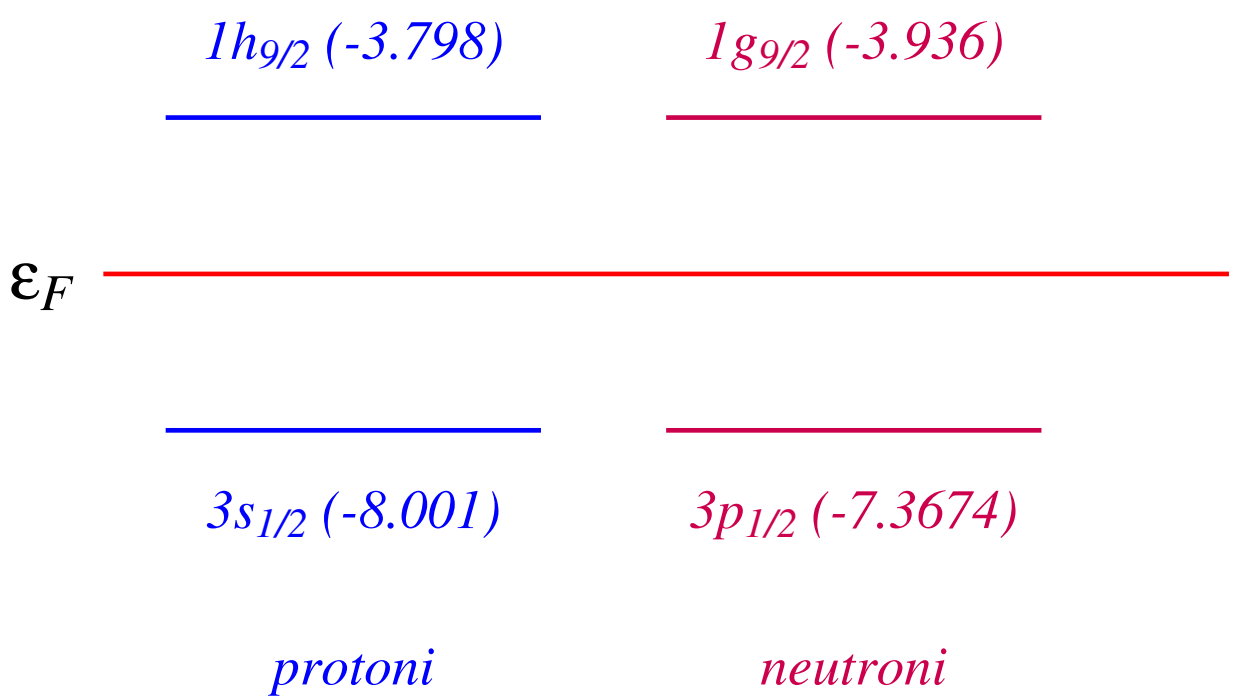
Stati eccitati

$$\Psi_n(1,2,...,A) = F(1,2,...,A)\Phi_n(1,2,....,A)$$

$$E_n = \frac{<\Phi_n|F^\dagger HF|\Phi_n>}{<\Phi_n|F^2|\Phi_n>} =<\Phi_n|H^{eff}|\Phi_n>$$

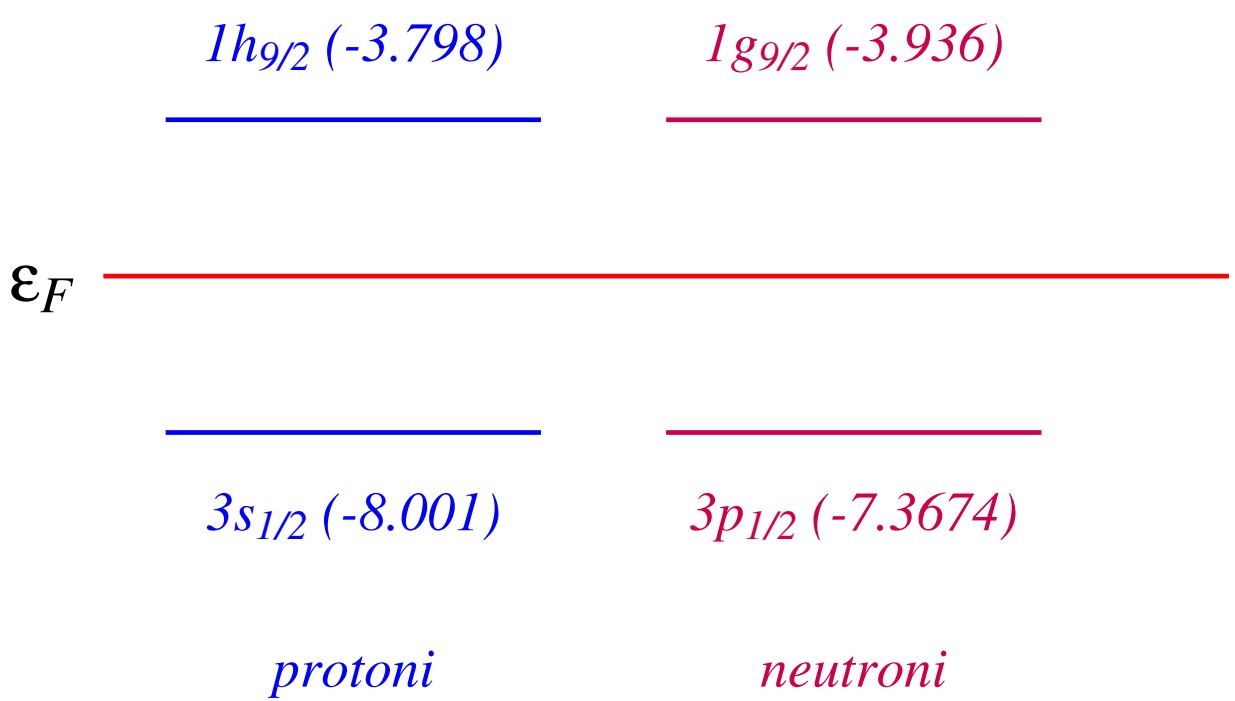

E
r
ε_F
MF

Stati di singola particella del ^{208}Pb



Energie di eccitazione 4.20 e 3.43 MeV
Multipoli compatibili 4^-, 5^-

Stati di singola particella del ^{208}Pb



Energie di eccitazione 4.20 e 3.43 MeV
Multipoli compatibili 4^-, 5^-

Il primo stato eccitato del ^{208}Pb è un 3^- a 2.63 MeV.

Random Phase Approximation

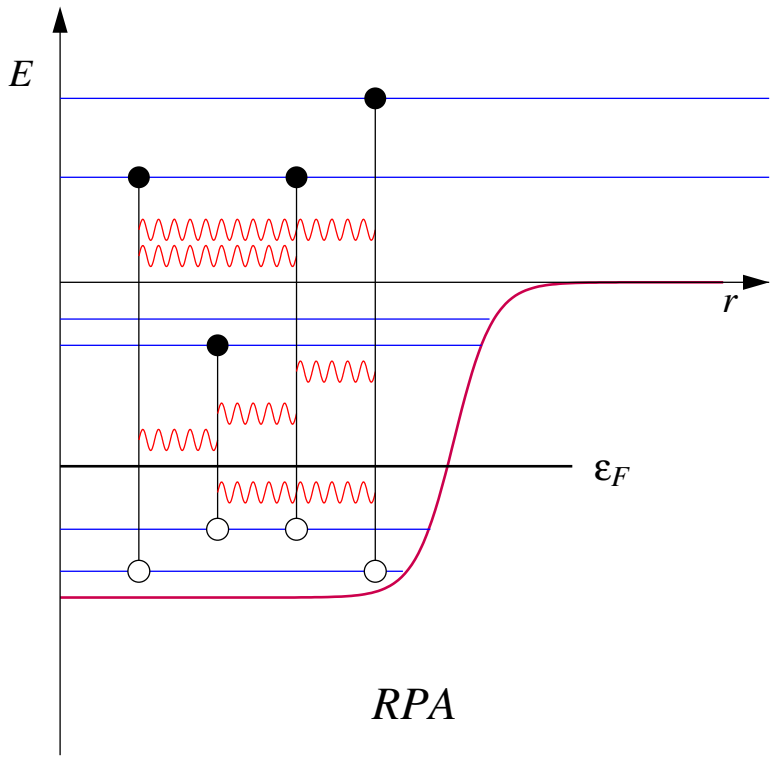
$$|\nu>= Q^{\dagger}_{\nu}|0> \qquad Q_{\nu}|0>= 0$$

$$Q^{\dagger}_{\nu} = \sum_{ph} X_{ph} a^{\dagger}_{p} a_{h} - \sum_{ph} Y_{ph} a^{\dagger}_{h} a_{p}$$

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

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

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


E
r
ε_F
RPA

Calcoli RPA

Input richiesto

Energie e funzioni d'onda di singola particella.
Interazione tra nucleoni.

Calcoli RPA

Input richiesto

Energie e funzioni d'onda di singola particella.
Interazione tra nucleoni.

- Interazione a range finito.
- Inclusione dei canali tensoriali.
- Approccio fenomenologico.
  Teoria di Landau dei liquidi fermionici.

