SUPERFLUIDITY IN NUCLEAR SYSTEMS

Enrico Vigezzi
INFN Milano

- Pairing interaction induced by the exchange of collective vibrations

- Two-particle transfer and the Josephson effect

PHYSICAL REVIEW C **72**, 054314 (2005)

Pairing matrix elements and pairing gaps with bare, effective, and induced interactions

F. Barranco,[1] P. F. Bortignon,[2,3] R. A. Broglia,[2,3,4] G. Colò,[2,3] P. Schuck,[5] E. Vigezzi,[3] and X. Viñas[6]

https://www.sif.it/riviste/sif/sag/ricordo/broglia

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Italian Physical Society

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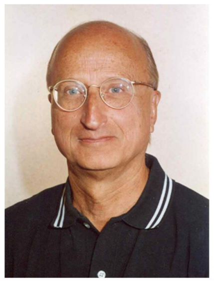
Ricardo Americo Broglia (1939-2022)

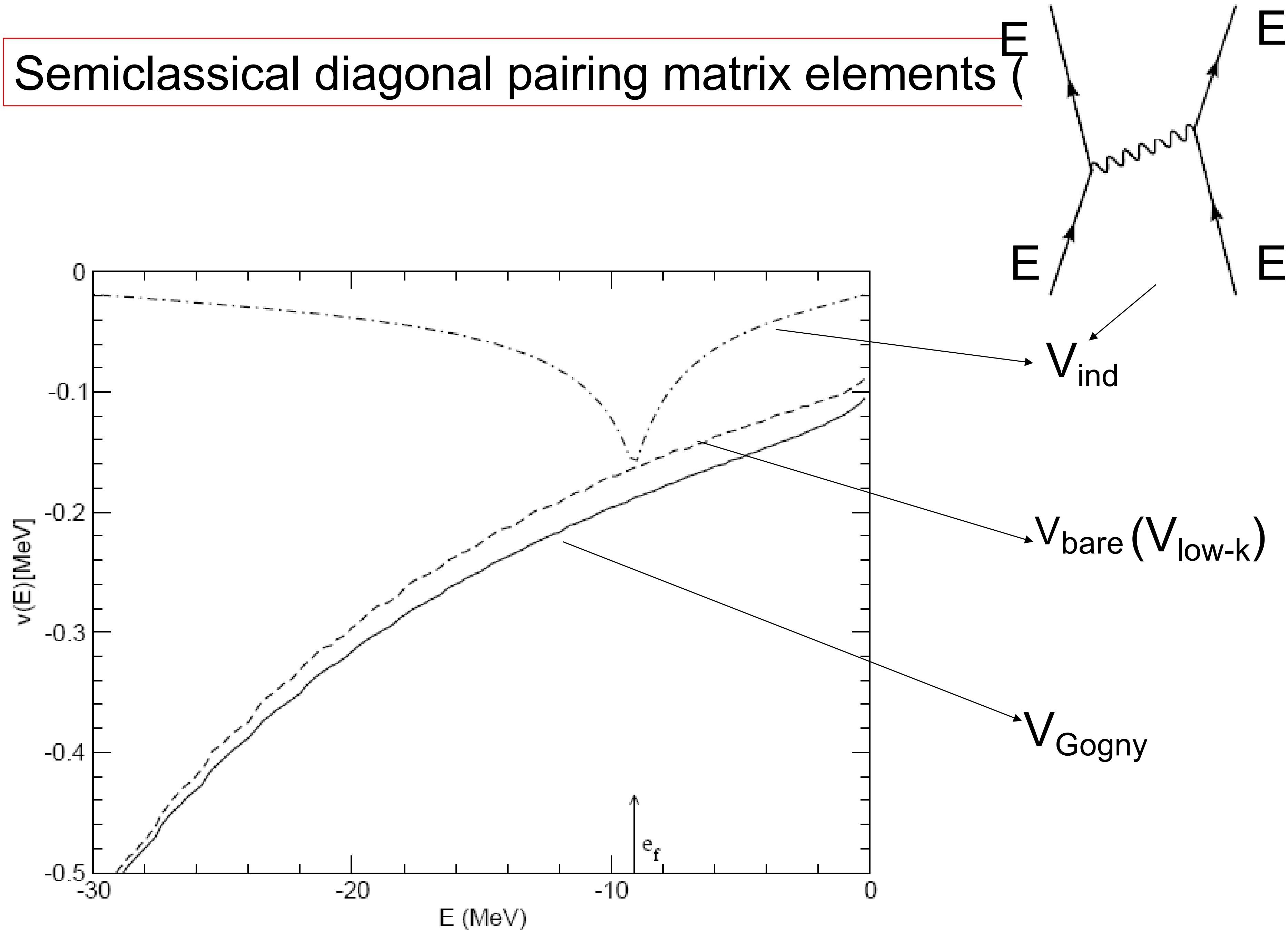
STAMPA CONDIVIDI LINK



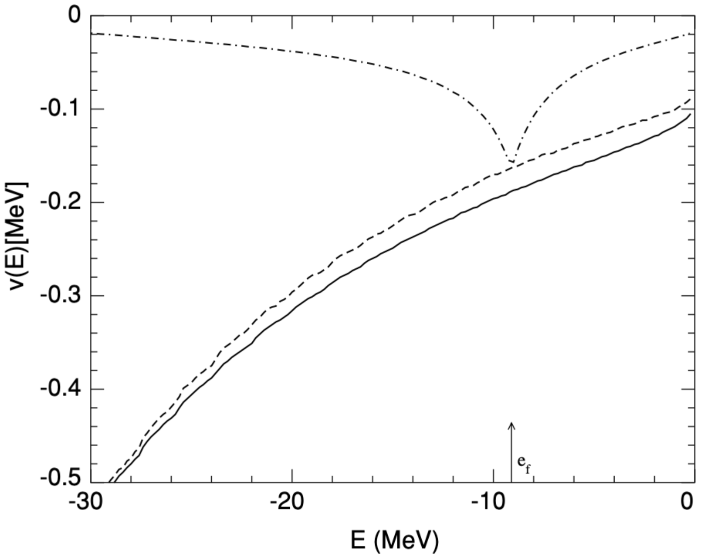
We started working with Ricardo in 1983- 1984, when we went to Copenhagen after our master's degree, and we have collaborated with him without interruption until his death on October 4th, 2022. In the following, we provide an outline of his scientific activity. This is not an easy task, because Ricardo coauthored around 500 papers, collaborating with around 150 theorists and with many experimentalists as well. A comprehensive curriculum can be found at the following link: https://home. mi.infn.it/broglia_CV.pdf

Ricardo Americo Broglia was born in Cordoba, Argentina, in 1939. He started his Master studies at Instituto Balseiro of the University of Cuyo in Bariloche and then went to Buenos Aires to pursue his Ph.D. under the supervision of Daniel R. Bès. This is how he later recollected those years:

