Medium polarization effects in neutron-proton pairing

Outline:

- *The puzzle of the missing neutron-proton pairing in nuclei*
- *Self-energy effects on n-p ($^3SD_1$) pairing energy gap*
- *Induced interaction theory (Landau limit)*
- *Vertex corrections in pairing interaction in $^3SD_1$ two-body channel*
- *Nuclear matter vs. finite nuclei*

The puzzle of neutron-proton pairing in nuclei

"The neglect of the neutron-proton interaction is the major weakness of the pairing force theory. This interaction is just as strong as that between a pair of like nucleons. In fact in the T=0 state is stronger." (A.M. Lane, Nuclear Theory, Benjamin 1964)

Later this statement received support by numerical estimates of np pairing gap in nuclear matter with realistic interactions (8-12 MeV). (for a review see U. Lombardo*, Superfluidity in nuclear matter, World Sci. 1999,Ed. M.Baldo)*

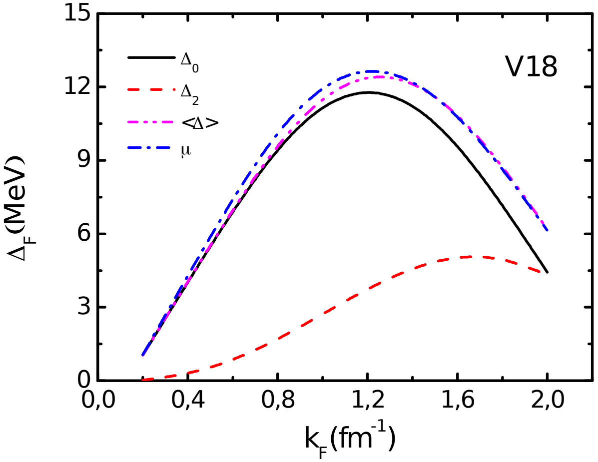
Despite the numerical predictions by A. Goodman (PRC 60,1999), no clear evidence for n-p pairing has so far been found in nuclei.

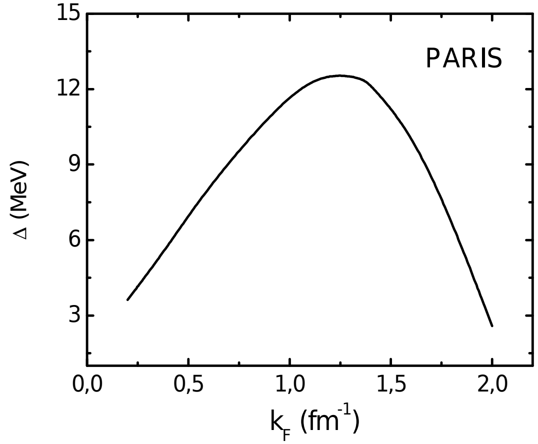
Recently, first Bertsch et al. (PRC 2010) and later Sagawa et al. (Phys.Scr. 2016) studied the competion between spin triplet and spin singlet pair correlations in nuclei
Bertsch predicted a transition from spin singlet (nn) to spin triplet (np) pairing in large N=Z nuclei (A=130-140) .

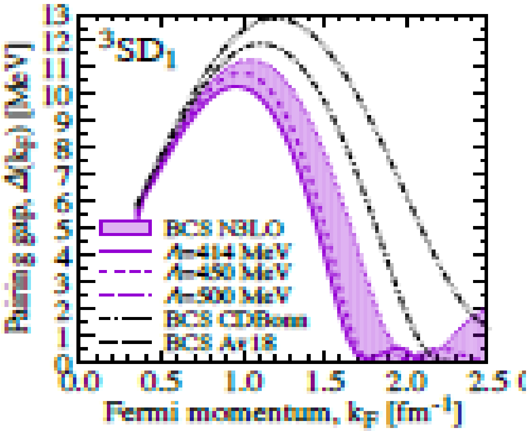
But the suppression of the np pairing in nuclei has not yet been completely understood. Possible candidates are many body effects, including self-energy and core polarization.
It is already established the role of self-energy effects (effective mass and quasi-particle strength).
The effects of core polarization have been predicted for nn and pp pairing (S=0,T=1) within the induced interaction theory either in nuclei (Milano group) and in nuclear

BARE FORCE

np pairing in SD-channel (spin-triplet)

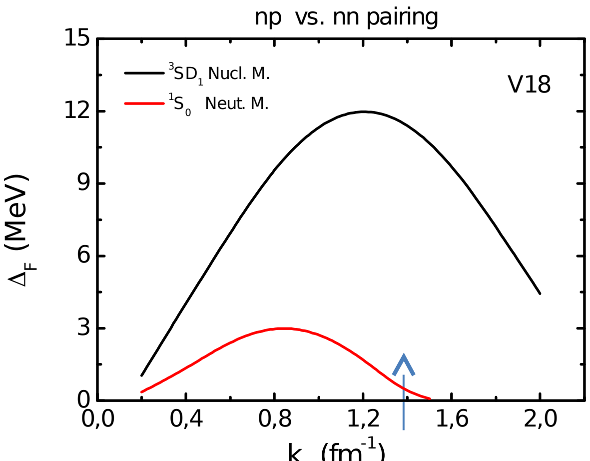






Rios et al arXiv:1707.0414

Comparison with nn pairing (spin-singlet)