Calcoli RPA

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Calcoli RPA

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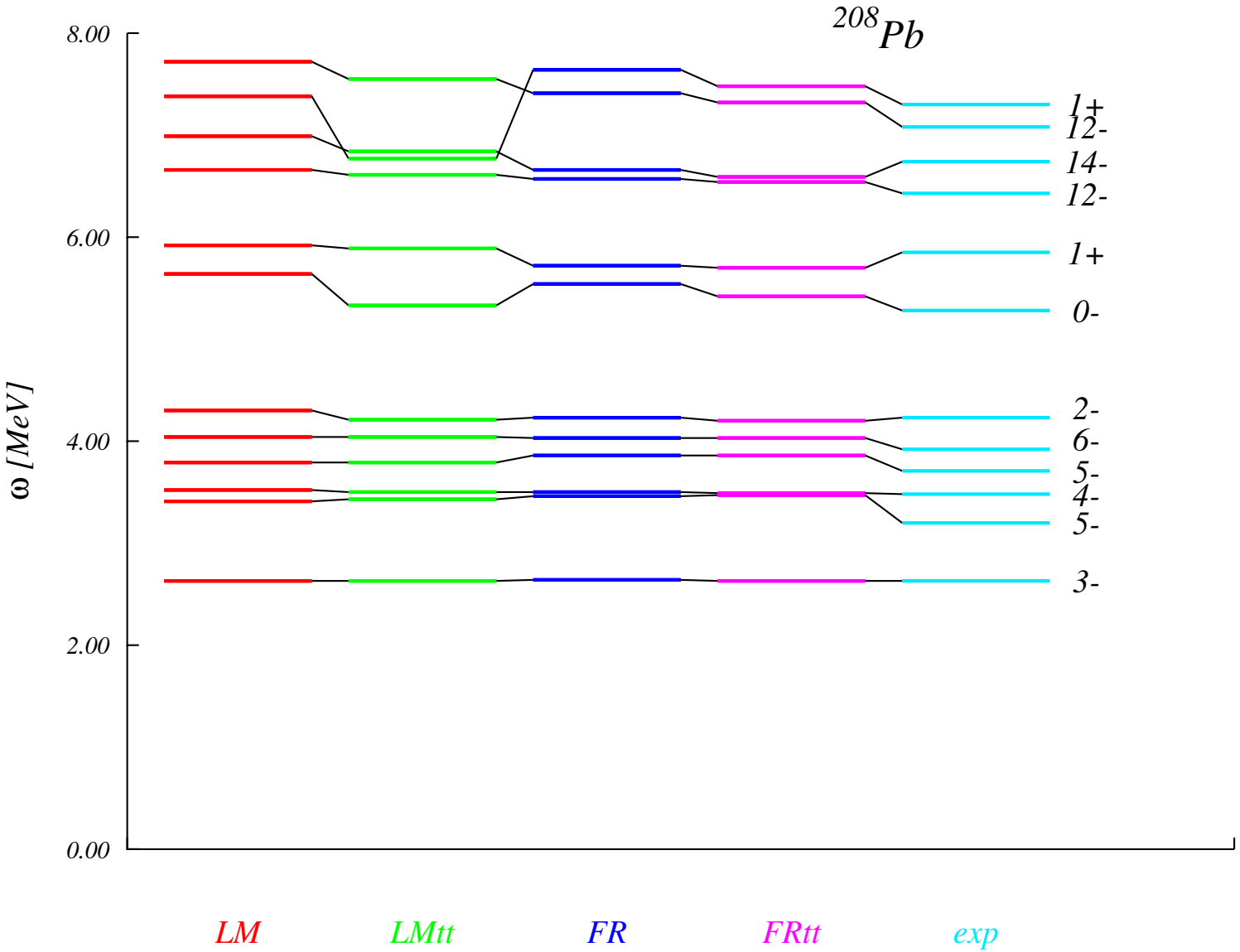
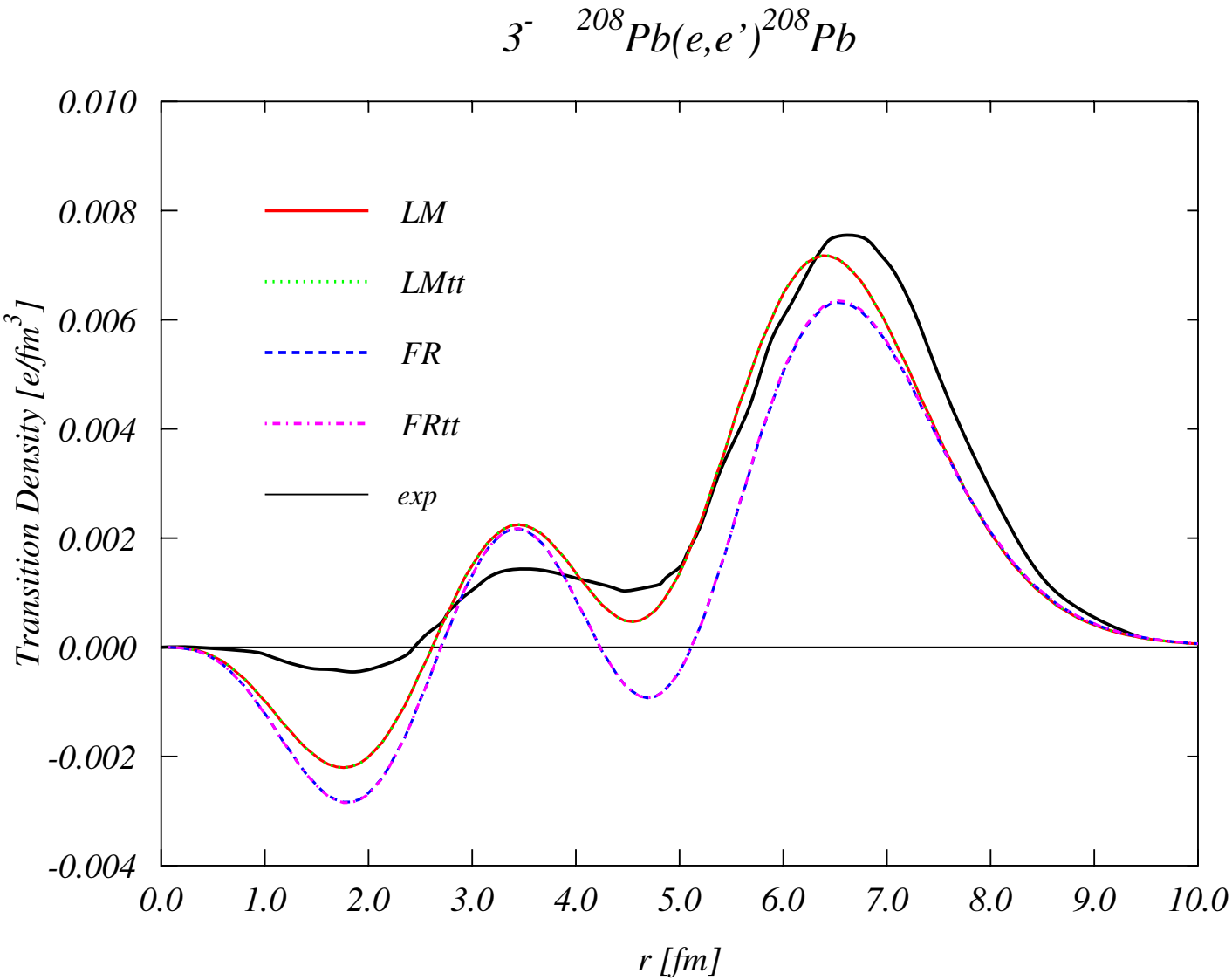
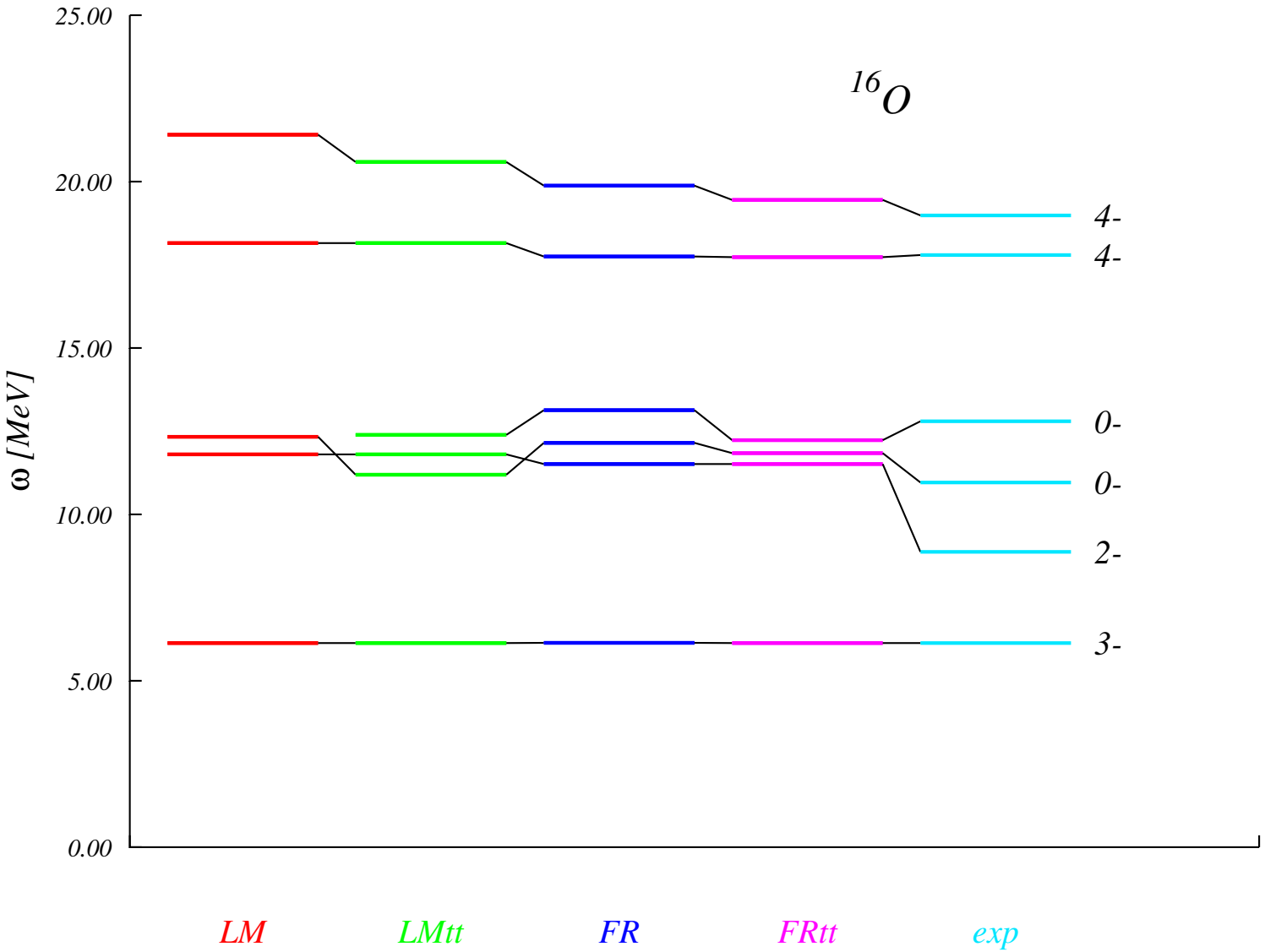
Spettro del ^{208}Pb