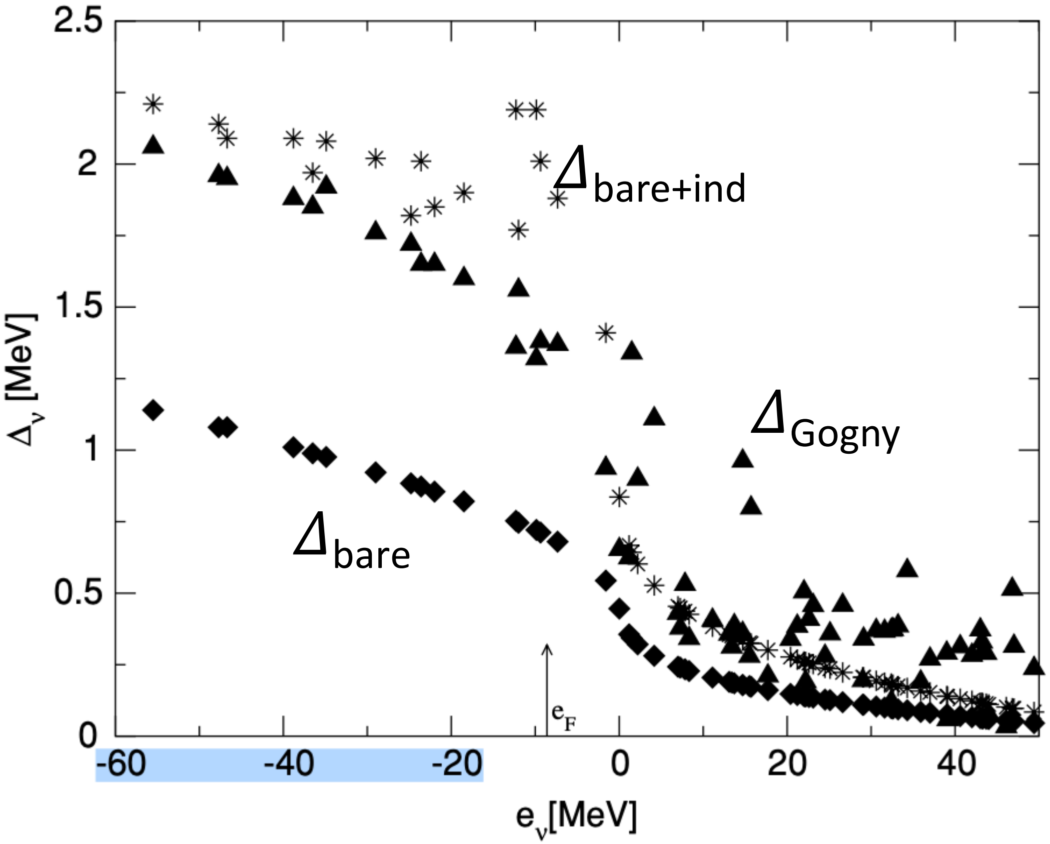
Semiclassical diagonal pairing matrix elements (



F. Barranco et al., Phys. Rev. 72(2005)054314

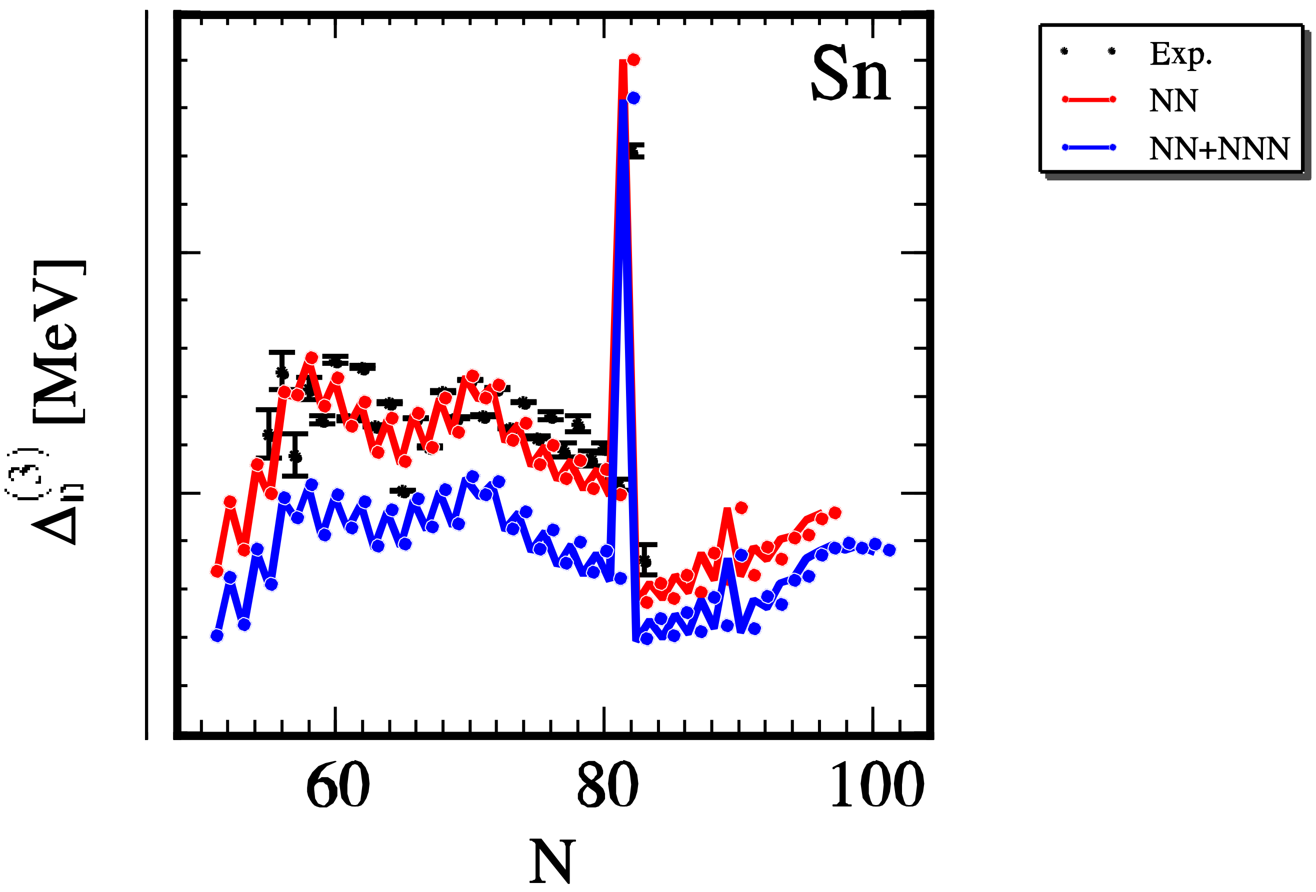


v(E)[MeV]
E (MeV)
e_f



$\Delta_{bare+ind}$
Δ_{Gogny}
Δ_{bare}
Δ_ν [MeV]
e_ν[MeV]
e_F

Mean field calculation with low-momentum 2N and 3N interactions: 3-body force reduces the pairing gaps



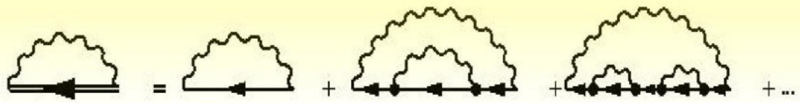
T. Lesinski, K. Hebeler, T. Duguet, A.Schwenk, J. Phys. G 39 (2012) 015108

NFT has been mostly used in normal nuclei.
Extension to superfluid, spherical nuclei within the Nambu-Gor'kov formalism
(cf. Van der Sluys et al., NPA551(1993)210)

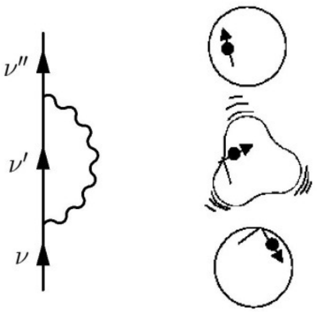
By extending the Dyson equation…

$$G_{\mu}^{-1}=(G_{\mu}^{o})^{-1}-\Sigma_{\mu}(\omega)$$

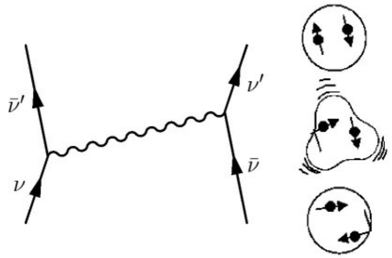
$$\Sigma_{\mu}(\omega)=\int_{-\infty}^{+\infty}\frac{d\omega'}{2\pi}\sum_{\mu'}\frac{1}{\hbar}G_{\mu'}(\omega')\sum_{\alpha}\frac{1}{\hbar}D_{\alpha}^{o}(\omega-\omega')*V^{2}_{\mu\mu',\alpha}$$



to the case of superfluid nuclei (Nambu-Gor'kov), it is possible to consider both



and

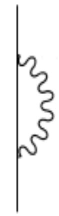


Renormalization of BCS quasiparticle energies and pairing gap

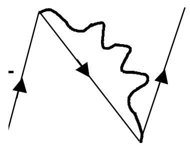
A. Idini et al., PRC 85 (2012) 014331

$$\begin{pmatrix} E_a + \Sigma_{11}(\tilde{E}_{a(n)}) & \Sigma_{12}(\tilde{E}_{a(n)}) \\ \Sigma_{12}(\tilde{E}_{a(n)}) & -E_a + \Sigma_{22}(\tilde{E}_{a(n)}) \end{pmatrix} \begin{pmatrix} x_{a(n)} \\ y_{a(n)} \end{pmatrix} = \tilde{E}_{a(n)} \begin{pmatrix} x_{a(n)} \\ y_{a(n)} \end{pmatrix}$$

