Nuclear excited states within Random Phase Approximation Theory

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AIM OF THE TALK:

Are nuclear excited states sensitive to the details of the Nucleon Nucleon interaction?

Outline

Generalities on RPA

DISCRETE RPA

- **Phenomenological approach**
- The phenomenological NN interactions
- Results: transverse form factors
- **Self consistent approach with D1 interaction**
- Results: transverse form factors (isospin doublets)

CONTINUUM RPA

- Sturmian basis
- Results: neutrino cross sections

Conclusions

Random Phase Approximation

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

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

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

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

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

RPA Calculations

Input

Single particle energies and wave functions.
Residual nuclear interaction.

RPA Calculations

Phenomenological Input

Single particle energies and wave functions: Woods-Saxon

Residual nuclear interaction:

$$V_{eff}(r_{1,2}) = V_1(r_{1,2},\rho) + V_2(r_{1,2},\rho)\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2} + \\ + V_3(r_{1,2})\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2} + V_4(r_{1,2})\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2} + \\ + V_5(r_{1,2})S_{12} + V_6(r_{1,2})S_{12}\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2}$$

$$S_{12}(\hat{r}_{1,2}) = 3\boldsymbol{\sigma_1}\cdot\hat{r}_{1,2}\boldsymbol{\sigma_2}\cdot\hat{r}_{1,2} - \boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}$$

$$V_{1,2}(r_{1,2},\rho) = V_{1,2} + V^{\rho}_{1,2}\rho^{\alpha}(r_{1,2})$$

$$\rho(r_{12}) = [\rho(r_1)\rho(r_2)]^{\frac{1}{2}}$$

Residual interaction

Zero-range: "Traditional" Landau Migdal (LM) and LM with additional tensor-isospin term (LMtt)

Residual interaction

Zero-range: "Traditional" Landau Migdal (LM) and LM with additional tensor-isospin term (LMtt)

Finite-range (FR e FRtt): Long-range behavior of Argonne $V_{18}+$ short range modifications:

$$V^{p=1,4}(r) = \widetilde{V}_{18}^{p=1,4}(r) + \sum_{\mu=1}^{M} a_\mu e^{-b_\mu (r-R_\mu)^2}$$

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$$V_{\rho,\tau}(r) = a_{\rho,\tau} e^{-b_{\rho,\tau} r^2}$$

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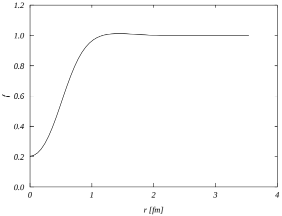
$$V_{\rho,\tau}(r) = a_{\rho,\tau} e^{-b_{\rho,\tau} r^2} \qquad V^{p=5,6}(r) = V_{18}^{5,6}(r) f(r)$$



Correlation function: Arias de Saavedra, Bisconti, Co', Fabrocini, Phys. Rep. 2007

Residual interaction

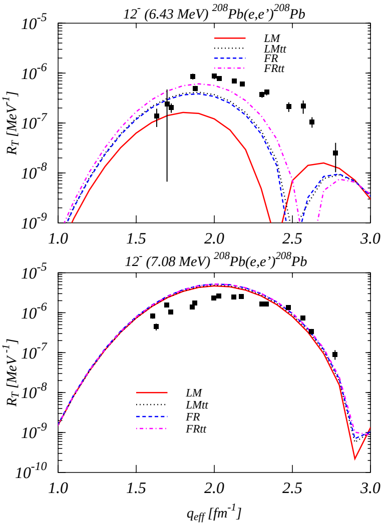
Spin, spin-isospin and tensor channels: chosen to reproduce 1^+ and 12^- states of ^{208}Pb and tested comparing