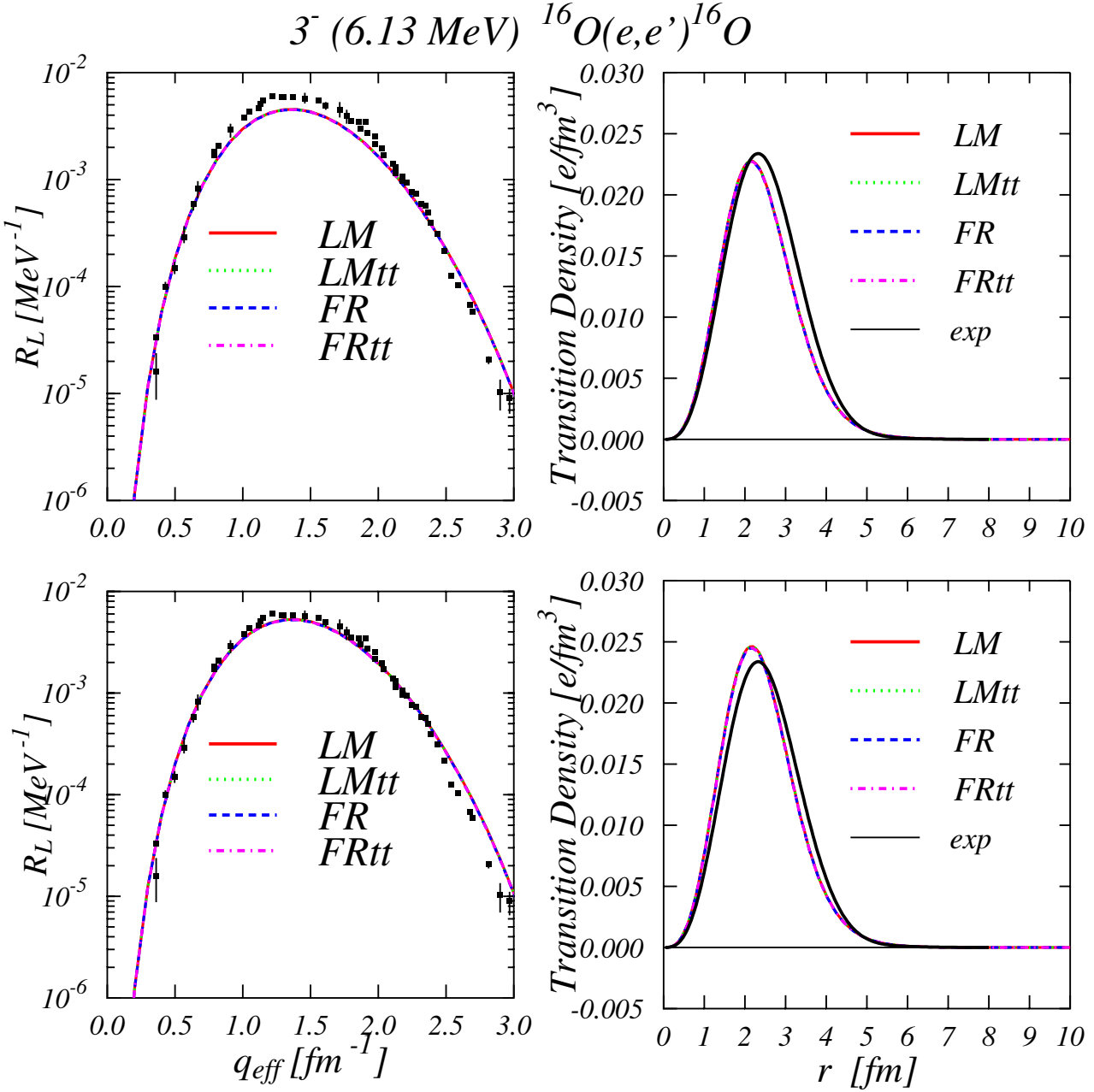


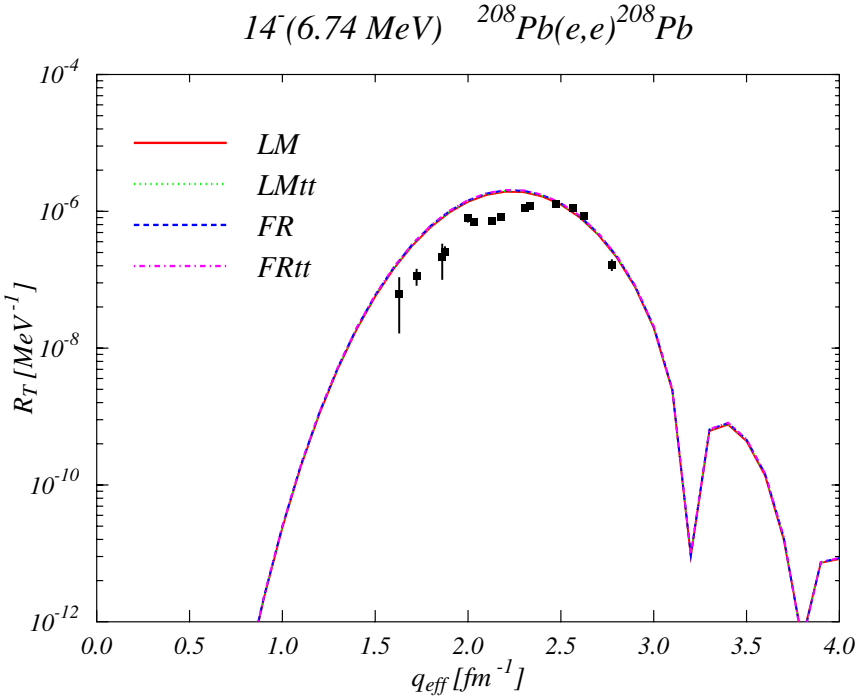
Densità di transizione del 3^- del ^{208}Pb