> nuclear surface >

free sp spectrum

Collaboration

- Guo W.M., Lombardo U. ,INFN (LNS, Catania)
- Schulze H.-J. : INFN (sez . Catania)
- Schuck P. : U. Paris Sud (IPN, Orsay)

Gap Eqs with self-energy corrections

BCS model for coupled channels ($^3SD_1$ np pairing):

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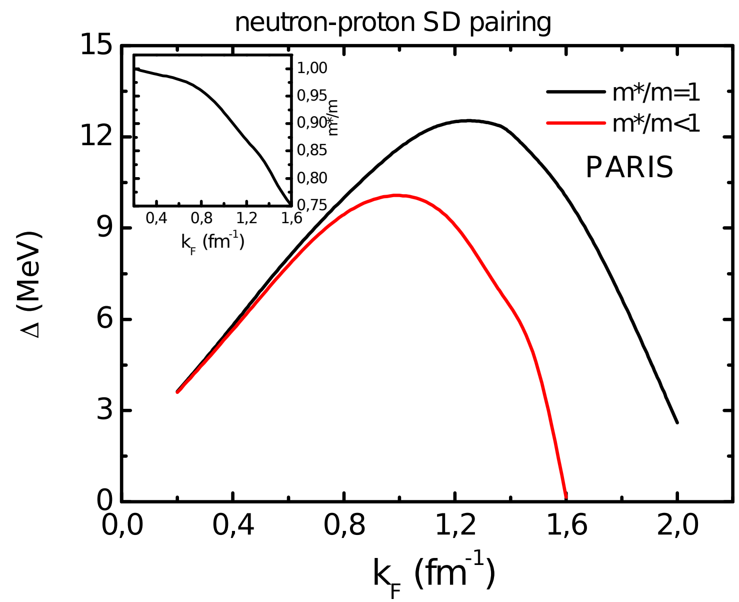
)

$$\Delta_L(k) = \Sigma_{L'} \int \quad V_{LL'}(k,k') \frac{1}{2E(k')} \Delta_{L'}(k')$$

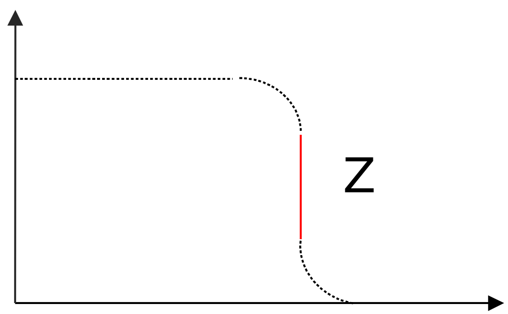
<u>effective mass</u>:

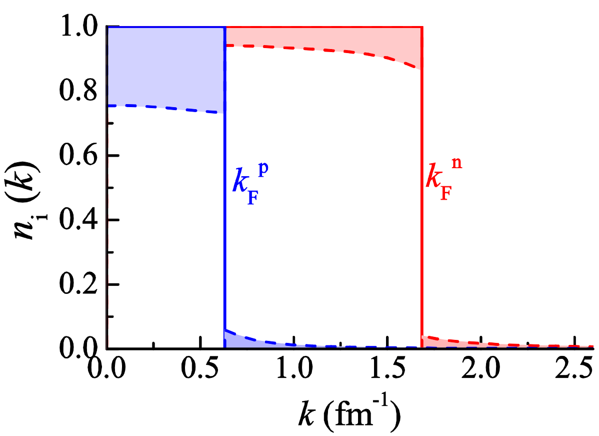
$E(k)^2 = (k^2/ 2m^* - k_F^2/2m^*)^2$
$+ \quad \Delta^2$



Quasi-Degenerate Fermi System

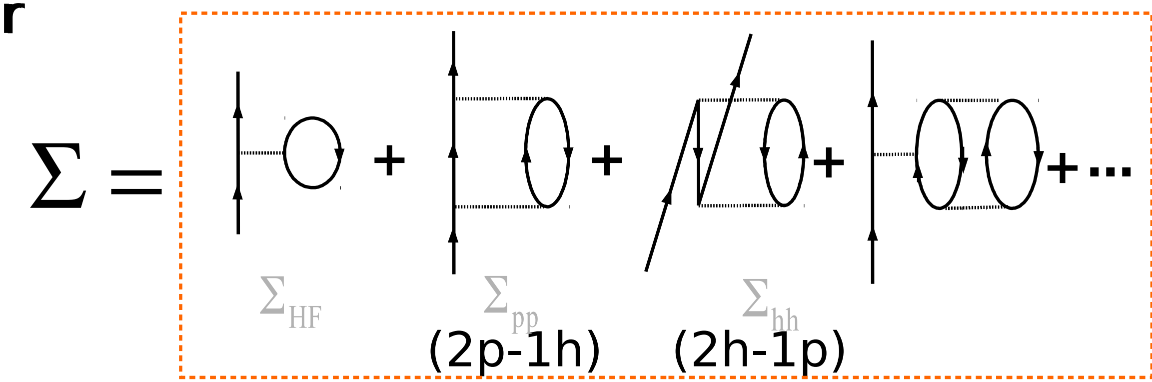
degeneracy Z-factors in asymmetric nuclear matter