- magnetic low-energy of ^{208}Pb
- 4^- state of ^{16}O
- 1^+ doublet of ^{12}C

Scalar and isospin terms

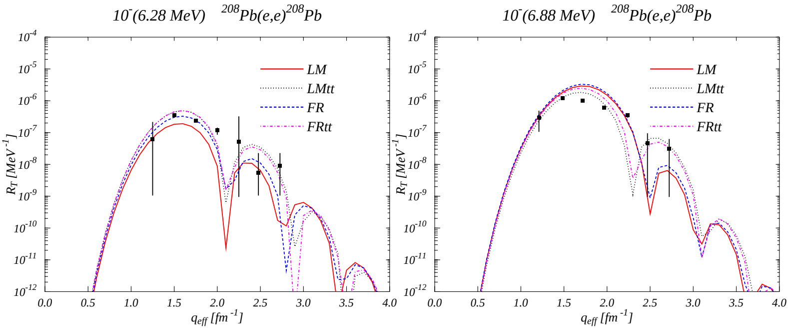
- chosen to get a reasonable description of the centroid energy of the isovector giant dipole resonance
- density-dependent part chosen to reproduce first 2^+ state for ^{12}C and first 3^- states for ^{16}O , ^{40}Ca , ^{208}Pb

Phenomenological RPA calculations: ^{208}Pb : 12^-



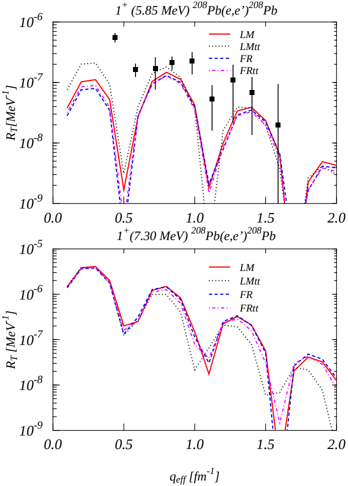
Experimental data: J. Lichtenstadt, et al., Phys. Rev. C 20 (1979) 497.

Phenomenological RPA calculations: ^{208}Pb : 10^{-}



Experimental data: J. Lichtenstadt, et al., Phys. Rev. C 20 (1979) 497.

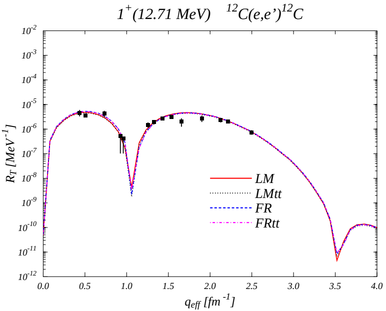
Phenomenological RPA calculations: ^{208}Pb : 1^+

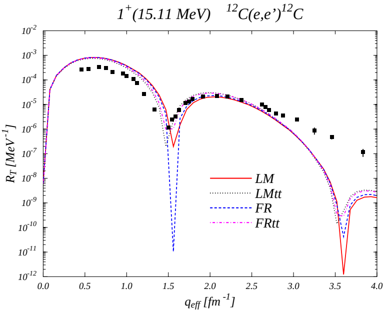


^{208}Pb					
excitation	LM	LMtt	FR	FRtt	exp
1^+	5.92	5.89	5.72	5.70	5.85
1^+	7.38	6.77	7.64	7.48	7.30

Experimental data: Müller and et al., Phys. Rev. Lett. 54 (1985) 293.

Phenomenological RPA calculations: ^{12}C : 1^+





^{12}C					
excitation	LM	LMtt	FR	FRtt	exp
1^+	14.41	14.41	13.89	13.87	12.71
1^+	18.13	17.97	18.17	18.05	15.11

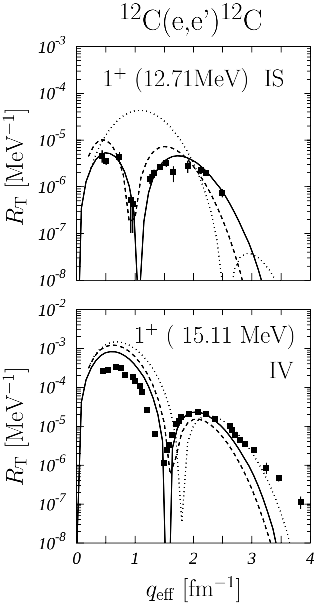
Experimental data: Hickes and et al., Phys. Rev. C 30 (1984) 1; Hyde-Wright, Ph.D. thesis, MIT(1984);

Williamson and et al., abst. subm. to PANIC (JAPAN), unpublished (1987).