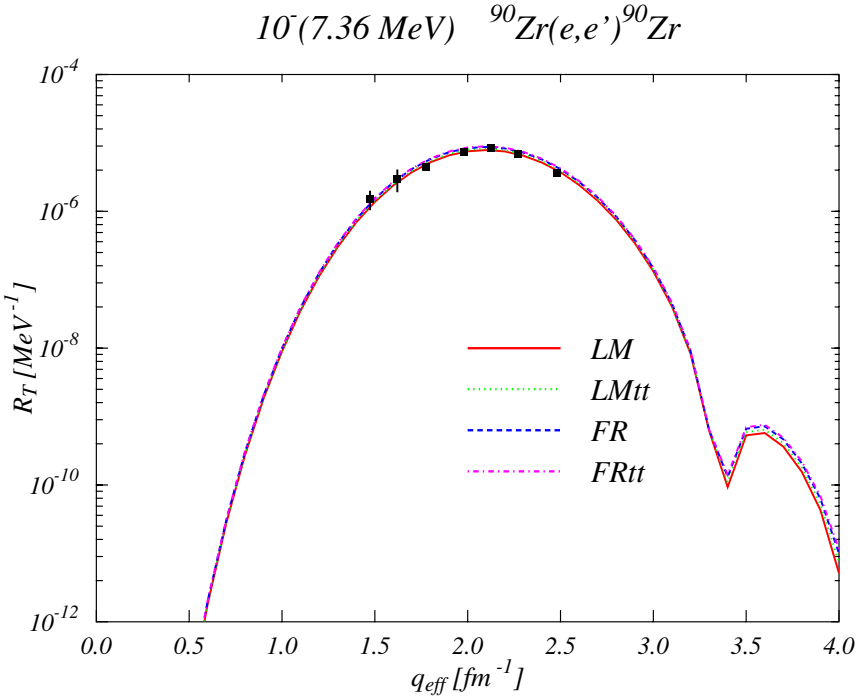


Spettro del ^{16}O



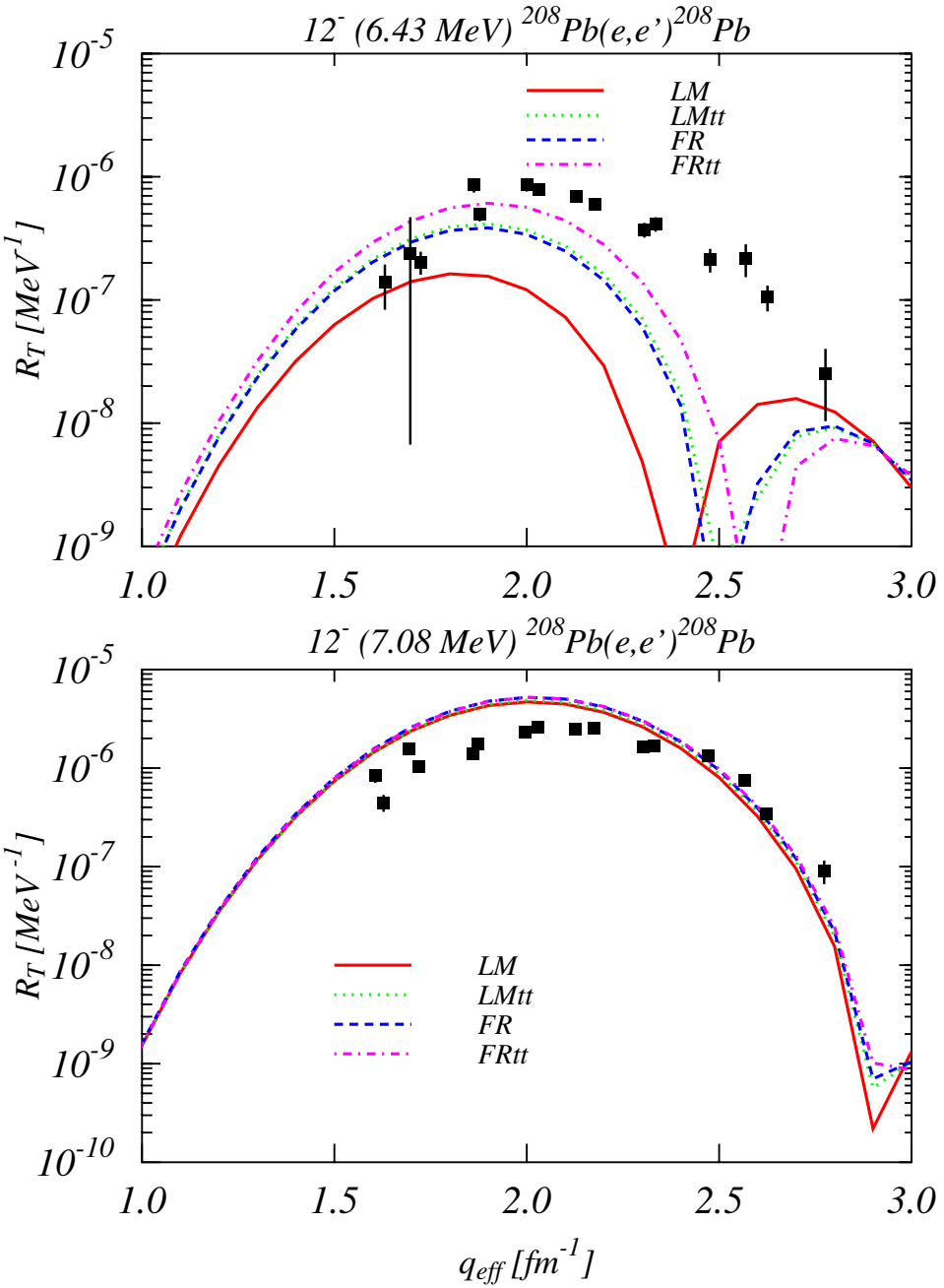

3- (6.13 MeV) 16O(e,e')16O
RL [MeV-1]
Transition Density [e/fm3]
LM
LMtt
FR
FRtt
exp
qeff [fm-1]
r [fm]



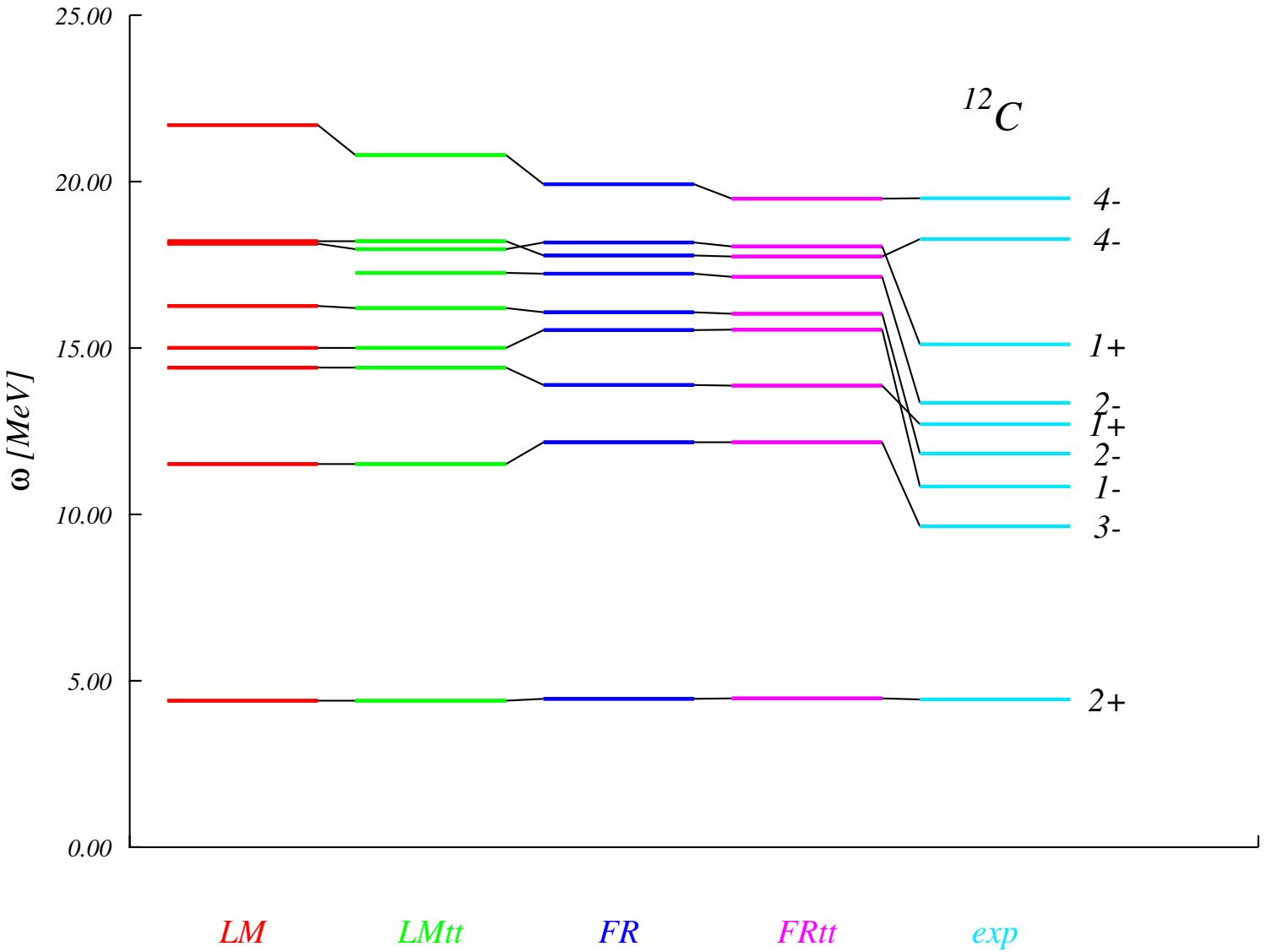


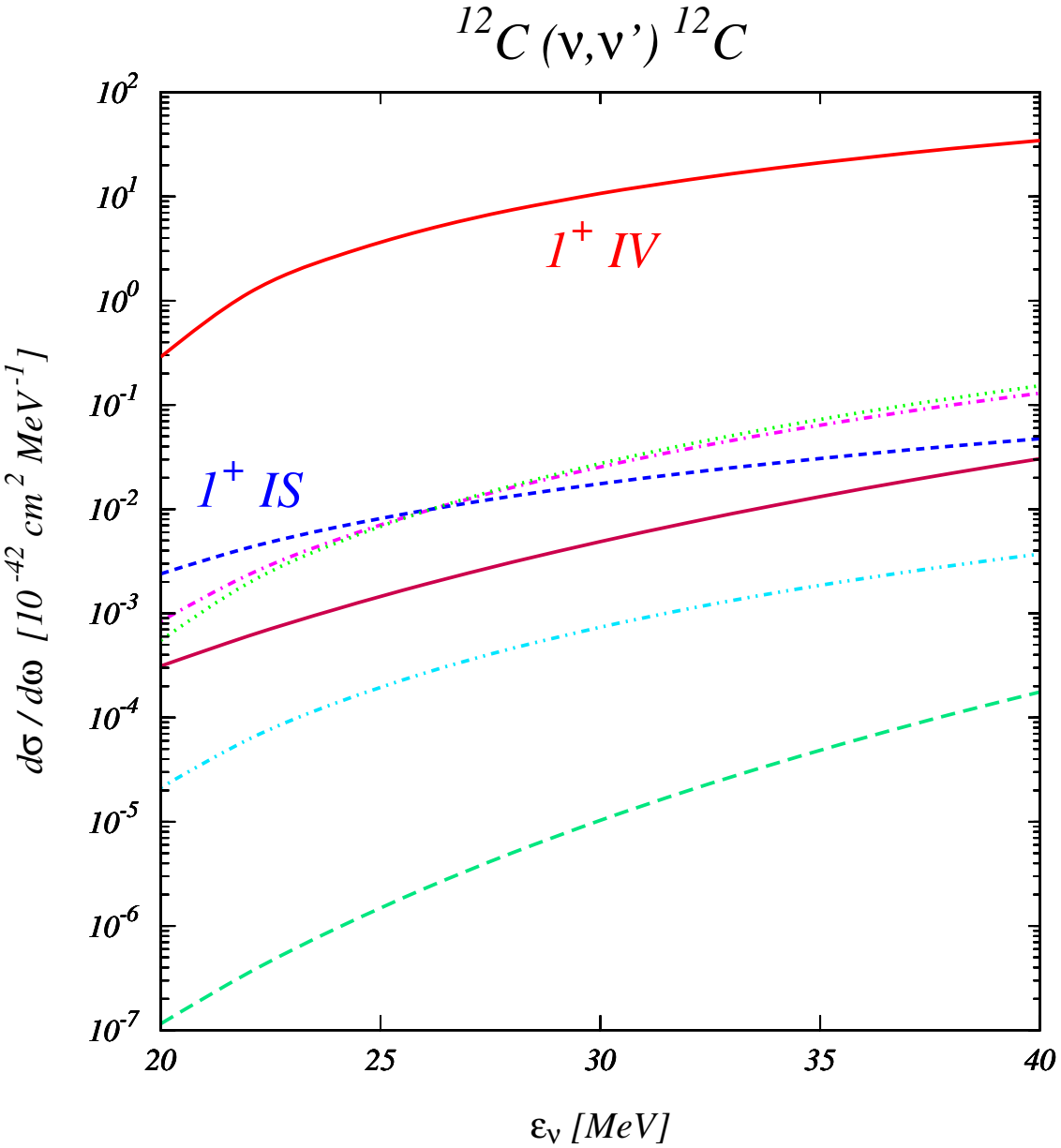
$^{208}Pb\ [(1j_{15/2})(1i_{13/2})^{-1}_{\nu}]$