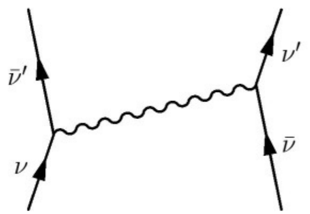
$$\Sigma_{11} = \sum_{b,m,J,\nu} \frac{V^2(a(n)b(m)J\nu)}{\tilde{E}_{a(n)} - \tilde{E}_{b(m)} - \hbar\omega_{J\nu}} +$$



$$\sum_{b,m,J,\nu} \frac{W^2(a(n)b(m)J\nu)}{\tilde{E}_{a(n)} + \tilde{E}_{b(m)} + \hbar\omega_{J\nu}}$$



$$\Sigma_{12}(\tilde{E}_{a(n)}) = -\sum_{b,m,J,\nu} V(a(n),b(m),J,\nu)W(a(n),b(m),J,\nu)$$
$$\left[\frac{1}{\tilde{E}_a(n) - \tilde{E}_b(m) - \hbar\omega_{J,\nu}} - \frac{1}{E_a(n) + \tilde{E}_b(m) + \hbar\omega_{J,\nu}}\right].$$

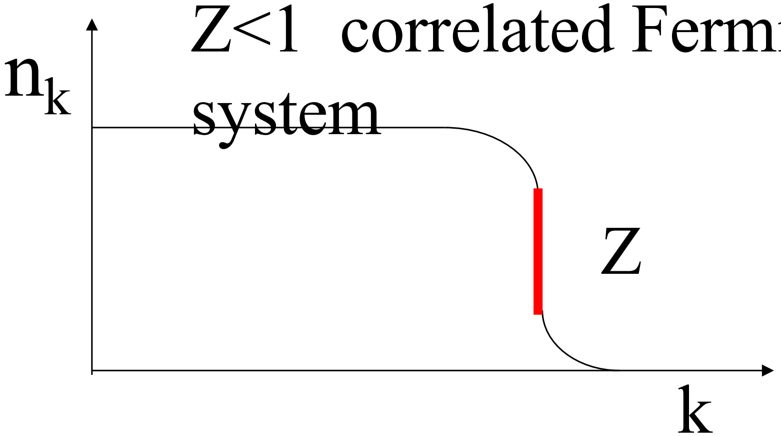


$$\begin{aligned} V(ab(m)\lambda\nu) &= h(ab\lambda\nu)(u_a^{BCS}\tilde{u}_{b(m)} - v_a^{BCS}\tilde{v}_{b(m)}) & \tilde{u}_{a(n)} &= x_{a(n)}u_a^{BCS} - y_{a(n)}v_a^{BCS} \\ W(ab(m)\lambda\nu) &= h(ab\lambda\nu)(u_a^{BCS}\tilde{v}_{b(m)} + v_a^{BCS}\tilde{u}_{b(m)}) & \tilde{v}_{a(n)} &= x_{a(n)}v_a^{BCS} + y_{a(n)}u_a^{BCS}, \end{aligned}$$

Generalized Gap Equation (schematic)

Z=1 free Fermi gas

Z<1 correlated Fermi system



Quasiparticle strength <1

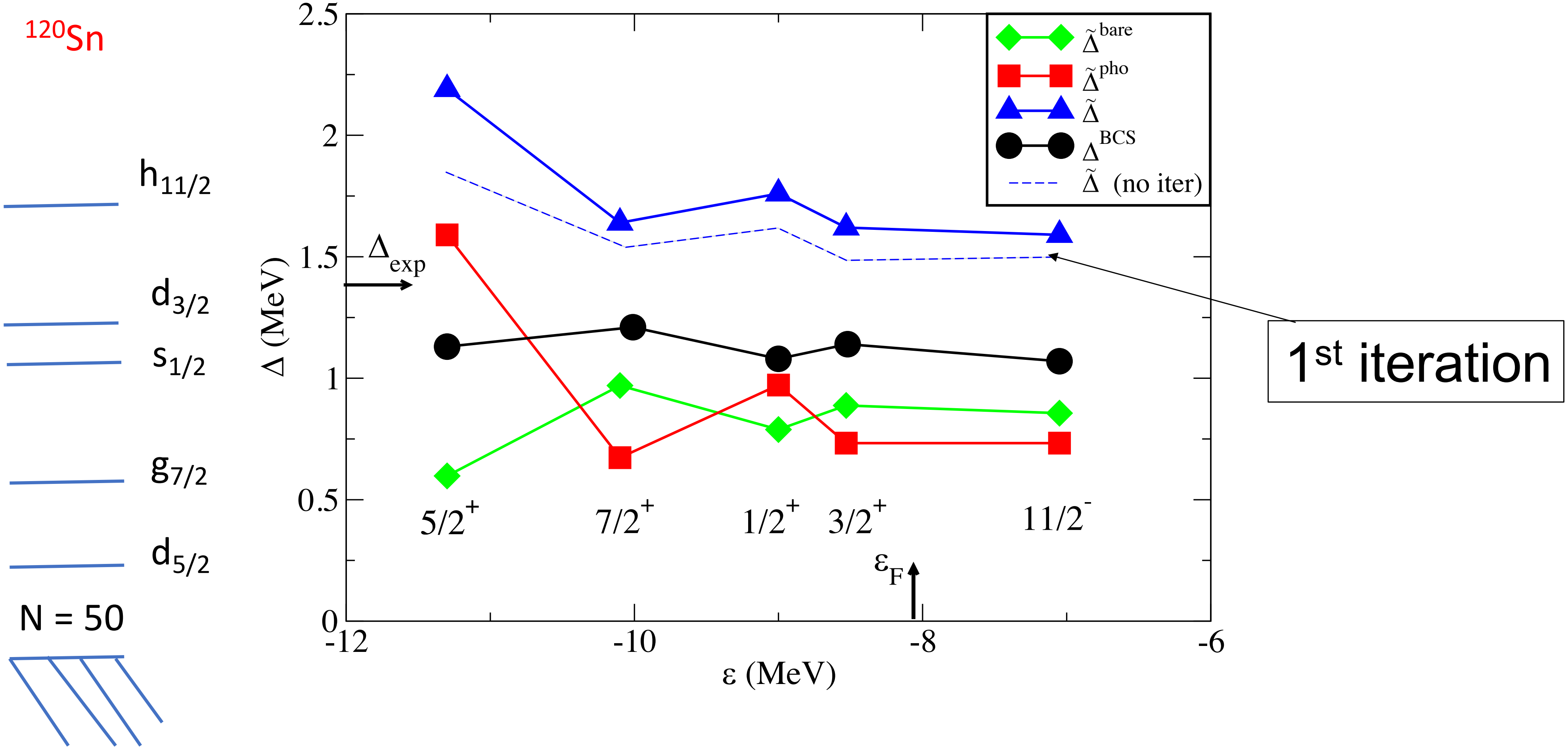
Pairing interaction

$$\Delta_p = -\frac{1}{2}\int d^3p' \frac{Z_p V_{pp'} Z_{p'}}{\sqrt{(\varepsilon_{p'}-\varepsilon_F)^2+\Delta_{p'}^2}}\Delta_{p'}$$