Self consistent approach

HF calculations for single particle energies and wave functions with Gogny D1 interaction
RPA with Gogny D1 interaction

Self-consistent RPA calculations: ^{12}C : 1$^+$

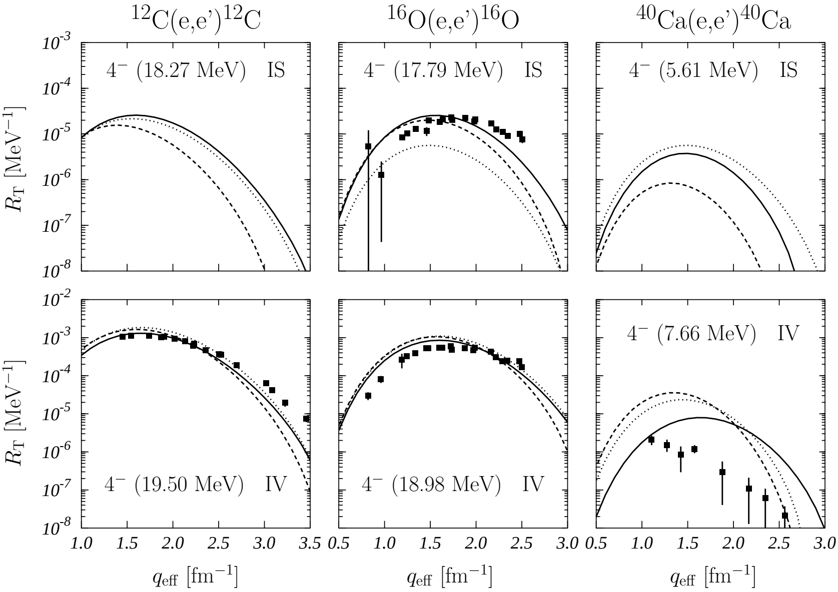


...... : MF
- - - : Self-consistent
—— : Phenomenological

^{12}C			
1$^+$	D1	FR	exp
IS	8.12	13.89	12.71
IV	3.85	18.17	15.11

Experimental data: Hyde-Wright, Ph.D. thesis, Massachusetts Institute of Technology (1984).

Self-consistent RPA calculations: 4^-

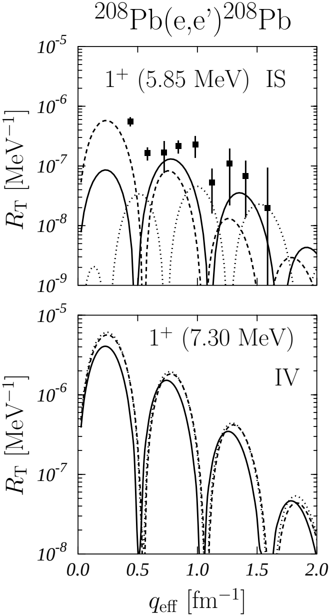


Experimental data: Hyde-Wright, Ph.D. thesis, Massachusetts Institute of Technology (1984).