$^{90}Zr\ [(1h_{11/2})(1g_{9/2})^{-1}_{\nu}]$

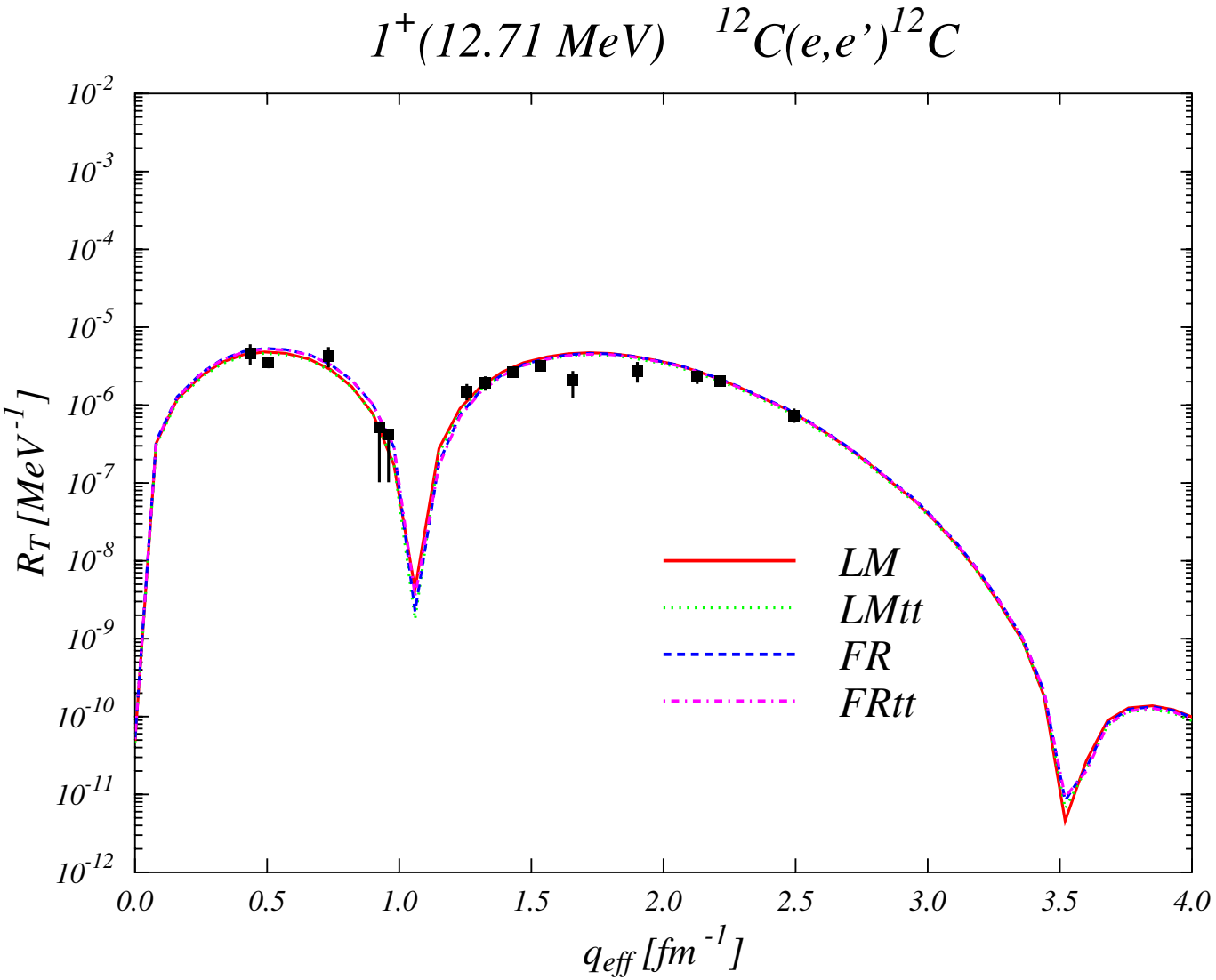

12- (6.43 MeV) 208Pb(e,e')208Pb
LM
LMtt
FR
FRtt
RT [MeV-1]
10-5
10-6
10-7
10-8
10-9
1.0
1.5
2.0
2.5
3.0
12- (7.08 MeV) 208Pb(e,e')208Pb
LM
LMtt
FR
FRtt
RT [MeV-1]
10-5
10-6
10-7
10-8
10-9
10-10
1.0
1.5
2.0
2.5
3.0
qeff [fm-1]