Dong, 2015: 4th order

Self-energy $\Sigma_k(\omega)$



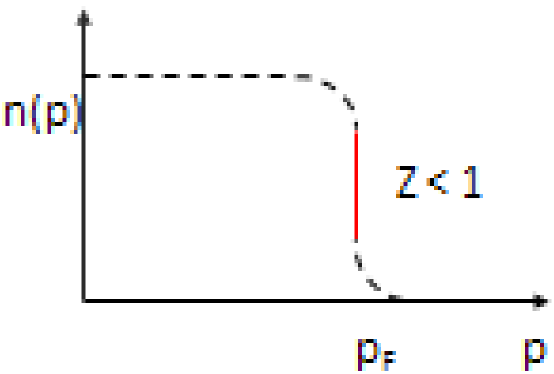
$$Z(k) = \left[1 - \frac{\partial \Sigma(k,\omega)}{\partial \omega}\right]^{-1}_{\omega=\varepsilon(k)}$$

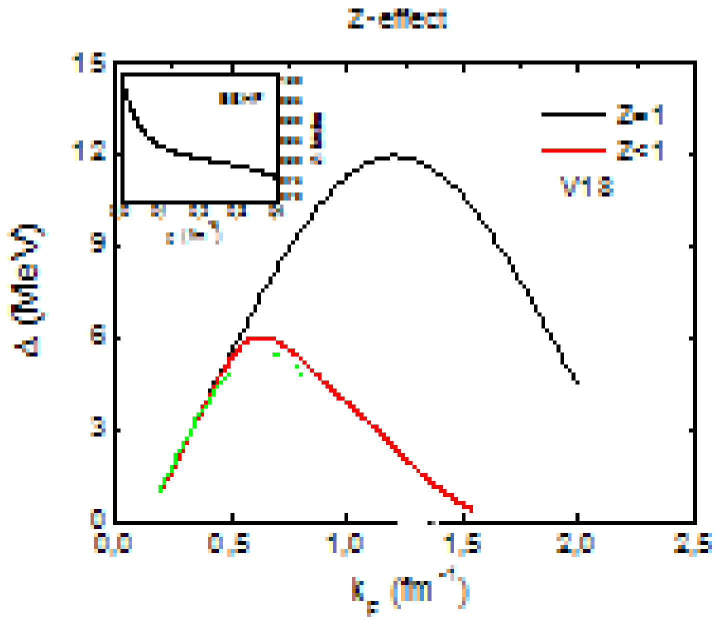
$$Z(k_F) = 1 \;?\; \Sigma_{BHF}(k,\omega) \;?\; \Sigma(k)$$

Degenerate Fermi System

Self-Energy corrections

quasi-particle strength



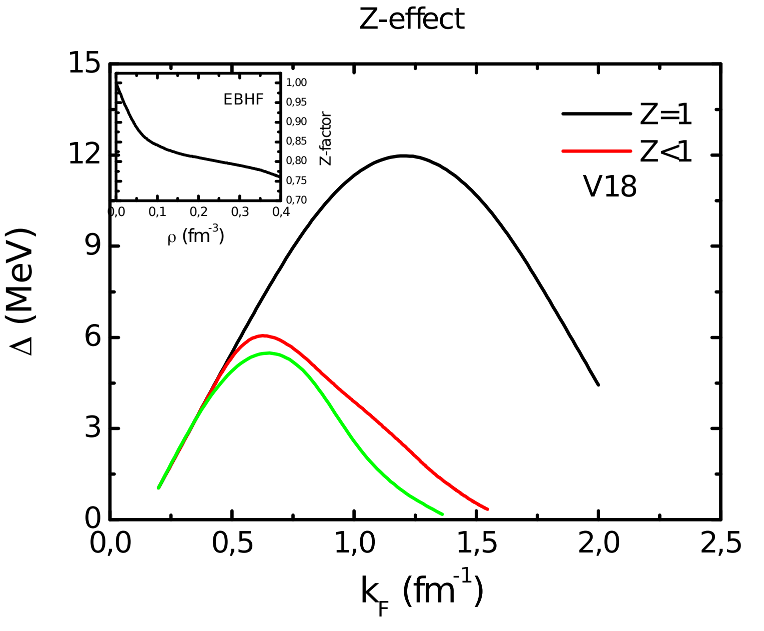


$$Z(k) = \left[1 - \frac{\partial \Sigma(k,\omega)}{\partial \omega}\right]^{-1}_{\omega=\varepsilon(k)}$$