Inversion of the 4^- states

4^-	D1	FR	exp
^{12}C			
IS	18.64	17.78	18.27
IV	1.64	19.92	19.50
^{16}O			
IS	18.81	17.75	17.79
IV	15.49	19.88	18.98
^{40}Ca			
IS	7.83	6.78	5.61
IV	7.59	7.42	7.66

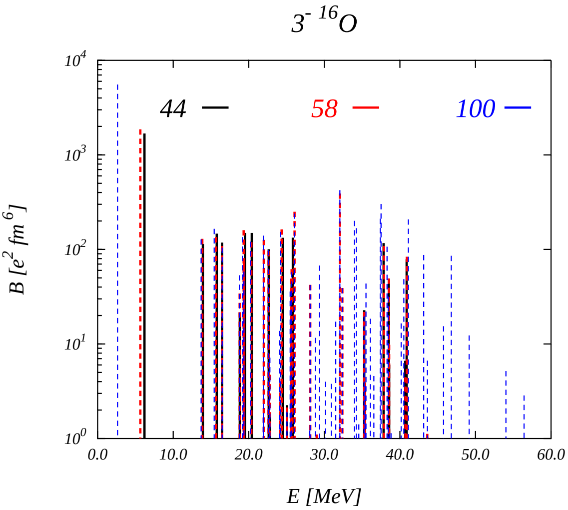
Self-consistent RPA calculations: 1^+ ^{208}Pb



^{208}Pb			
1^+	D1	FR	exp
IS	9.40	5.72	5.85
IV	6.75	7.64	7.30

Experimental data: Müller and et al., Phys. Rev. Lett. 54 (1985) 293.

Sensitivity to the size of the configuration space



Continuum Random Phase Approximation

$$Q_\nu^\dagger = \sum_{ph,\epsilon_p<0} X_{ph}(\epsilon_p) a_p^\dagger a_h - \sum_{ph,\epsilon_p<0} Y_{ph}(\epsilon_p) a_h^\dagger a_p$$

$$+ \sum_{[p]h} \int_0^\infty d\epsilon_p X_{ph}(\epsilon_p) a_p^\dagger a_h - \sum_{[p]h} \int_0^\infty d\epsilon_p Y_{ph}(\epsilon_p) a_h^\dagger a_p$$

$$(\epsilon_p - \epsilon_h - \omega) X_{ph}(\epsilon_p) + \sum_{p'h'}^{dis} [v_{ph,p'h'} X_{p'h'} + u_{ph,p'h'} Y_{p'h'}]$$

$$+ \sum_{p'h'} \int_0^\infty d\epsilon_{p'} [v(\epsilon_p, \epsilon'_p)_{ph,p'h'} X_{p'h'}(\epsilon'_p) + u(\epsilon_p, \epsilon'_p)_{ph,p'h'} Y_{p'h'}(\epsilon'_p)] = 0$$

$$(\epsilon_p - \epsilon_h + \omega) Y_{ph}(\epsilon_p) + \ldots\ldots = 0$$

Continuum Random Phase Approximation

$$f_{[p],h}(r) = \sum_{\epsilon_p=\epsilon_F}^{0} X_{ph}(\epsilon_p) R_p(r,\epsilon_p) + \int_0^\infty d\epsilon_p X_{ph}(\epsilon_p) R_p(r,\epsilon_p)$$

$$g_{[p],h}(r) = \sum_{\epsilon_p=\epsilon_F}^{0} Y_{ph}(\epsilon_p) R_p(r,\epsilon_p) + \int_0^\infty d\epsilon_p Y_{ph}(\epsilon_p) R_p(r,\epsilon_p)$$