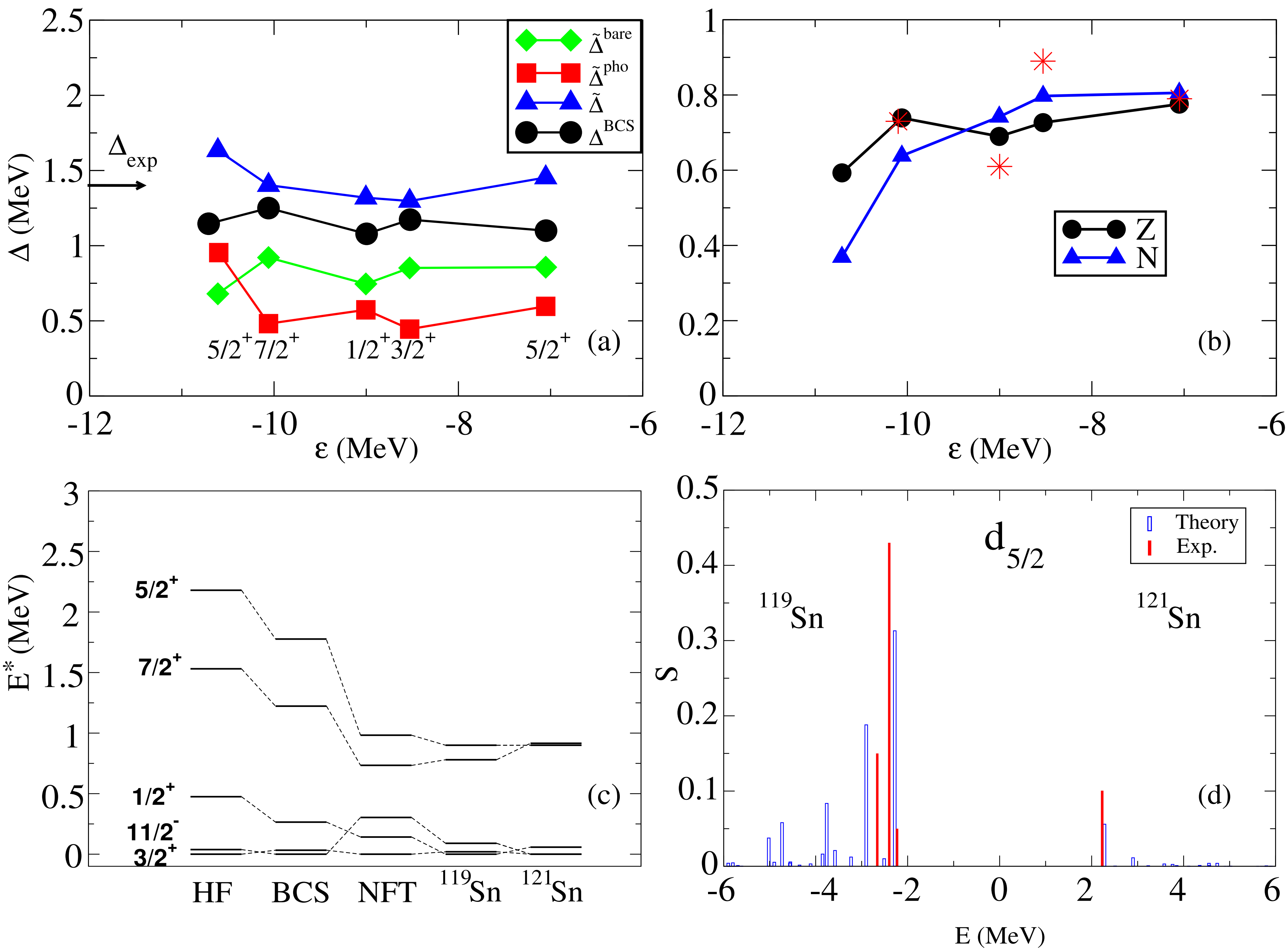
Sensitive to effective mass

Migliorare

Renormalization of BCS pairing gap for states close to the Fermi energy (single node approximation, SLy4 mean field)



Experimental phonons were used for natural parity modes with λ=2,3,4,5



(a)
Δ (MeV)
ε (MeV)
$\tilde{\Delta}^{bare}$
$\tilde{\Delta}^{pho}$
$\tilde{\Delta}$
Δ^{BCS}
Δ_{exp}
5/2+ 7/2+ 1/2+ 3/2+ 5/2+
(b)
ε (MeV)
Z
N
(c)
E* (MeV)
5/2+
7/2+
1/2+
11/2-
3/2+
HF
BCS
NFT
119Sn
121Sn
(d)
S
E (MeV)
Theory
Exp.
d5/2
119Sn
121Sn

Many-Body Perturbation Theory

Holt, Menendez,Schwenk, J. Phys. G 40 (2013) 075105

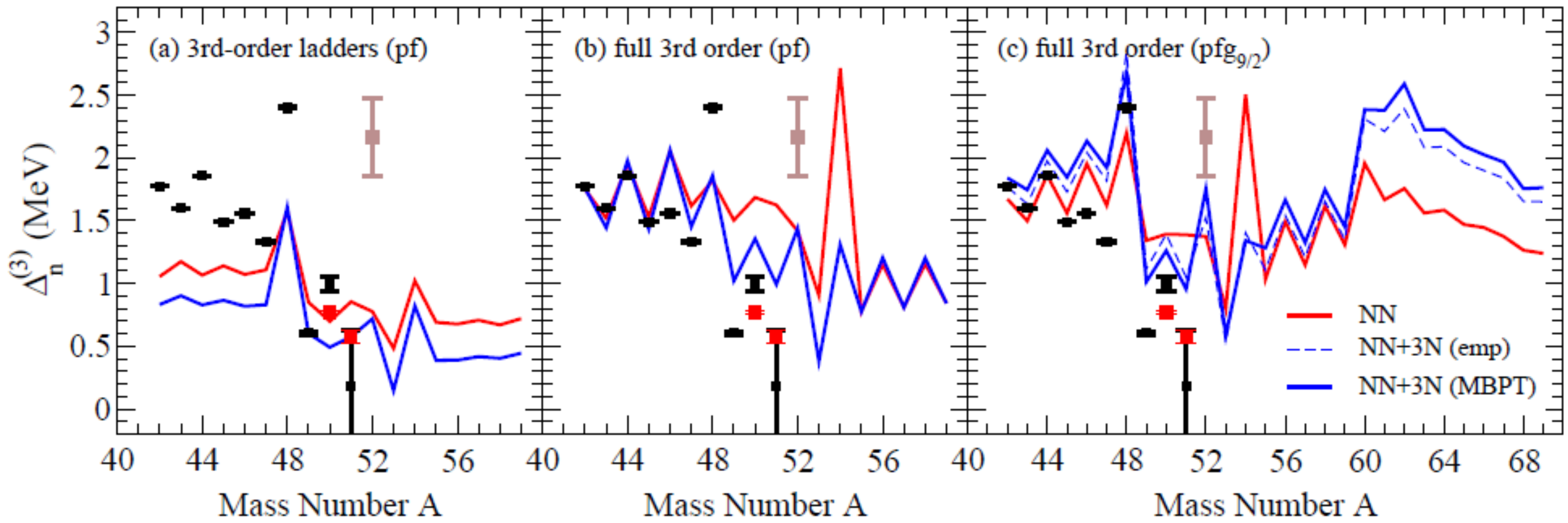


FIG. 3. (Color online) Three-point mass differences $\Delta_n^{(3)}$ in the calcium isotopes calculated to third order in MBPT with and without the leading chiral 3N forces, and in comparison with experiment [24, 67]. The legend is as in Fig. 1. Panel (a) shows the results of the third-order ladder contributions. Panels (b) and (c) include all MBPT diagrams to third order in the pf-shell and the extended $pfg_{9/2}$ valence space, respectively. The results in the pf-shell are with empirical SPEs. For the $pfg_{9/2}$ space, we show pairing gaps for both the MBPT and empirical SPEs.