$$Z(k_F) = 1 \rightarrow \Sigma_{BHF}(k,\omega) \equiv \Sigma(k)$$

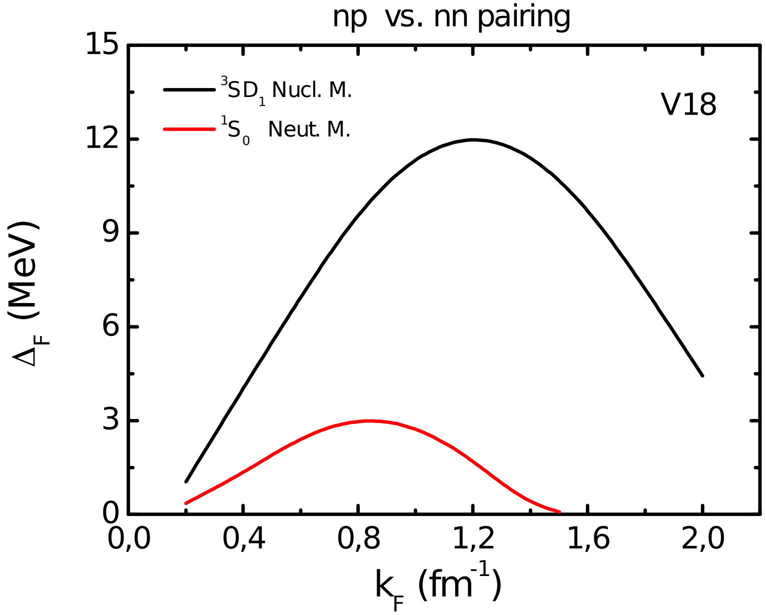
Self-Energy corrections

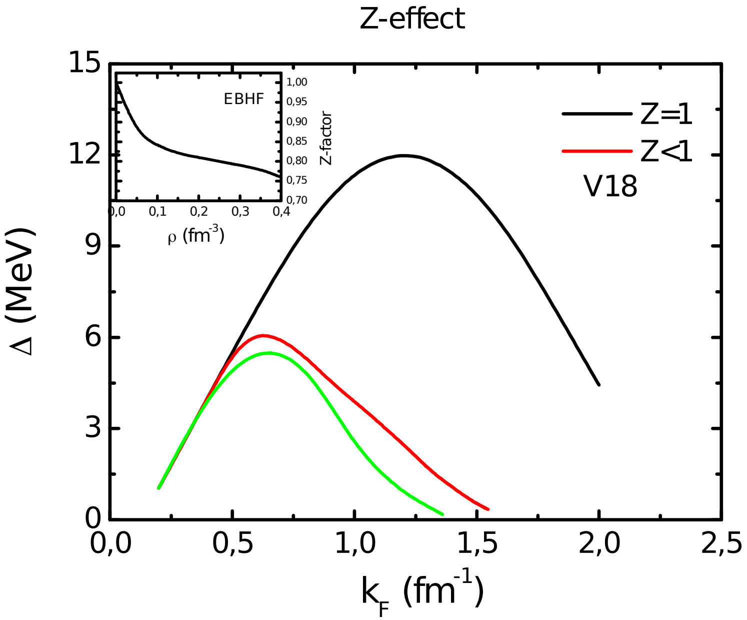
Full self-energy corrections



Self-Energy corrections

Full self-energy corrections

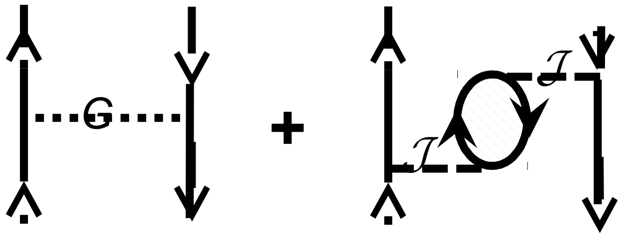




$$\Delta_{np} / \Delta_{nn} \sim 2$$

Core polarization : ph excitations within the BandB induced interaction theory

$\mathcal{J}^{ph} = G^{ph} + \mathcal{J}_i^{ph} =$



G = BHF G-matrix (LNS)

$\mathcal{J}$ = induced interaction

Λ= dressed polarization propagator(DPP)

particle-hole coupling

$$\mathcal{J}^S(q) = G^S(q) + \mathcal{J}_i^S(q)$$

$$\mathcal{J}_i^0(q) = \frac{1}{2}\sum_{S'}(2S'+1)\mathcal{J}^{S'}(q)\Lambda^{S'}(q)\mathcal{J}^{S'}(q)$$

$$\mathcal{J}_i^1(q) = \frac{1}{2}\sum_{S'}(-1)^{S'}\mathcal{J}^{S'}(q)\Lambda^{S'}(q)\mathcal{J}^{S'}(q).$$

particle-particle coupling

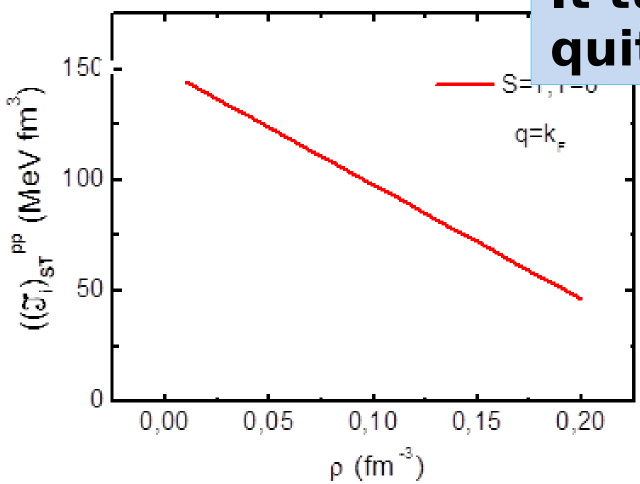
spin-singlet (e.g., neutron-neutron $^1S_0$ channel)

$$4(\mathcal{J}_i)_{01}^{pp} = \Sigma_T [(\mathcal{J}_i)_{0T}^{ph} - 3(\mathcal{J}_i)_{1T}^{ph}] = -\left(\frac{F_0^2\lambda}{1+F_0\lambda} + \frac{F'^2_0\lambda}{1+F'_0\lambda}\right) - 3\left(\frac{G_0^2\lambda}{1+G_0\lambda} + \frac{G'^2_0\lambda}{1+G'_0\lambda}\right)$$

spin-triplet (e.g., neutron-proton $^3SD_1$ channel)

$$4(\mathcal{J}_i)_{10}^{pp} = \Sigma_T [(-)^T(2T+1)((\mathcal{J}_i)_{0T}^{ph} + (\mathcal{J}_i)_{1T}^{ph})] = \left(\frac{F_0^2\lambda}{1+F_0\lambda} - \frac{F'^2_0\lambda}{1+F'_0\lambda}\right) + \left(3\frac{G_0^2\lambda}{1+G_0\lambda} - 3\frac{G'^2_0\lambda}{1+G'_0\lambda}\right)$$