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

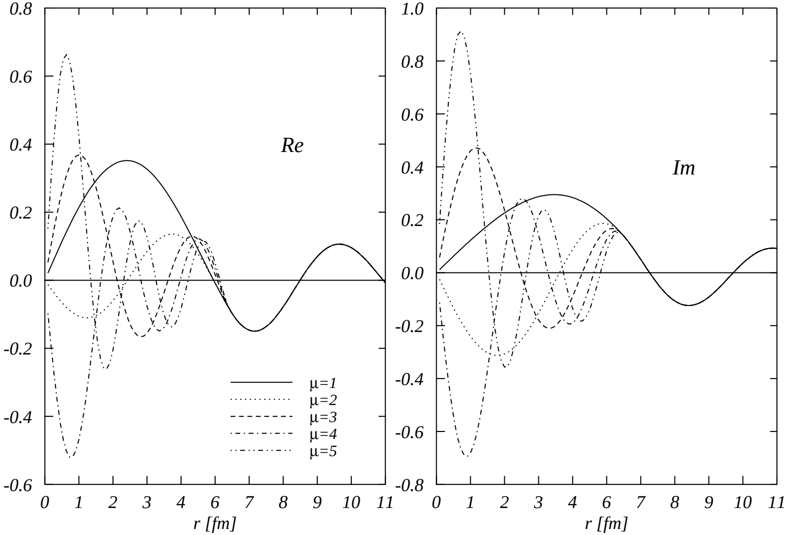
$$\Big\{ R_{h'}(r')[R_h(r) f_{[p'],h'}(r') v^{dir}_{ph,p'h'}(r,r') - f_{[p'],h'}(r) R_h(r') v^{exc}_{ph,p'h'}(r,r')] +$$

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

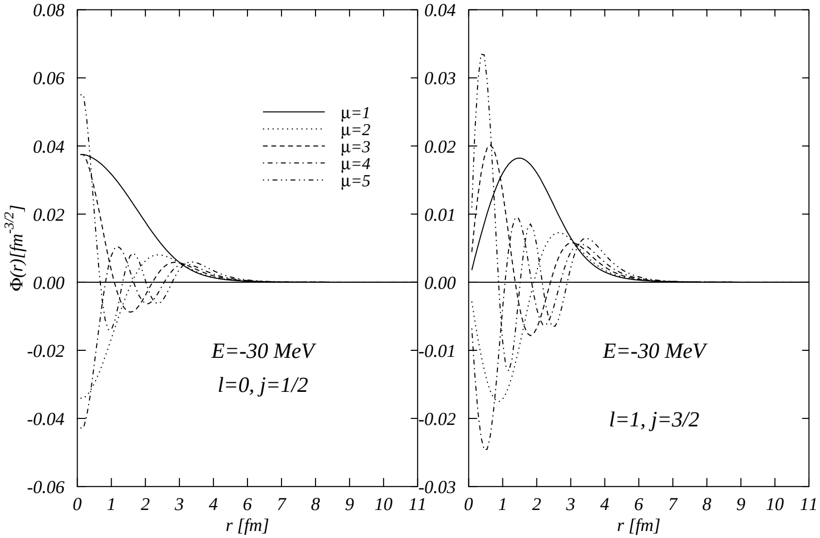
$$(h_0 - \epsilon_h + \omega) g_{[p],h}(r) = ...$$

Sturmian functions

E=30 MeV, l=1, j=3/2



Sturmian functions



Percentage contribution of the various multipoles to the energy integrated cross sections

exit angle	J^π	(ν,ν')	$(\overline{\nu},\overline{\nu'})$	(ν,e^-)	$(\overline{\nu},e^+)$
$\theta = 30°$	1^-	0.47	0.49	0.30	0.28
	1^+	0.04	0.04	0.03	<0.01
	2^-	0.43	0.39	0.57	0.69
	2^+	0.02	0.04	<0.01	<0.01
	oth	0.04	0.04	0.10	0.03
$\theta = 150°$	1^-	0.48	0.50	0.49	0.28
	1^+	0.04	0.04	0.03	0.02
	2^-	0.43	0.39	0.45	0.63
	2^+	0.02	0.04	0.01	0.03
	oth	0.03	0.03	0.02	0.04