When particle-hole contributions are included in a full third-order calculation, we find in Fig. 3 a clear improvement compared to including only ladder diagrams. In the pf-shell, the three-point mass differences are increased, leading to reasonable agreement with experimental data. This clearly demonstrates the importance of particle-hole many-body processes, such as core-polarization, on pairing in nuclei. Our results show that they can provide the missing pairing strength required to reproduce experiment on top of the direct NN+3N interactions. Analogously, the systematic differences between theoretical and experimental pairing gaps found in the EDF approach of Ref. [15] may be attributed to these effects.

PHYSICAL REVIEW C **102**, 034310 (2020)

Many-body correlations in nuclear superfluidity

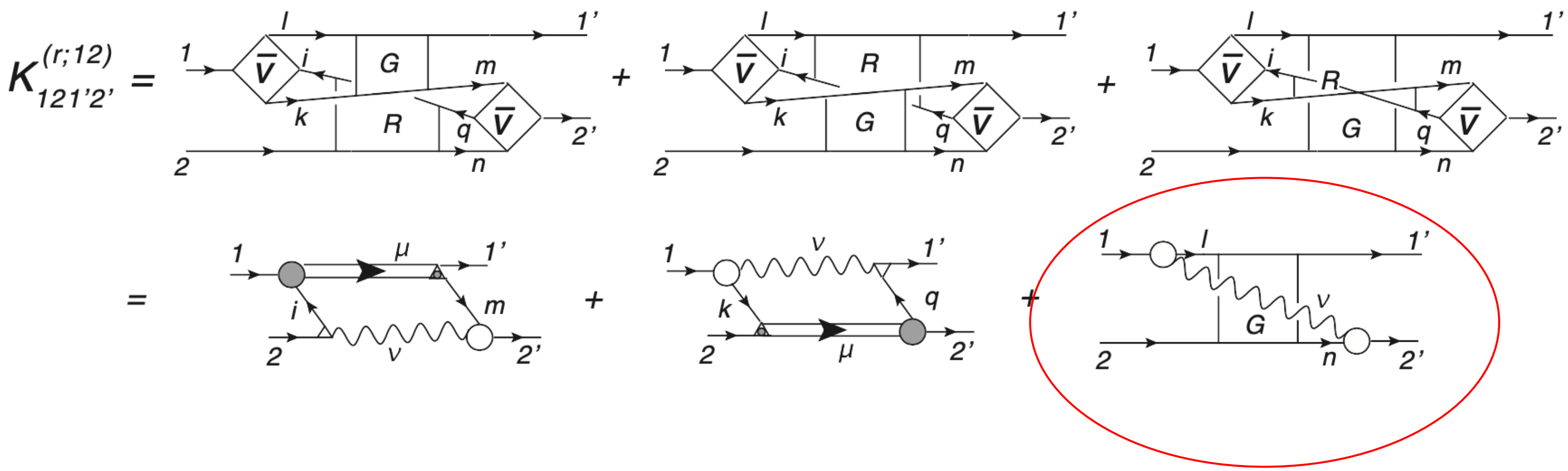
Elena Litvinova[1,2,3] and Peter Schuck[4,5]

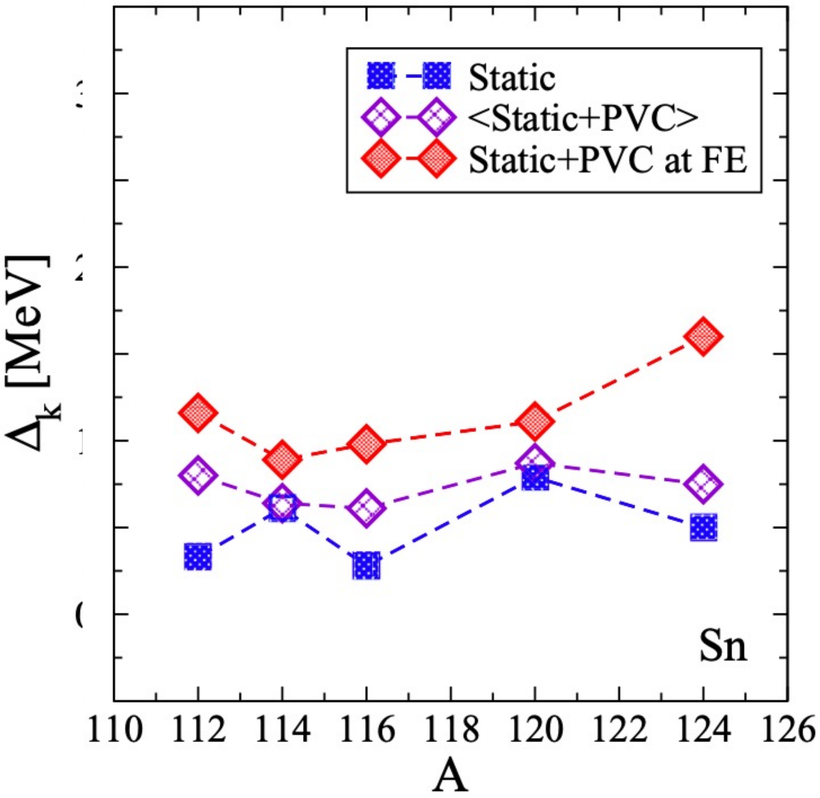
$$\Delta_1 = -\sum_2 \mathcal{V}_{1\bar{1}2\bar{2}} \frac{\Delta_2}{2E_2}, \tag{66}$$

where the bar denotes the conjugate or the time-reversed state [7] and the interaction matrix elements read

$$\mathcal{V}_{121'2'} = \frac{1}{4}\sum_{34} \delta_{1234} K_{341'2'}(2\lambda) = \frac{1}{2}\Big[K^{(0)}_{121'2'} + K^{(r)}_{121'2'}(2\lambda)\Big]. \tag{67}$$

The integral part of the gap Eq. (66), thus, contains all the microscopic effects of the kernel K "on shell," regardless of the approximations made for its static $K^{(0)}$ and dynamical $K^{(r)}$ parts.





Static
<Static+PVC>
Static+PVC at FE
Sn
Δ_k [MeV]
A
110 112 114 116 118 120 122 124 126

PHYSICAL REVIEW C **105**, 044330 (2022)

Gorkov algebraic diagrammatic construction formalism at third order

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Thomas Duguet
IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
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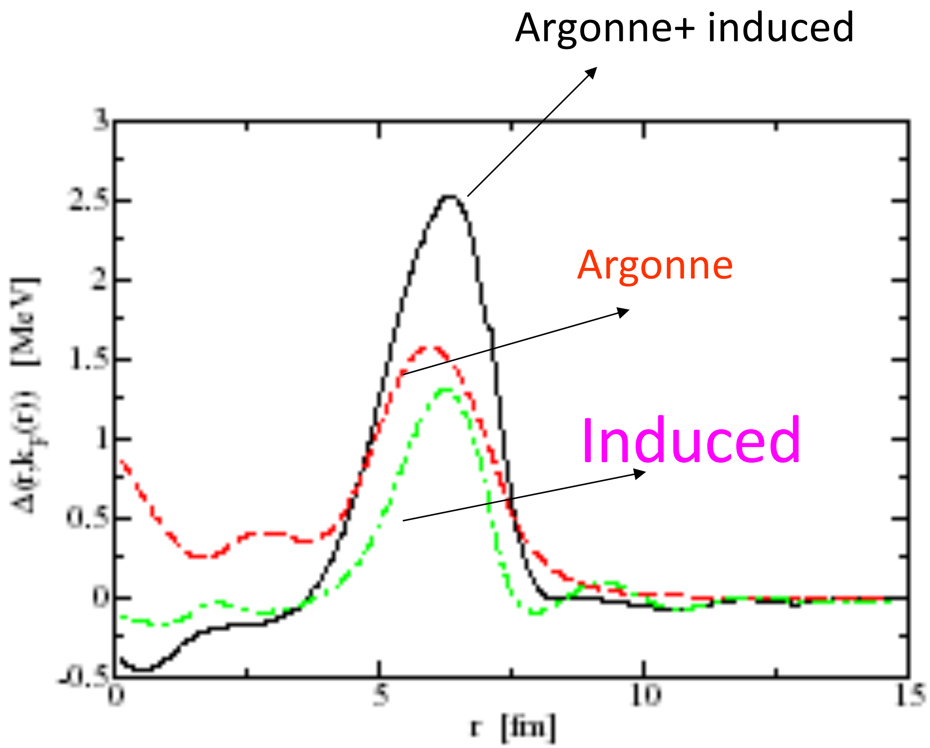
Vittorio Somà
IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