It turns out tio be repulsive at any density, quite small in comparison wih bare interaction

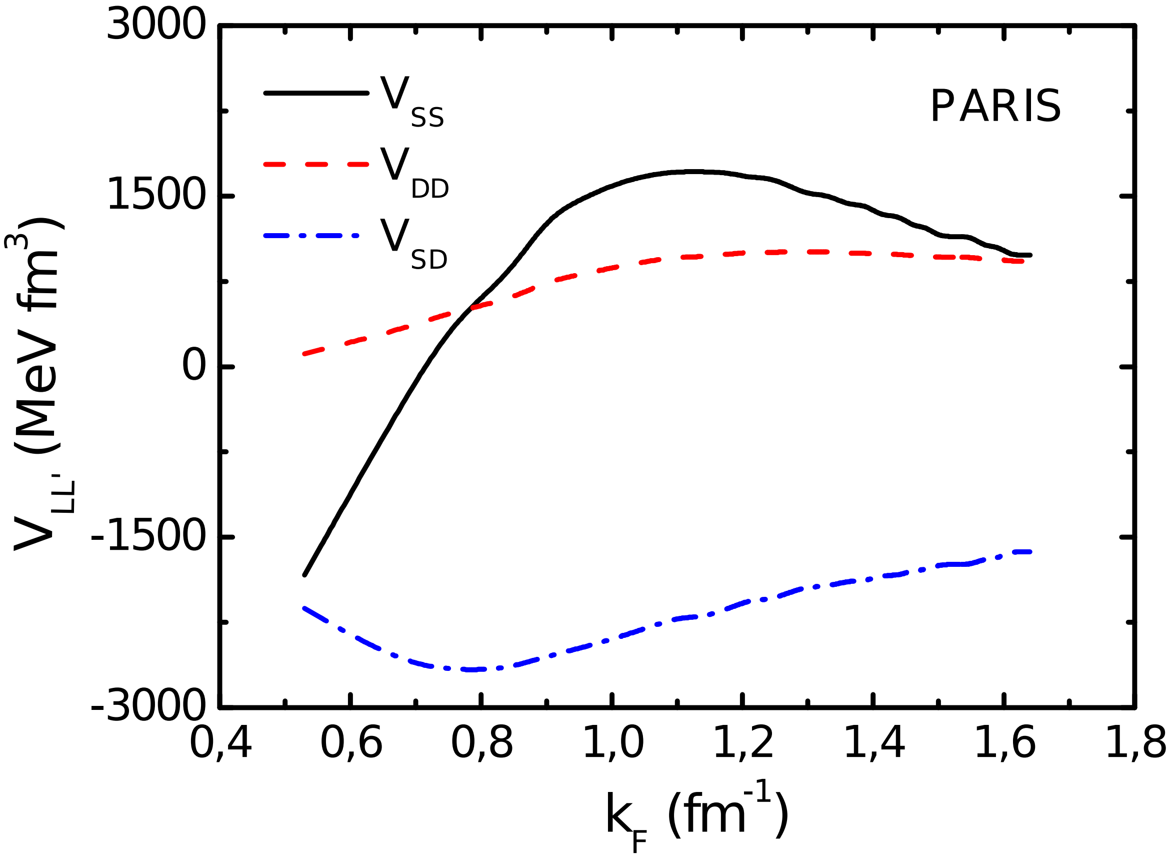


Landau limit : *:* $p = p' = p_F$

$(0 \le q \le 2p_F)$

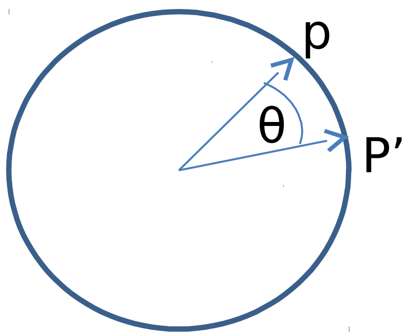
$(\mathcal{J}_i)_{10}^{pp}\ (p_F, p_F, q)$

main drawback : missing off-diagonal m.e.



3000
1500
0
-1500
-3000
0,4
0,6
0,8
1,0
1,2
1,4
1,6
1,8
V_{SS}
V_{DD}
V_{SD}
PARIS
$V_{LL'}$ (MeV fm^3)
k_F (fm^{-1})