Ref. A.Botrugno, G.Co', Nucl. Phys. A 761(2005) 200-231

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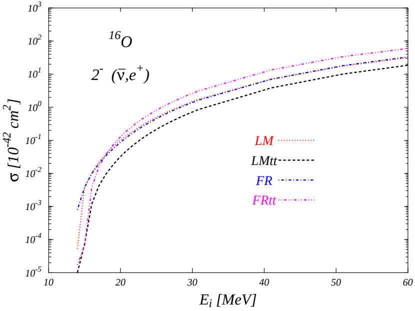
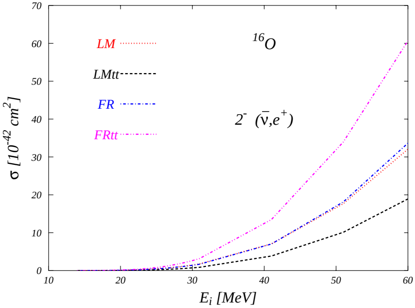
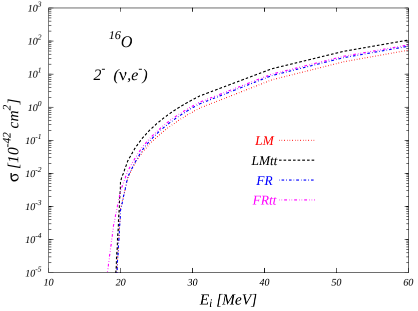
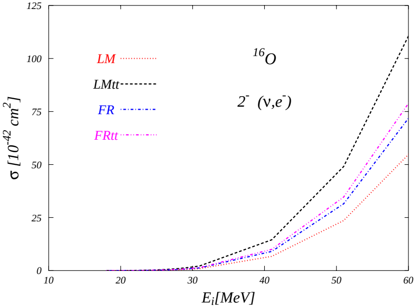
Cross section dependence on the interaction





Cross section dependence on the interaction





Conclusions

- We have observed that in general finite-range and tensor components do not produce sizable effects in discrete excited states, but we have found some cases in which these effects are important, and these states can be useful to impose severe constraints on the Nucleon Nucleon interaction.
- The comparison of phenomenological and self-consistent calculations illustrates well the difficulties related to a complete self-consistent approach. For all the cases we studied the Gogny D1 interaction inverts the isospin doublets indicating the presence of a problem in the isospin channel.

Conclusions

- Our continuum RPA technique allows us to do calculations with interactions with finite range and tensor channel.
- The inelastic neutrino cross sections (at the energy of supernova neutrinos) show how important it is a correct definition of the interaction.

REFERENCES

V. De Donno, *Ph.D. Thesis*, Univ. of Salento,(Lecce)-ITALY- July 2008 (unpublished)

V. De Donno, G.Co, C.Maieron, M. Anguiano, M.Lallena. M.Moreno Torres - *Low-lying magnetic excitations of doubly-closed shell nuclei and the nucleon-nucleon effective interaction*, Phys. Rev. C 79 (2009) 044311 (arXiv: 0904.0548, nucl-th)

C. Maieron, V. De Donno, G. Co', M. Anguiano, A.M. Lallena and M. Moreno Torres - *Effective nucleon-nucleon interaction and low lying magnetic nuclear states*, Contribution to the XII workshop on problems in Theoretical Physics, Cortona 8-10th Oct. 2008. (arXiv:0901.2449,nucl-th)

Sturmian functions

$$(h_0 - V_{WS}(r) - \epsilon_p)\Phi_p^\mu(r) = -\frac{\hbar^2}{2m}\overline{U}_p^\mu(r)\Phi_p^\mu(r) \qquad se\ \epsilon_p > 0$$

$$(h_0 - \epsilon_p)\Phi_p^\mu(r) = -\alpha_p^\mu V_{WS}(r)\Phi_p^\mu(r) \qquad se\ \epsilon_p < 0$$

$$\Phi_p^\mu(r \to \infty) \to \lambda H_p^-(\epsilon_p, r) \qquad se\ \epsilon_p > 0$$

$$\Phi_p^\mu(r \to \infty) \to \chi \frac{1}{r} exp\left(-r\left(\frac{2m|\epsilon_p|}{\hbar^2}\right)^{\frac{1}{2}}\right) \qquad se\ \epsilon_p < 0$$

M.Buballa, S. Drożdż, S. Krewald, J.Speth, Ann. of Phys. 208 (1991) 346.