Spettro del ^{12}C

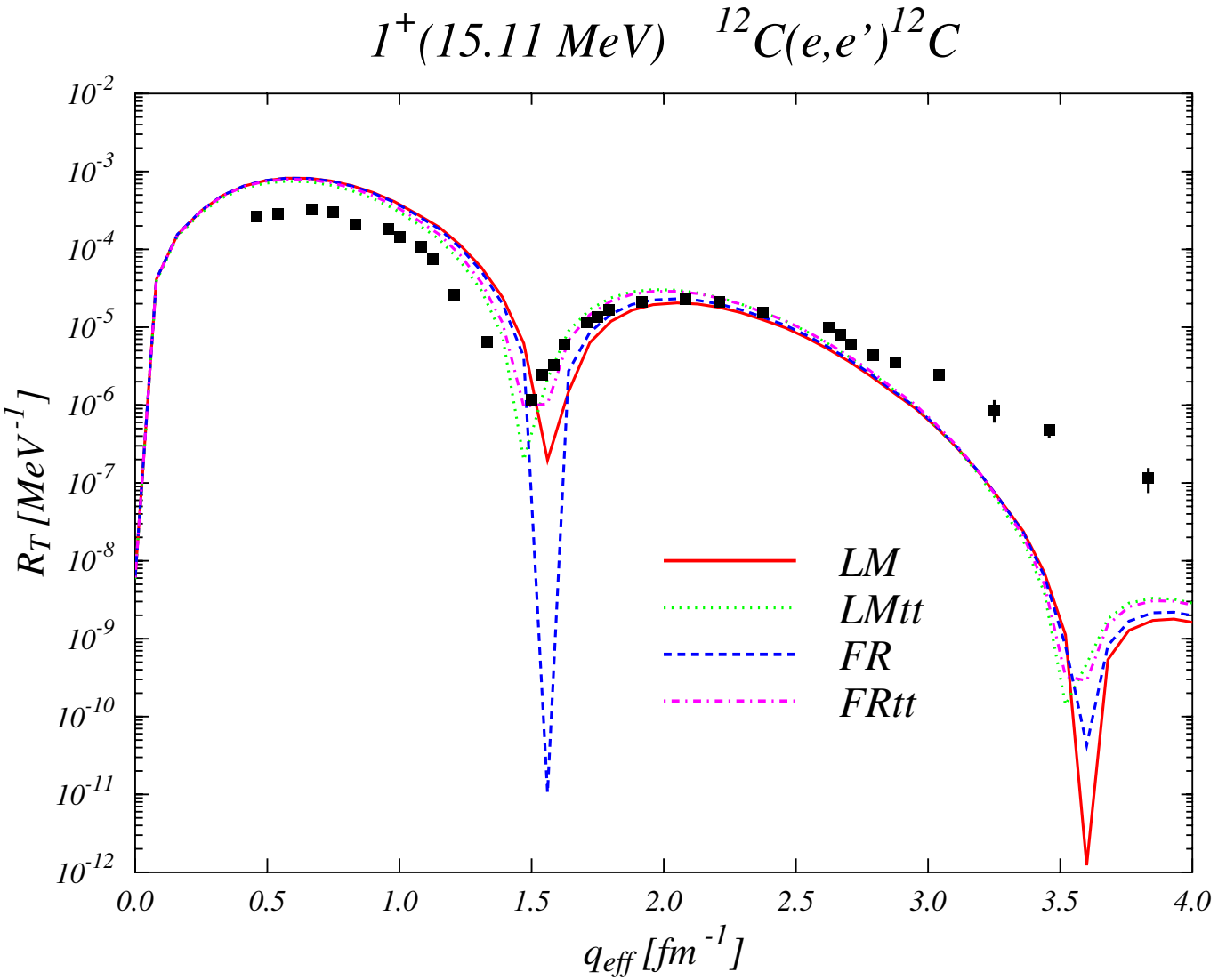


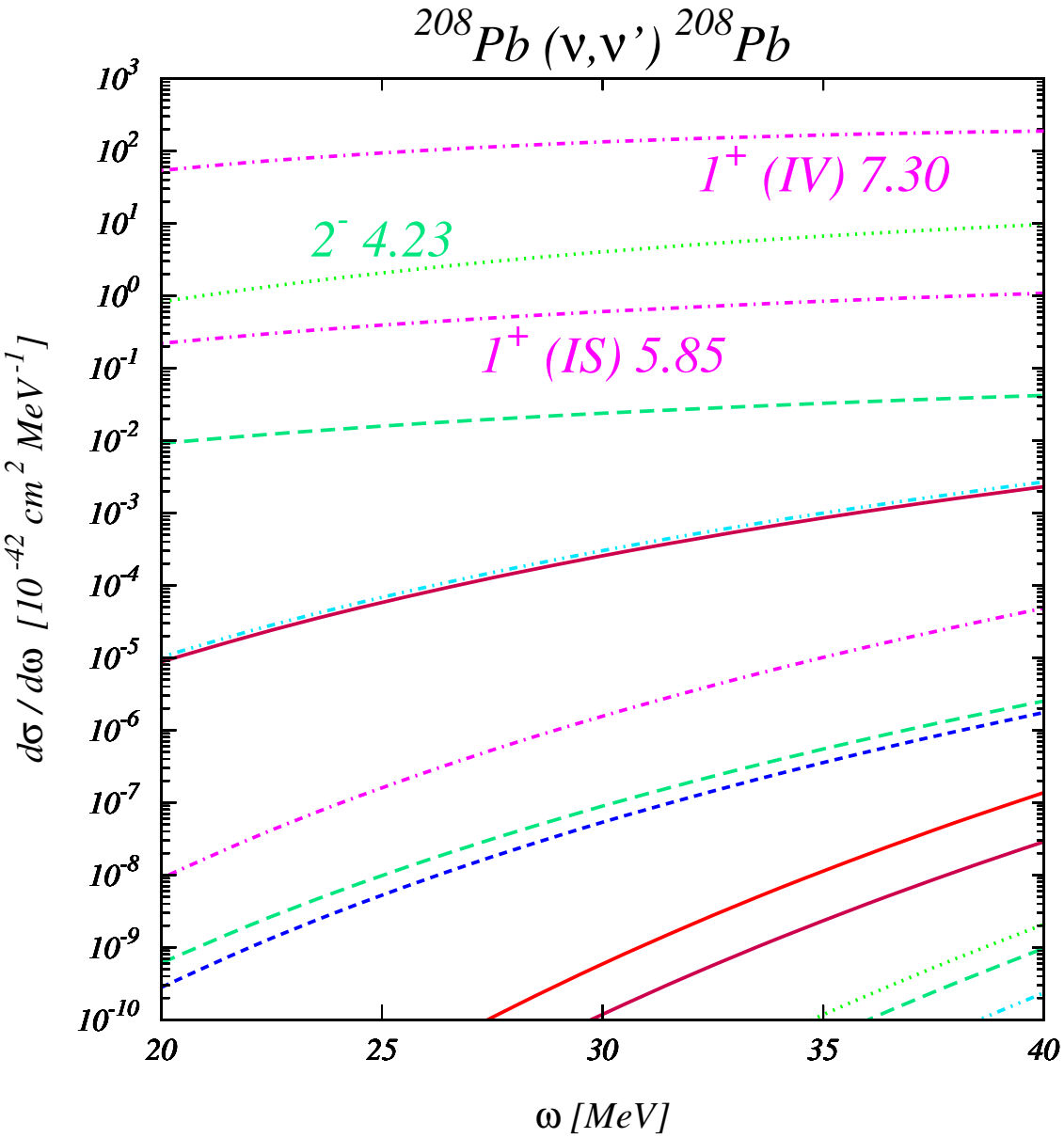

$^{12}C\ (\nu,\nu')\ ^{12}C$
$1^+\ IV$
$1^+\ IS$
$d\sigma / d\omega\ [10^{-42}\ cm^2\ MeV^{-1}]$
$\varepsilon_\nu\ [MeV]$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
20
25
30
35
40

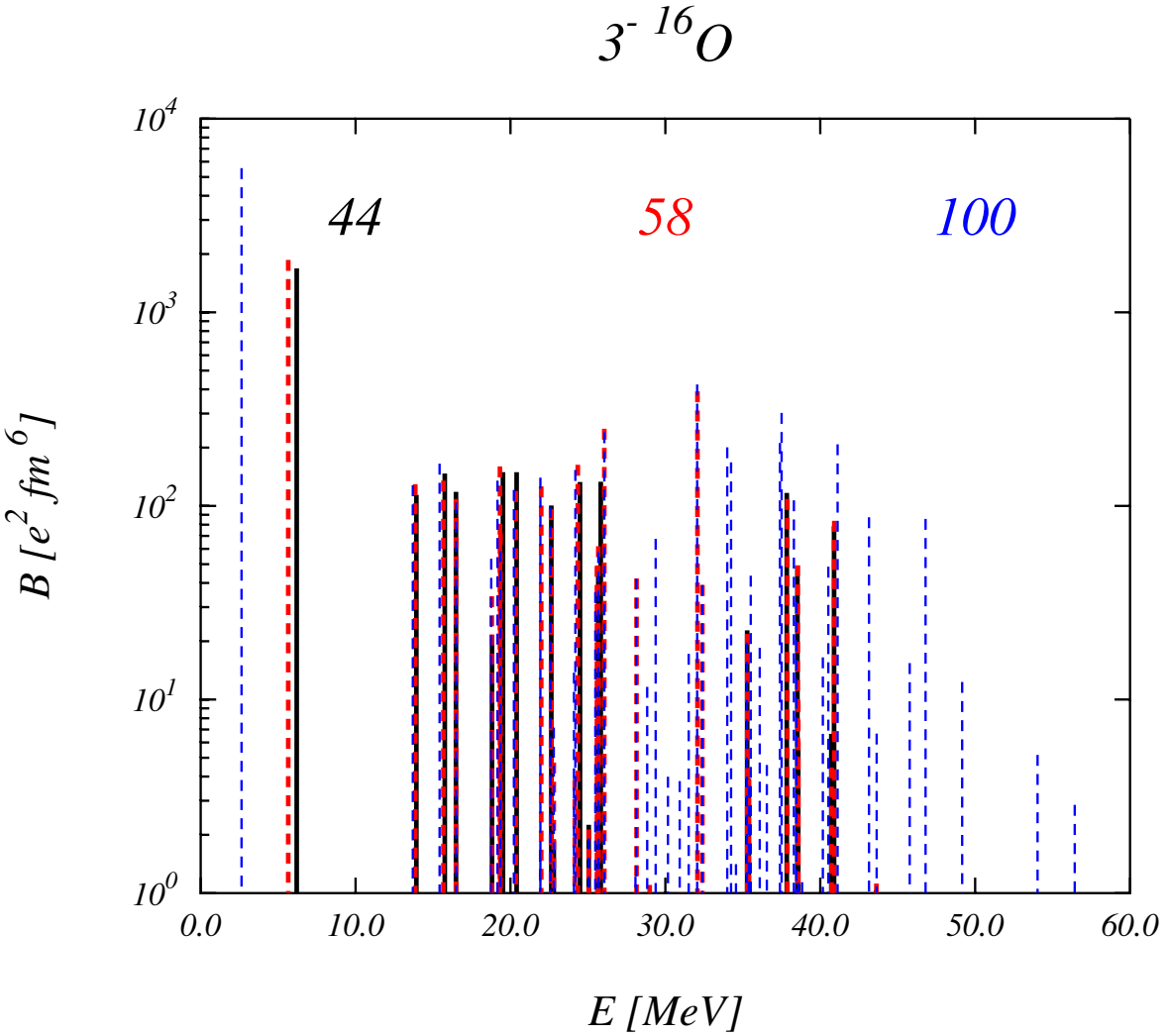
^{12}C : 1^+ Isoscalare

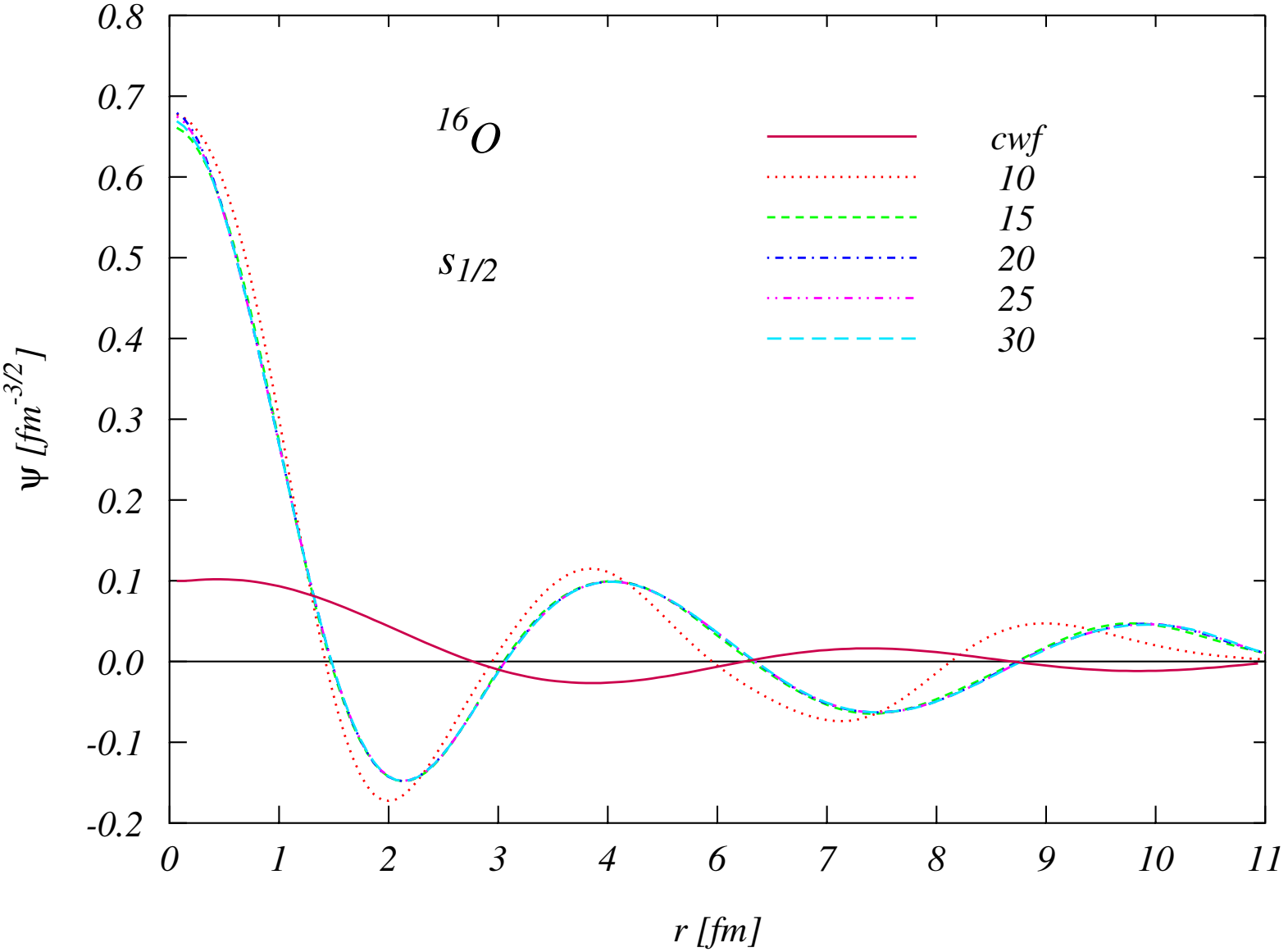


^{12}C : 1^+ Isovettoriale




$^{208}Pb\ (\nu,\nu')\ ^{208}Pb$
1^+ (IV) 7.30
2^- 4.23
1^+ (IS) 5.85
$d\sigma / d\omega\ [10^{-42}\ cm^2\ MeV^{-1}]$
$\omega\ [MeV]$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
20
25
30
35
40