spin-triplet Induced Interaction



Fermi surface

$q = |p - p'| = 2p_F \sin\theta/2$

partial wave expansion

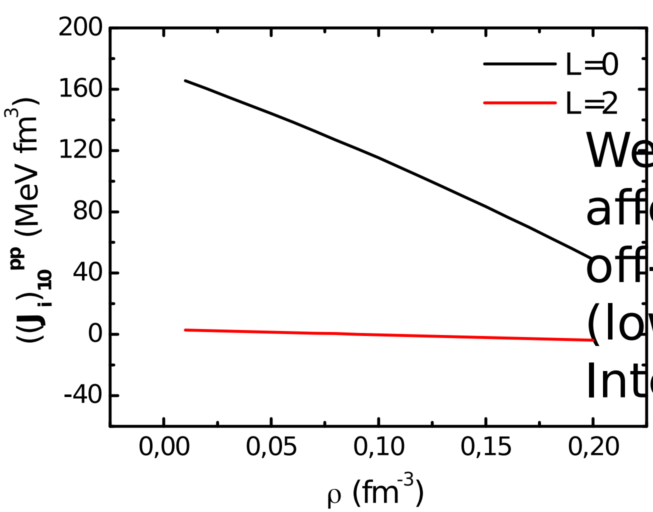
$$(\mathcal{J}_i)^{pp}{}_L = \tfrac{1}{2} \int_{-1}^{1} d\cos\theta \, P_L(\cos\theta) \, (\mathcal{J}_i)^{pp}(q)$$

$q = |p - p'| = 2p_F \sin\theta/2$

partial wave expansion

$(\mathcal{J}_i)^{pp}{}_L = \tfrac{1}{2}$

S and D partial waves



We need to understand how the induced interaction affects the pairing gap, that can be done incorporating off-diagonal m.e. of the bare interaction (low and high momentum transitions) into the pairing Interaction at the Fermi surface.

BCS model for coupled channels ($^3SD_1$ np pairing):

$$\Delta_L(k) = \Sigma_{L'} \int V_{LL'}(k,k') \frac{1}{2E(k')} \Delta_{L'}(k')$$

Renormalization of the pairing interaction:

Momentum space

I = P + Q

$$\Delta(k) = -\int_{|k-kf|<w} \mathbb{V}(k,k') \frac{1}{2E(k')} \Delta(k')$$

$$\mathbb{V}(k,k') = V(k,k') - \int_{|k-kf|>w} V(k,k'') \frac{1}{2E(k'')} \mathbb{V}(k'',k')$$

Two main advantages:

The constant gap approximation is a good approximation in the case of weak coupling ($\Delta \ll \varepsilon_F$) . In the strong coupling limit it can be applied if w is small enough.

The window gap equation makes it more unstandable the role of off-diagonal matrix elements of the pairing interaction vs. , in particular

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Numerical procedure

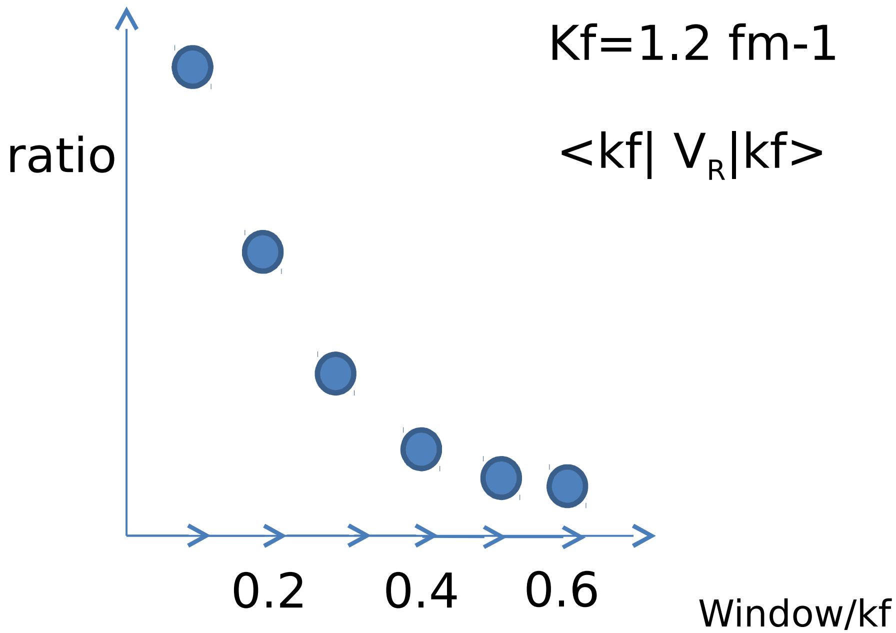
For $w \ll kf$ we can assume $\Delta(k) \sim \Delta(kf)$ and the gap eqs. go over into a coupled system of (non-linear) algebraic equations:

$$\Delta_0(kf) = -\Delta_0(kf) \int_{|k-kf|<w} \mathbb{V}_{00}(k,k') \frac{1}{2E(k')} - \Delta_2(kf) \int_{|k-kf|<w} \mathbb{V}_{02}(k,k') \frac{1}{2E(k')}$$

$$\Delta_2(kf) = -\Delta_0(kf) \int_{|k-kf|<w} \mathbb{V}_{20}(k,k') \frac{1}{2E(k')} - \Delta_2(kf) \int_{|k-kf|<w} \mathbb{V}_{22}(k,k') \frac{1}{2E(k')}$$