Local approximation



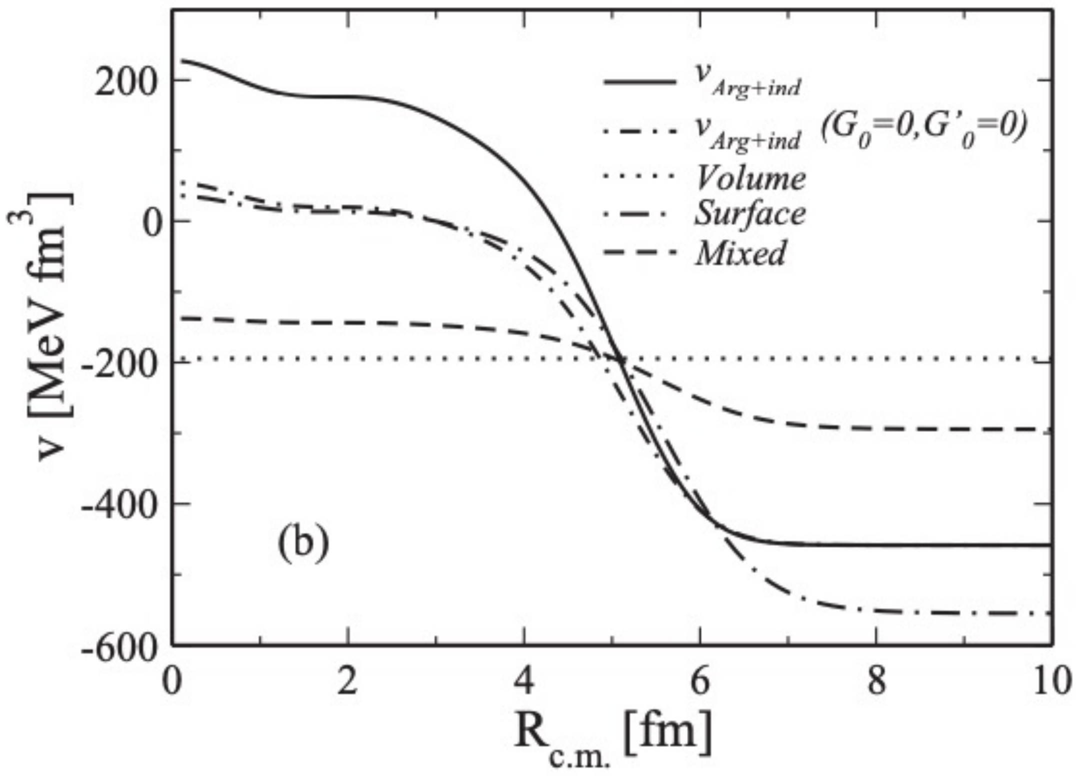
The pairing gap associated with the bare interaction is surface peaked;
the induced interaction reinforces this feature

Microscopic justification of surface peaked, density-dependent pairing force

A. Pastore et al., Phys. Rev. C78 (2008) 024315

Interaction	α	η
v_{Arg}	0.66	0.84
$v_{\mathrm{Arg+ind}}$	2.0	1.32

$$v^{\delta}(\vec{r}_1,\vec{r}_2)=v_0\left[1-\eta\left(\frac{\rho\left(\frac{\vec{r}_1+\vec{r}_2}{2}\right)}{\rho_0}\right)^{\alpha}\right]\delta(\vec{r}_1-\vec{r}_2),$$



A. Pastore et al., Phys. Rev. C78 (2008) 024315

One of the basic questions about nuclear pairing is the role of induced interactions in the effective pairing interaction [5,54–57]. Indirect information about this can in principle be obtained by exhibiting the density dependence and the isospin dependence of the effective interaction. It is therefore of interest to examine interactions including a density dependence to see the sensitivity.
The rms residual for the neutron OES with volume, mixed, and surface pairing in HF+BCS theory are shown in Table IV. There is a slight favoring of the surface interaction, but we deem that the difference in the residuals (10%) is too slight to be significant.
The weak sensitivity to the density dependence confirms the results of other studies [10,58].
G.F. Bertsch et al., PRC 79 (2009) 034306

Binding energies do not provide a clean measure of pairing correlations since they have contributions which are not directly related to them. These include the impact of (quasi)particle-vibrational coupling on the binding energies of odd-mass nuclei. The inclusion of particle-vibrational coupling increases the accuracy of the description of the single-particle configurations in odd-A nuclei but such studies are limited to spherical nuclei (see Refs. [76,77])
It is interesting that such features have already been mentioned in seminal article of Dechargé and Gogny [78] where they indicated that treating explicitly the residual interaction through configuration mixing in odd and even nuclei is expected to lower the OES by approximately 300 keV in the Sn isotopes.
S. Teeti and A.V. Afanasjev, Phys. Rev. C 103 (2021) 034310

Peter Schuck
screening
To: enrico.vigezzi@mi.infn.it

3 May 2016 at 14:49

Dear Enrico,

Umberto Lombardo is in Orsay and we are discussing screening of the pairing interaction in the different channels (in infinite matter). In this respect I have a question: in finite nuclei, did you ever consider screening in the p-n S=1, T=0, ie deuteron, channel ? I mean vibration renormalisation in this channel ?
Would be interesting and would specifically interest me.

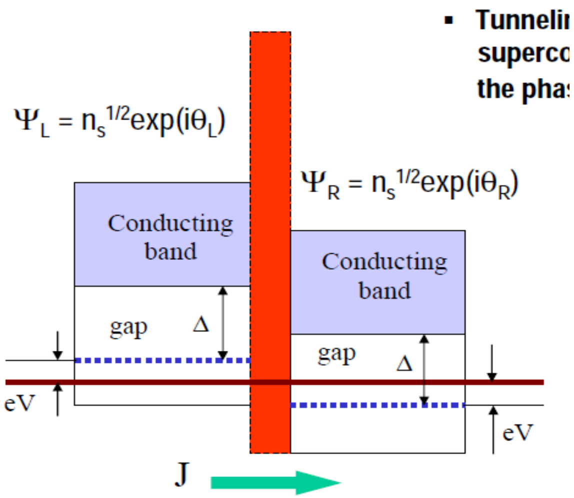
Hope you are fine.

Best regards,

Peter.