3- 16O
44
58
100
B [e2 fm6]
E [MeV]
10^4
10^3
10^2
10^1
10^0
0.0
10.0
20.0
30.0
40.0
50.0
60.0


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
0
1
2
3
4
6
7
8
9
10
11
ψ [fm^-3/2]
r [fm]
16O
s1/2
cwf
10
15
20
25
30

Continuum Random Phase Approximation

$$Q^{\dagger}_{\nu} = \sum_{ph,\epsilon_p<0} X_{ph}(\epsilon_p) a^{\dagger}_p a_h - \sum_{ph,\epsilon_p<0} Y_{ph}(\epsilon_p) a^{\dagger}_h a_p$$
$$+ \sum_{[p]h} \int d\epsilon_p X_{ph}(\epsilon_p) a^{\dagger}_p a_h - \sum_{ph} \int d\epsilon_p Y_{ph}(\epsilon_p) a^{\dagger}_h a_p$$

$$(\epsilon_p - \epsilon_h - \omega) X_{ph}(\epsilon_p) + \sum_{p'h'}^{dis} [v_{ph,p'h'} X_{p'h'} + u_{ph,p'h'} Y_{p'h'}]$$
$$+ \sum_{p'h'} \int d\epsilon_{p'} [v(\epsilon_p, \epsilon'_p)_{ph,p'h'} X_{p'h'}(\epsilon'_p) + u(\epsilon_p, \epsilon'_p)_{ph,p'h'} Y_{p'h'}(\epsilon'_p)] = 0$$
$$(\epsilon_p - \epsilon_h + \omega) Y_{ph}(\epsilon_p) + ... = 0$$

Continuum Random Phase Approximation

$$f_{[p],h}(r) = \sum_{p=\epsilon_F}^{0} X_{ph}(\epsilon_p) R_p(r,\epsilon_p) + \int d\epsilon_p X_{ph}(\epsilon_p) R_p(r,\epsilon_p)$$

$$g_{[p],h}(r) = \sum_{p=\epsilon_F}^{0} Y_{ph}(\epsilon_p) R_p(r,\epsilon_p) + \int d\epsilon_p Y_{ph}(\epsilon_p) R_p(r,\epsilon_p)$$

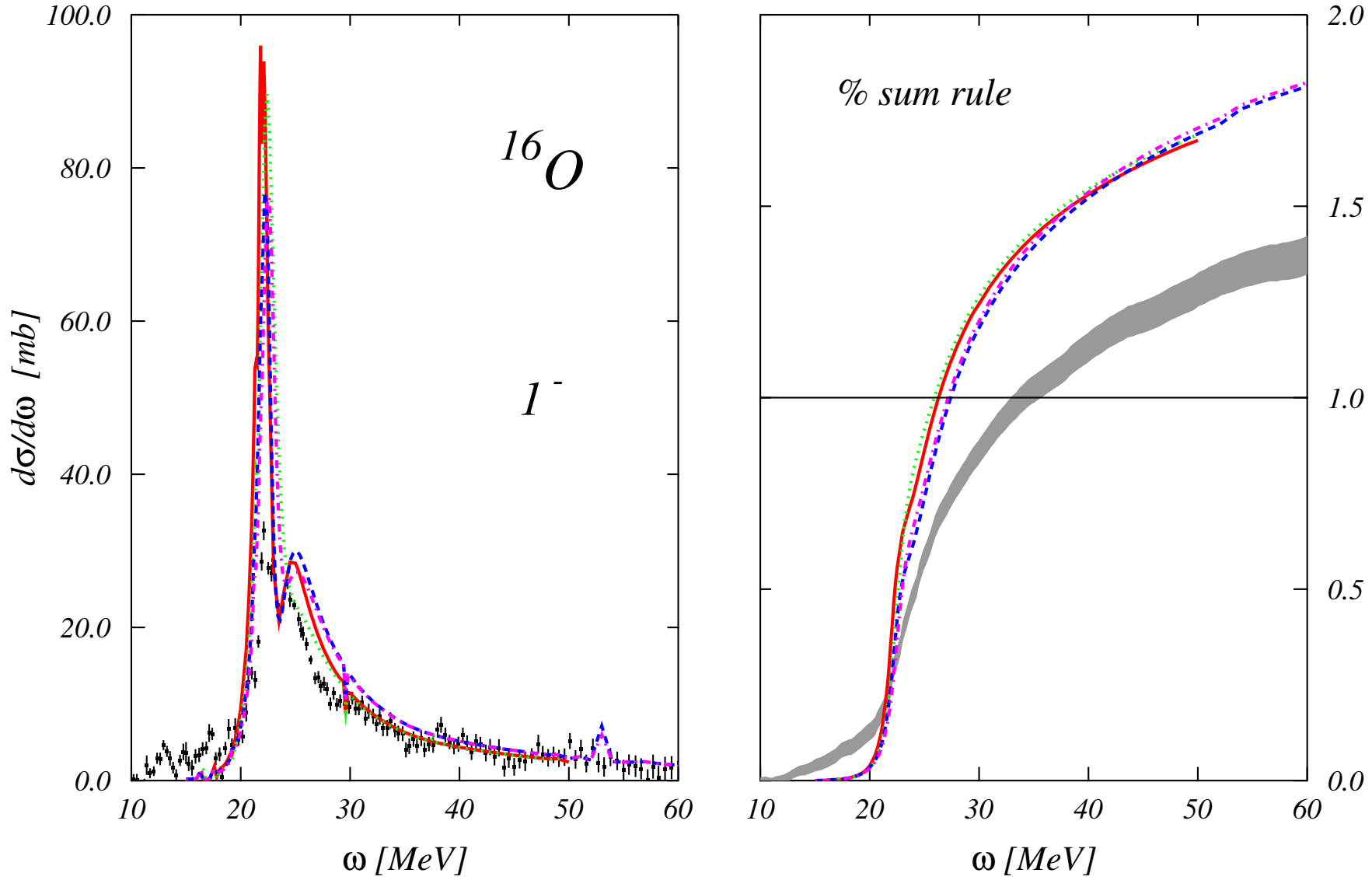
$$(h_0 - \epsilon_h - \omega) f_{[p],h}(r) = -\sum_{[p']h'} \int dr' r'^2 \Big[$$

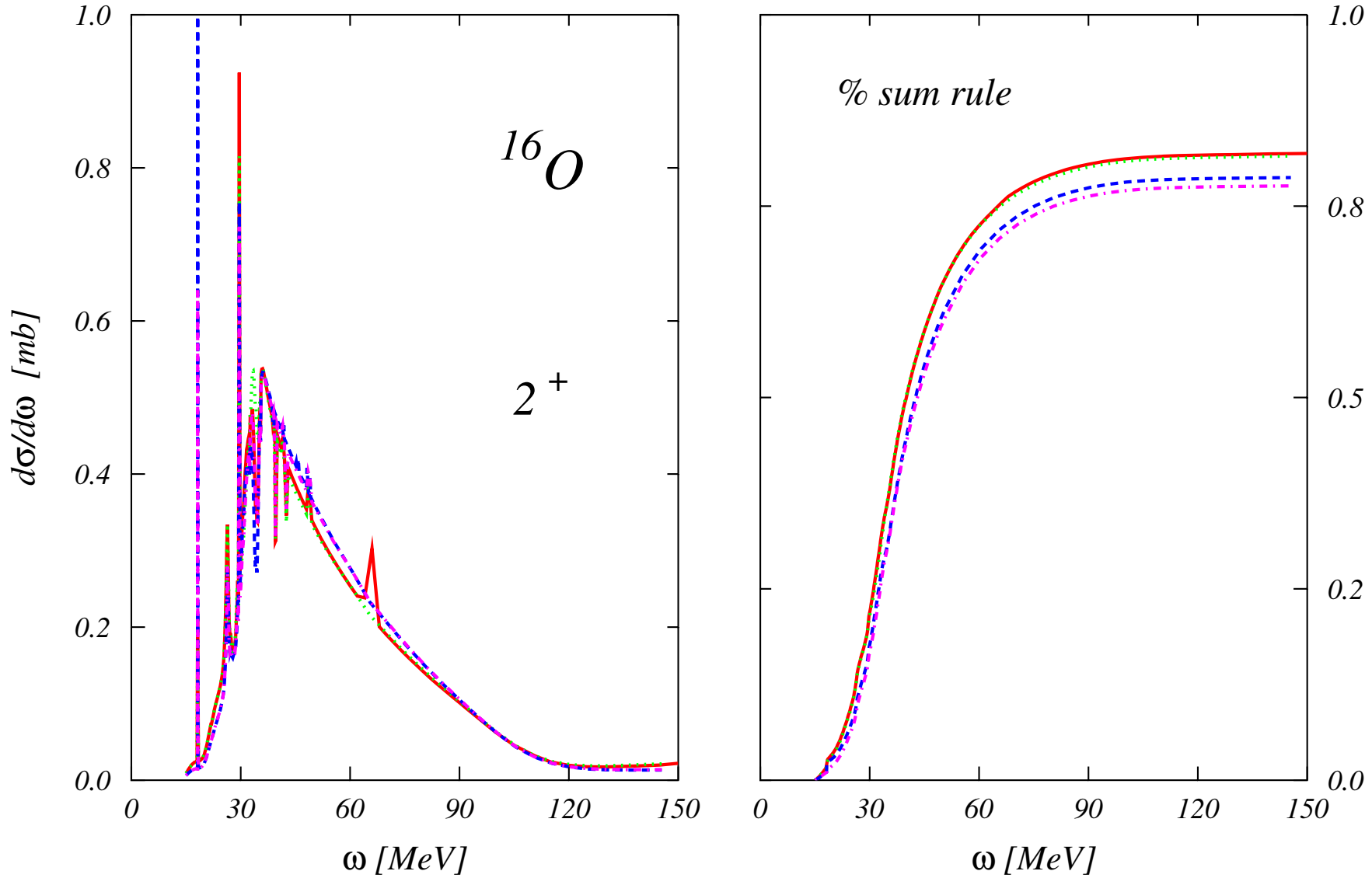
$$f_{[p'],h'}(r') R_{h'}(r') R_h(r) v^{dir}_{ph,p'h'}(r,r') -$$