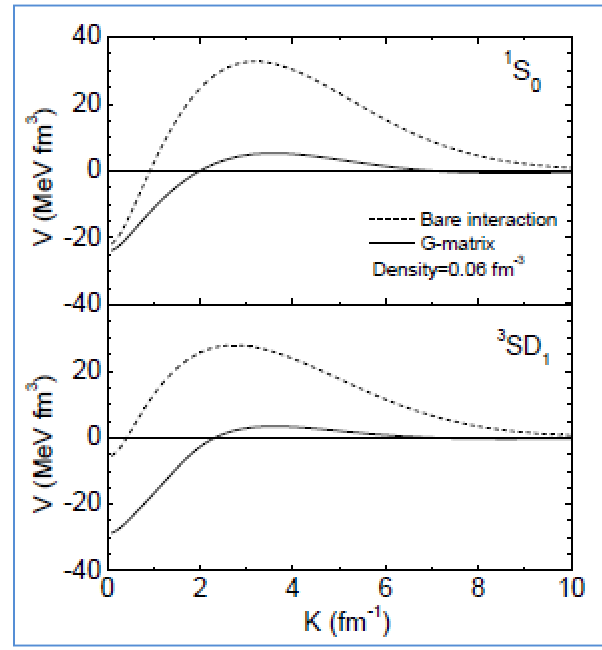
where $E^2(k) = (\varepsilon_k - \varepsilon f)^2 + (\Delta^2_0(kf) + \Delta^2_2(kf)) \equiv (\varepsilon_k - \varepsilon f)^2 + \Delta^2(kf)$. It can be numerically solved along with equations for the renormalized interaction by means of linearization and iteration.

Off-diagonal matrix elements V(kf,k)



Kf=1.2 fm-1

$<kf|\ V_R|kf>$



$(\mathcal{J}_i)_{10}{}^{pp} << \ <kf\ |V_R\ ||kf\ >$

No appreciable effect expected!

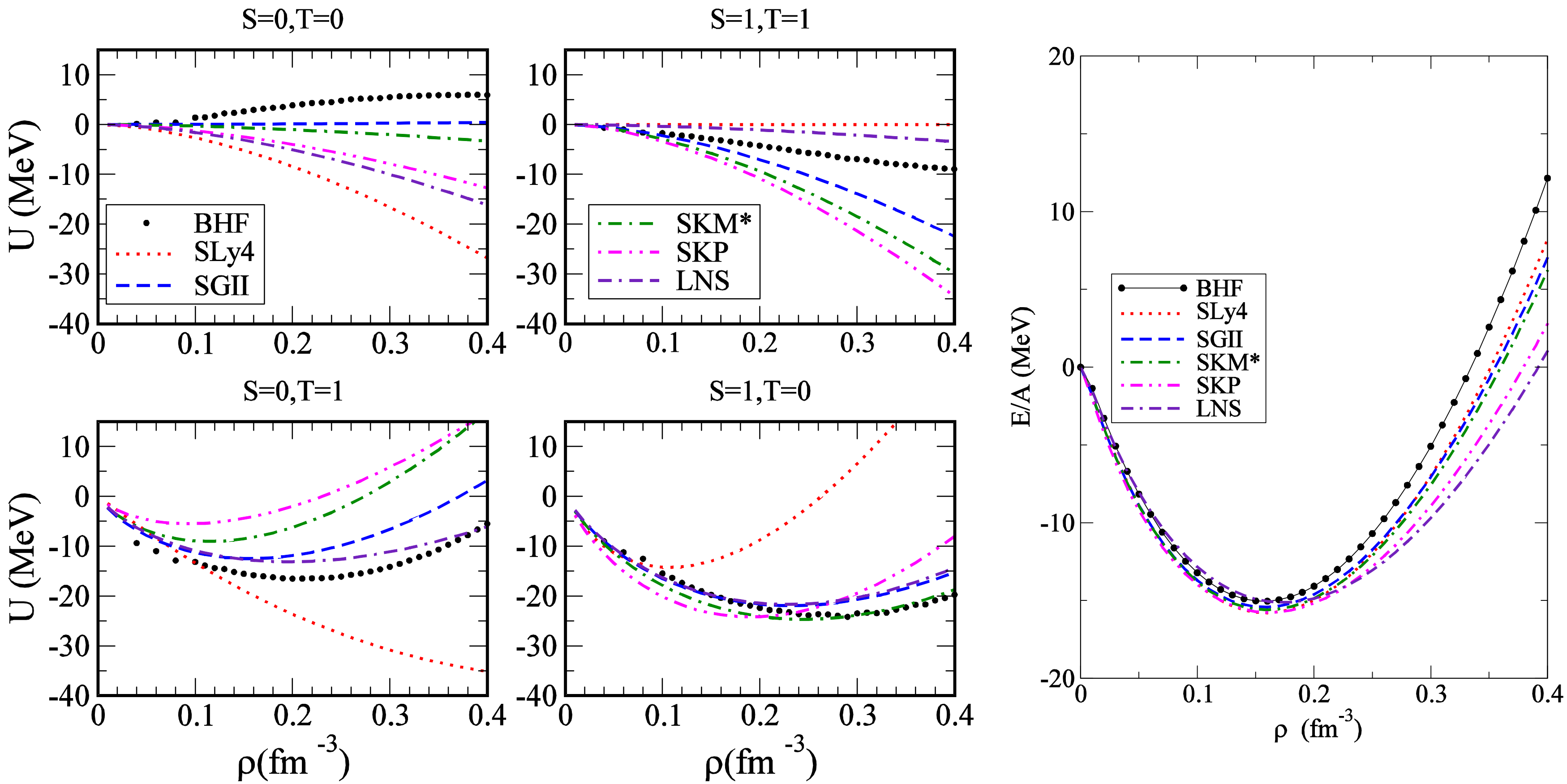
nclusions:

ere is a general consensus that self-energy corrections conspire against kinds of pair correlations, including the neutron proton 3SD1 pairing. nuclear matter they severely reduce the pairing gaps and shink the pairing main to lower densities, typical of nuclear surface

e vertex corrections could provide a screening to the pair interaction d could be good candidates to solve the puzzle of the missing neutron-proton ps in nuclei . We found in fact that , in the deuteron channel, they have a repuls ect in contrast with what happens in the case of 1S0 channel. However we foun negligible effect in the approximation adopted in the present calcs.

proaches in finite nuclei attribute the missing np pairing to the spin-orbit splittin t for N=Z very heavy nuclei a crossover from nn (pp) pairing to np pairing is edicted . This result is consistent with the present calculation.