- The Josephson effect and two-nucleon transfer reactions

Josephson Junction in Condensed Matter



Because of the phase coherence, each superconductor behaves as a single-level quantum-mechanical system

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix} = \begin{pmatrix}eV & K\\ K & -eV\end{pmatrix}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix}$$

$$\dot{n}_A = \frac{2K\sqrt{n_A n_B}}{\hbar}\sin\varphi.$$

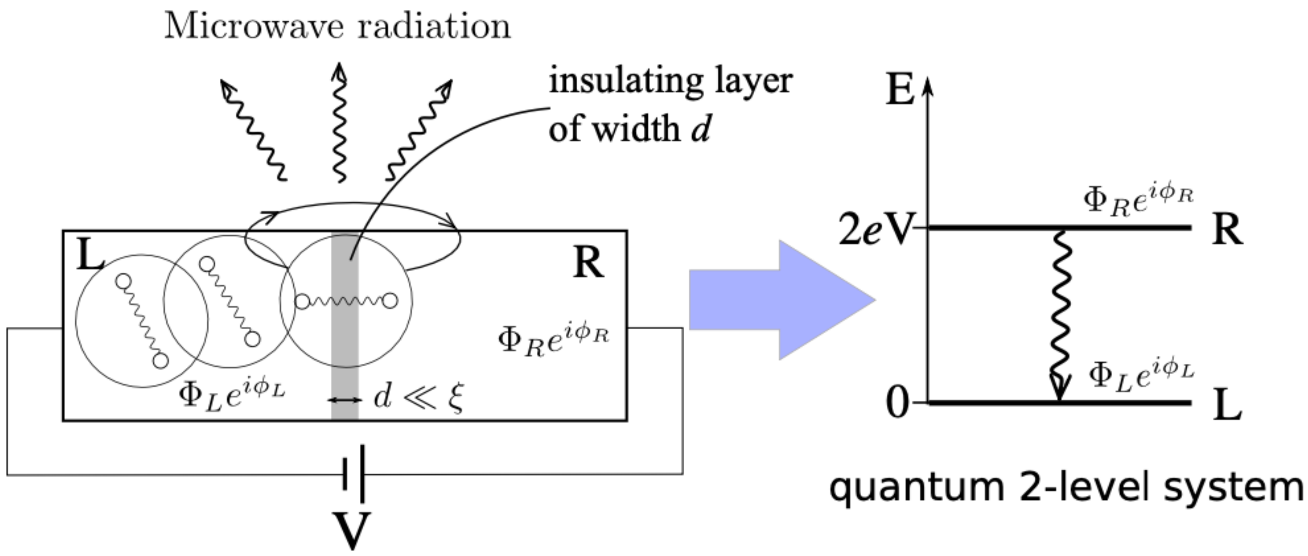
$$\frac{\partial\varphi}{\partial t} = \frac{2eV(t)}{\hbar}$$

$$I(t) = I_c\sin(\varphi(t))$$

$$\frac{\partial\varphi}{\partial t} = \frac{2eV(t)}{\hbar}$$

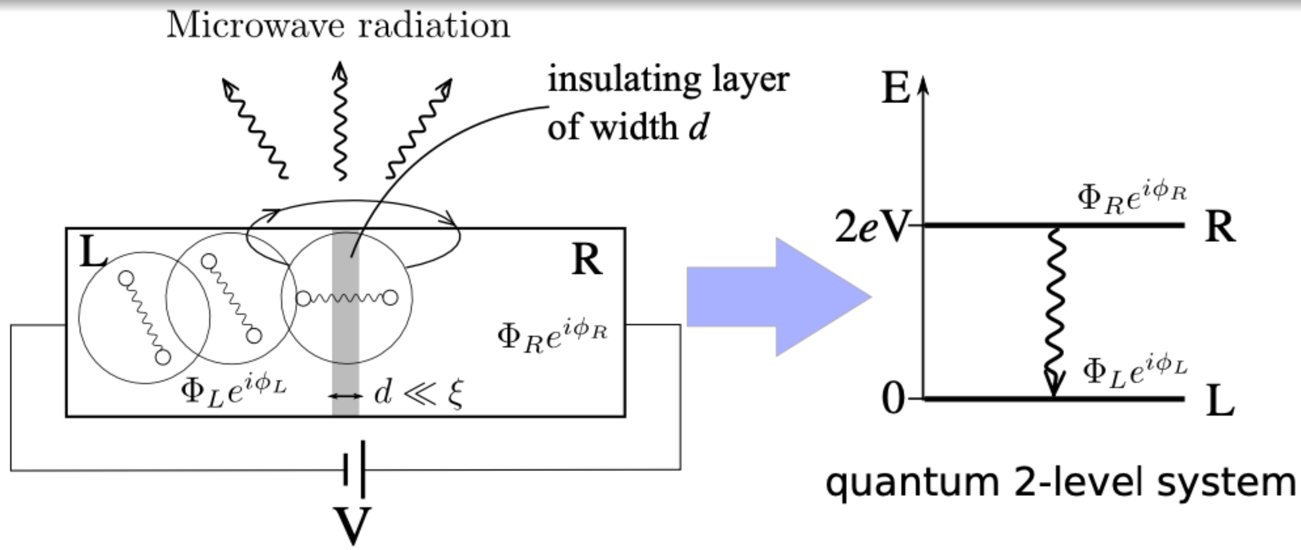
$$\varphi = \phi_B - \phi_A$$

Josephson effect



- Josephson junction: 2 superconductors separated by an insulating barrier of width d.
- When a constant potential (battery) V is applied, an alternating current (ac) of frequency $\nu_J = 2eV/h$ is induced, and the corresponding radiation is emitted.
- The charge carriers are Cooper pairs tunneling through the insulating junction.

Josephson effect



- If $d \ll \xi$, the Josephson current is $I_J \approx I_N$, where I_N is the normal (single-electron) current.
- The correlation length can be estimated to be $\xi = \hbar v_F/(\Delta\pi) \approx 10^4$Å, $v_F \equiv$ Fermi velocity.

If $d > \xi$

The supercurrent vanishes and only a direct (dc) normal current I_N of single electron carriers flows.

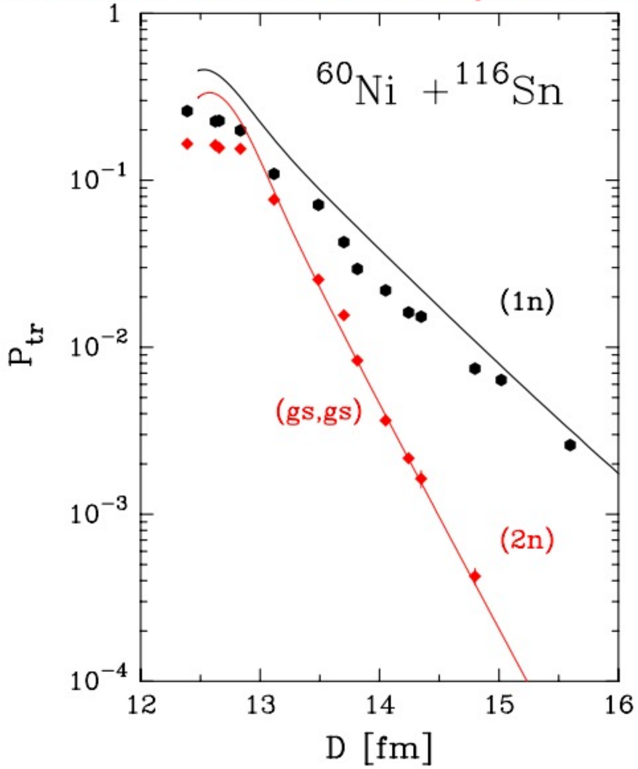
The Legnaro experiment

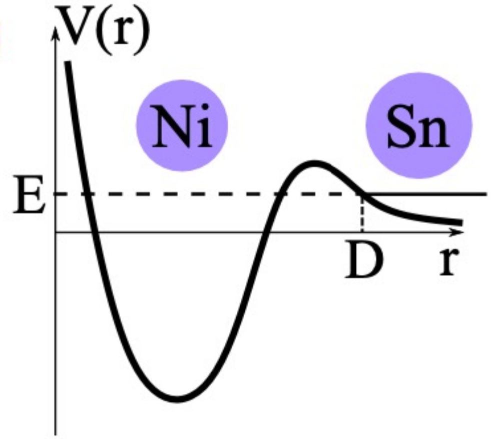
PRL **113,** 052501 (2014) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2014