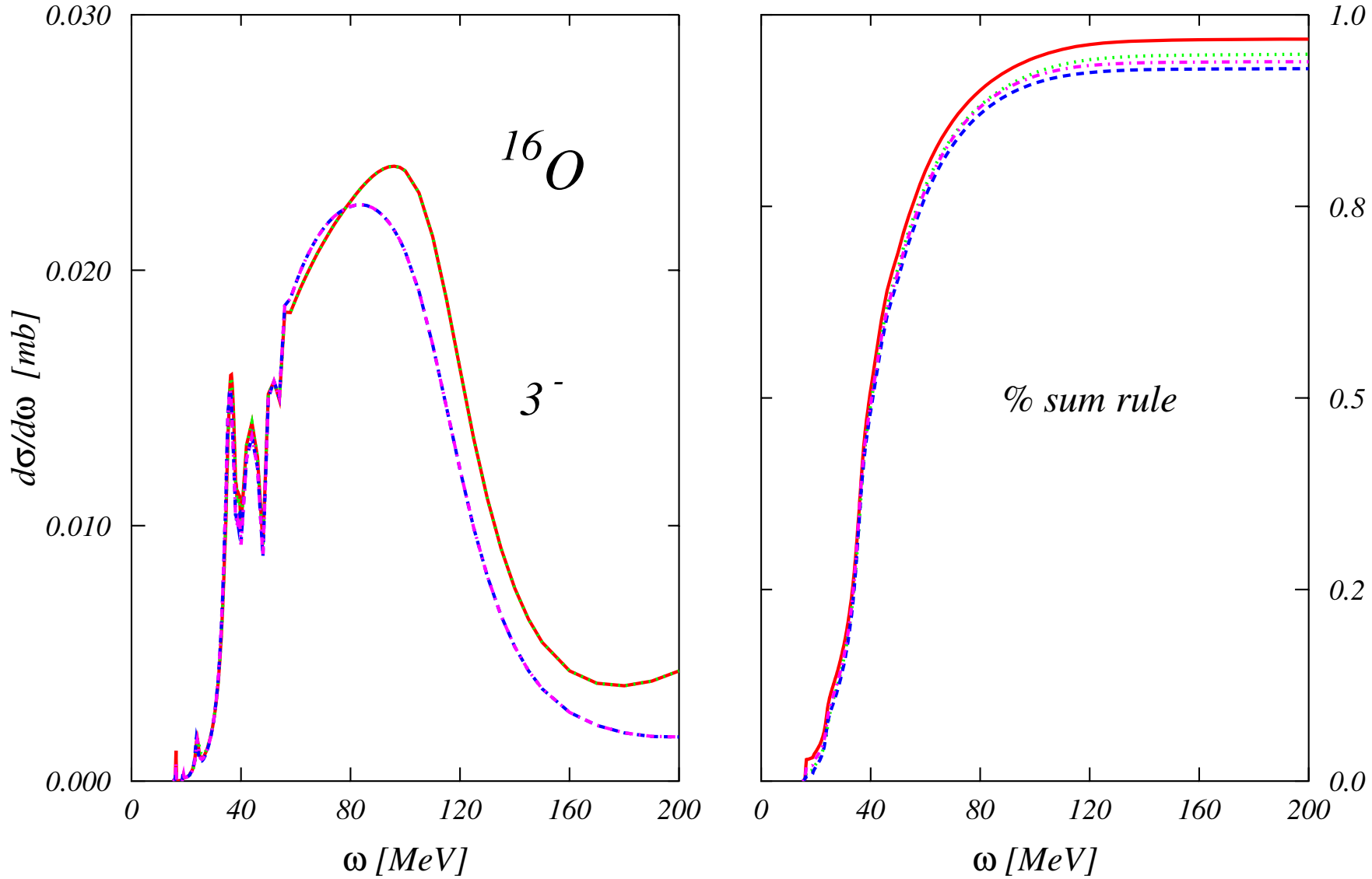
$$f_{[p'],h'}(r') R_{h'}(r') R_h(r) v^{exc}_{ph,p'h'}(r,r') +$$

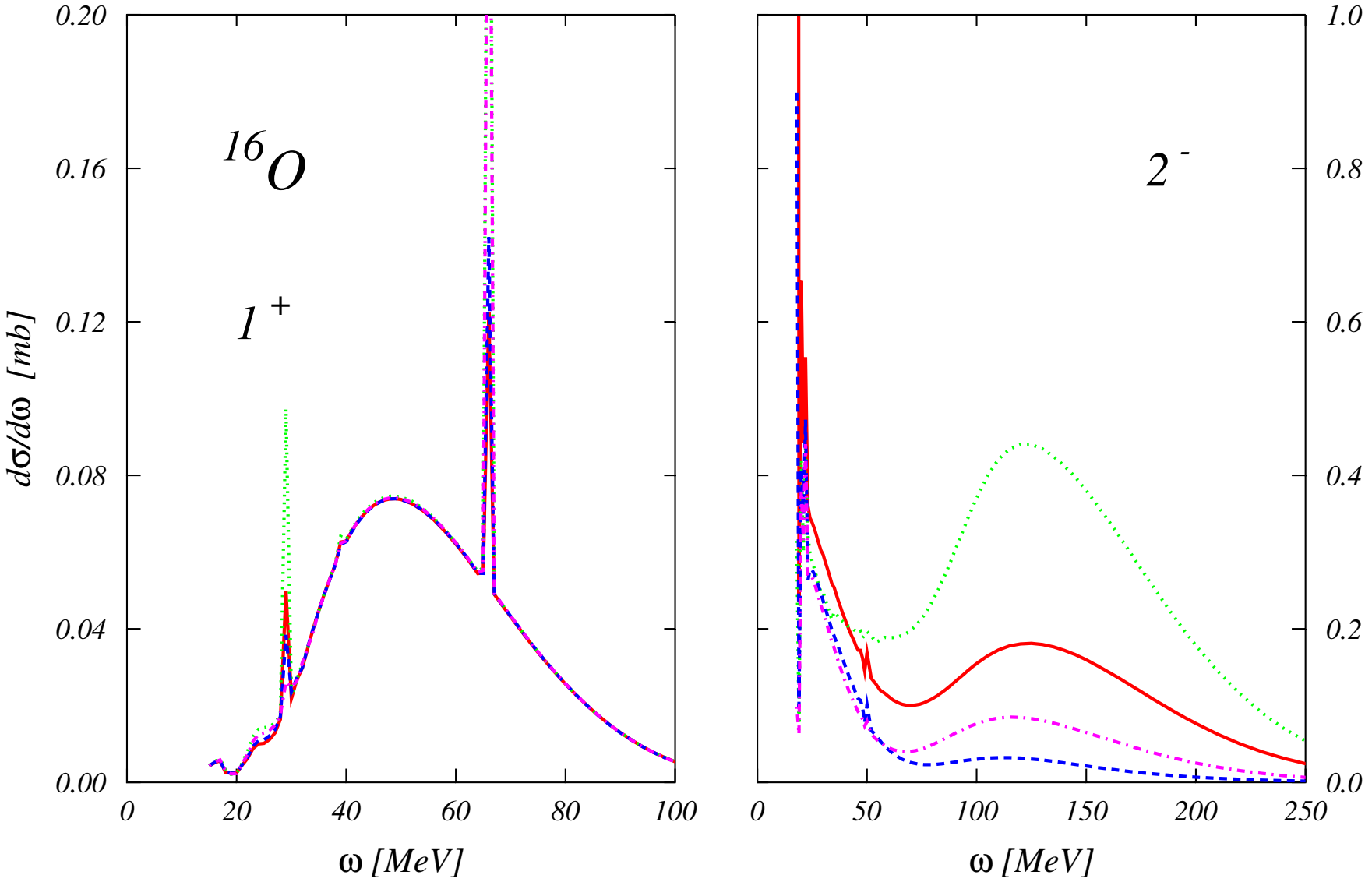
$$g_{[p'],h'}(r') R_{h'}(r') R_h(r) u^{dir}_{ph,p'h'}(r,r') -$$

$$g_{[p'],h'}(r') R_h(r') R_{h'}(r) u^{exc}_{ph,p'h'}(r,r') \Big] + BST$$


100.0
80.0
60.0
40.0
20.0
0.0
dσ/dω [mb]
16O
1-
10
20
30
40
50
60
ω [MeV]
% sum rule
2.0
1.5
1.0
0.5
0.0
10
20
30
40
50
60
ω [MeV]


1.0
0.8
0.6
0.4
0.2
0.0
dσ/dω [mb]
16O
2+
0
30
60
90
120
150
ω [MeV]
% sum rule
1.0
0.8
0.5
0.2
0.0
0
30
60
90
120
150
ω [MeV]


0.030
0.020
0.010
0.000
dσ/dω [mb]
16O
3-
0
40
80
120
160
200
ω [MeV]
1.0
0.8
0.5
0.2
0.0
% sum rule
0
40
80
120
160
200
ω [MeV]


^{16}O
1^+
2^-
$d\sigma/d\omega$ [mb]
ω [MeV]
ω [MeV]
0.20
0.16
0.12
0.08
0.04
0.00
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
0
50
100
150
200
250

Conclusioni

Stato Fondamentale

Stati eccitati

Conclusioni

Stato Fondamentale

Calcoli con interazioni realistiche

interazione a 3 corpi

funzioni di struttura

...

Stati eccitati

Conclusioni

Stato Fondamentale

Calcoli con interazioni realistiche

Stati eccitati

- RPA con interazioni a range finito e tensore
- Trattazione degli spettri discreti e continui
- Calcoli autoconsistenti nel discreto
- Calcoli autoconsistenti nel continuo
- Electron e neutrino scattering con CRPA
- Eccitazioni di cambio carica
- Estensione RPA (2p2h)

Conclusioni

Stato Fondamentale

Calcoli con interazioni realistiche

Stati eccitati

2p-2h RPA con interazioni effettive

Costruzione dell'hamiltoniana effettiva dalla teoria CBF