Isospin splitting of potential energy
(BHF: Bonn+3BF)



E/A= K + U

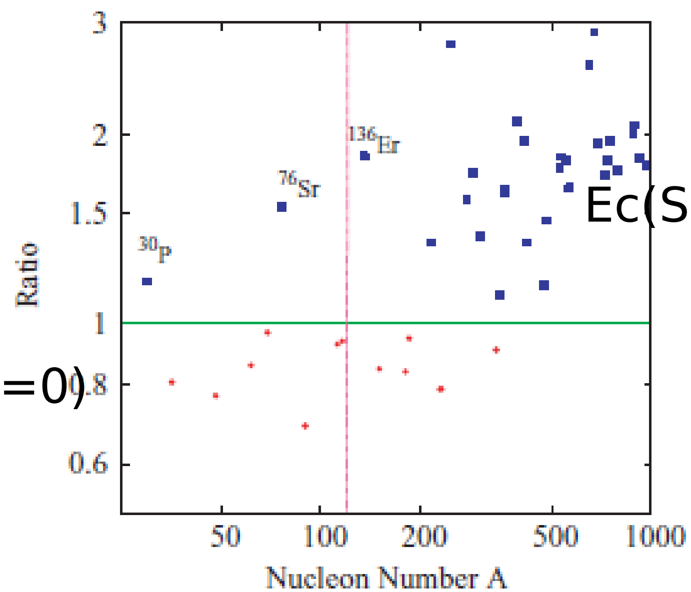
a_S (ρ)=U(ρ ,β=1)- U(ρ ,β=0)

Strong

compensation for SLy4 Tensor component U_{10} the largest

ChEFT: U_{10}≈U_{SD}≈-17 MeV (Kohno,2013)

Correlation energies $Ec_{S=1}/Ec_{S=0}$

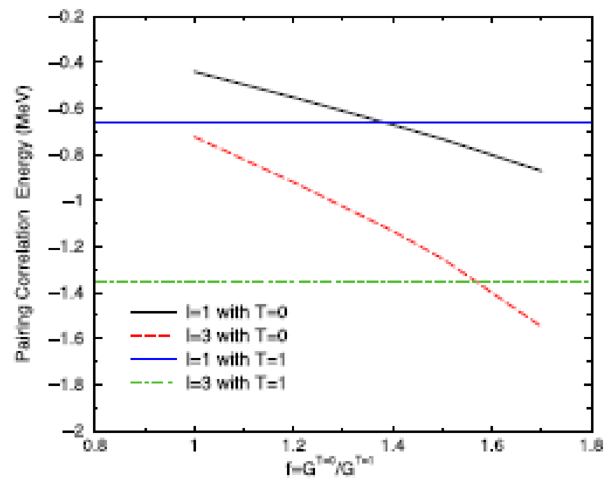


Ec(S=1) > Ec(S=0)

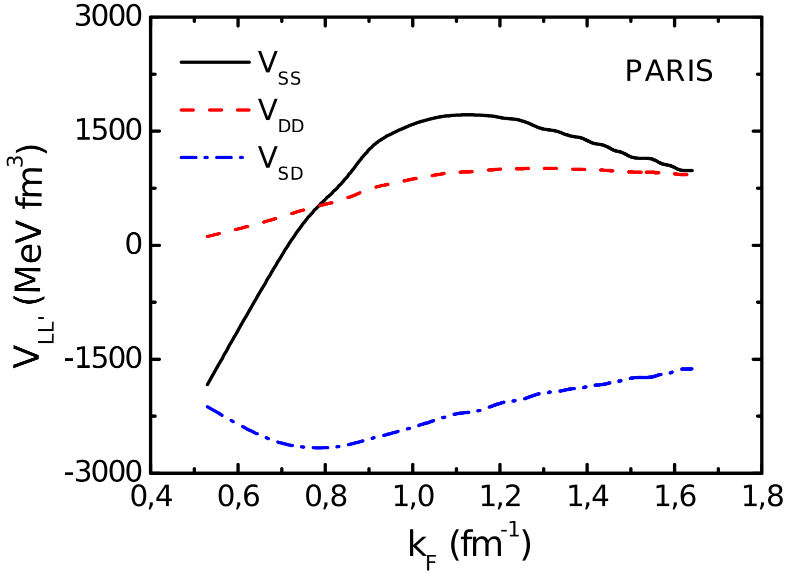
Ec(S=1) < Ec(S=0)

Bertsch et al. PRC 81 (2010)

Sagawa et al. Phys.Scr.91,2016



Xavier,
Welcome into the club of die-hard physicists!



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V_SS
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PARIS
V_LL' (MeV fm^3)
k_F (fm^-1)