Neutron Pair Transfer in ^{60}Ni + ^{116}Sn Far below the Coulomb Barrier

D. Montanari,[1] L. Corradi,[2] S. Szilner,[3] G. Pollarolo,[4] E. Fioretto,[2] G. Montagnoli,[1] F. Scarlassara,[1] A. M. Stefanini,[2] S. Courtin,[5] A. Goasduff,[5,6] F. Haas,[5] D. Jelavić Malenica,[3] C. Michelagnoli,[2] T. Mijatović,[3] N. Soić,[3] C. A. Ur,[1] and M. Varga Pajtler[7]

collision between 2 superfluid nuclei

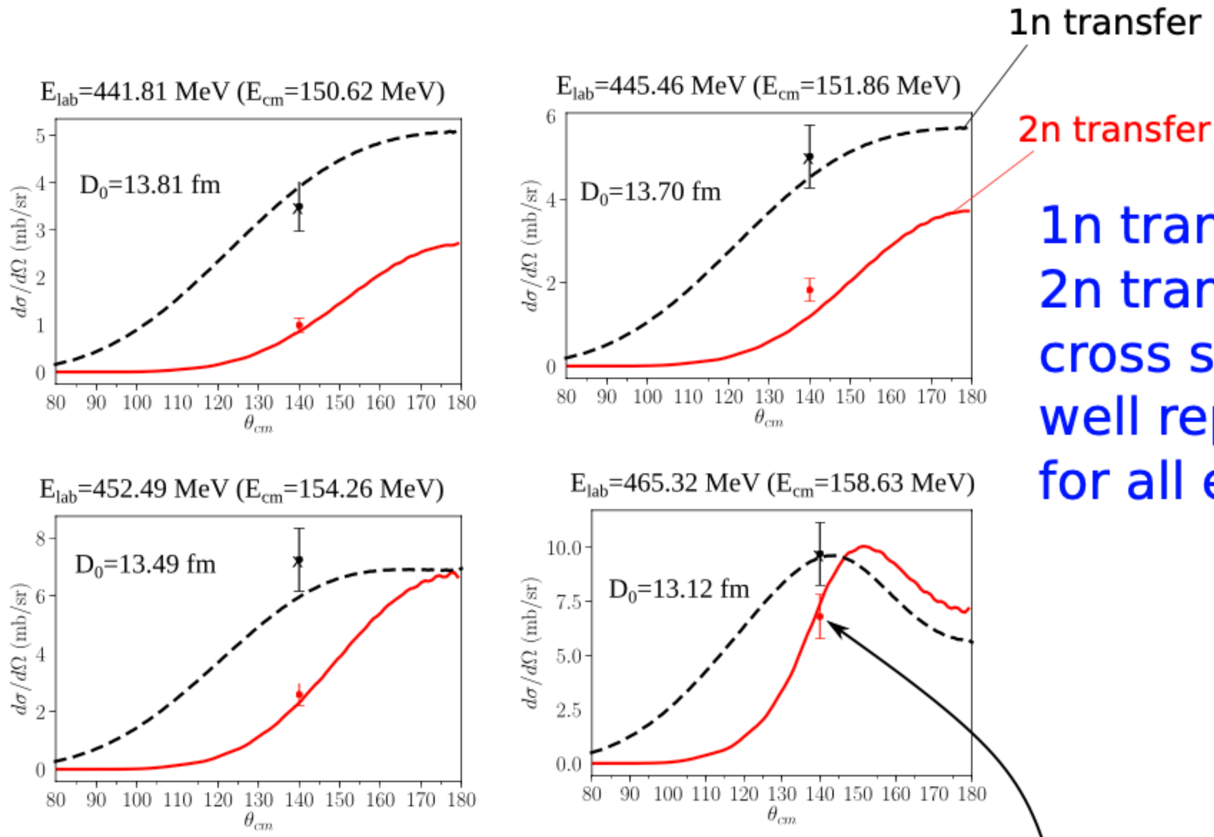




1 and 2 neutron transfer measured for 12 bombarding energies E

the distance of closest approach D can be determined from the bombarding energy E

Can we reproduce the cross sections?

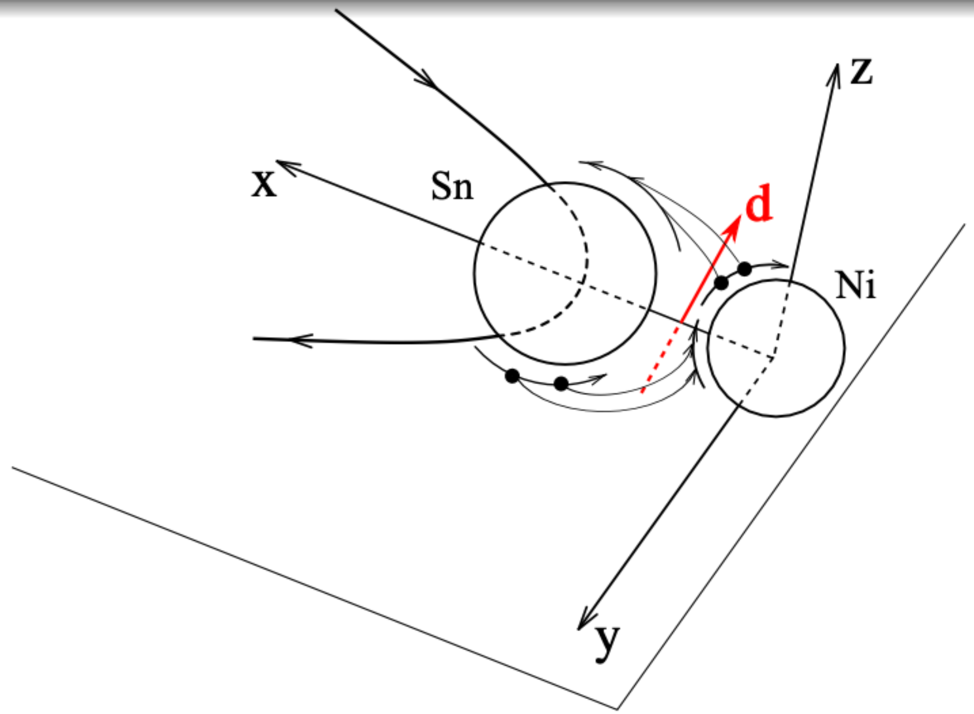


1n transfer and 2n transfer cross sections well reproduced for all energies

cross sections measured at 140°

σ_{1n} and σ_{2n} are calculated for the reaction between the two superfluid nuclei ^{116}Sn and ^{60}Ni.

Is there a nuclear Josephson effect?



- Neutrons have effective charge
  $e_{eff} = -e(Z_1 + Z_2)/(A_1 + A_2) = -0.44e$.
- An oscillating electric dipole $\vec{d}$ is induced during the 2n transfer process.
- The dipole emits electromagnetic radiation like an antenna during a very short time $\tau_{coll} \sim 10^{-21}$ s.

How do we do the calculations?

Cross sections and dipoles

- 2-n cross section: $\sigma_{2n} \to T_{2n} = \sum_\gamma \langle\phi_f|v(r_1)|\phi_\gamma\rangle\langle\phi_\gamma|v(r_2)|\phi_i\rangle$
- dipole vector: $\vec{d} \to T_d = e_{eff} \sum_\gamma \langle\phi_f|v(r_1)|\phi_\gamma\rangle(\vec{r}_1 + \vec{r}_2)\langle\phi_\gamma|v(r_2)|\phi_i\rangle$
- 3D projections of $\vec{d}$:
  $d_i \to T_{d_i} = e_{eff} \sum_\gamma \langle\phi_f|v(r_1)|\phi_\gamma\rangle(r_{1i} + \mathbf{r}_{2i})\langle\phi_\gamma|v(r_2)|\phi_i\rangle$

γ emission strength function

- amplitude for emission of photon of polarization q in direction θ_γ:

$$\mathcal{T}^q(\theta_\gamma) = \sum_i \mathcal{D}^1_{i,q}(\theta_\gamma)\, T_{d_i},$$

- differential cross section for γ emission:

$$\frac{d^2\sigma_\gamma}{d\Omega_\gamma dE_\gamma} = \rho(E_f)\left(\frac{E_\gamma^2}{(\hbar c)^3}\right)\sum_q |\mathcal{T}^q(\theta_\gamma)|^2\,\delta(E - E_\gamma - E_f + Q)$$

Is there a nuclear Josephson effect? A prediction

PHYSICAL REVIEW C **103**, L021601 (2021)

Letter | Editors' Suggestion | Featured in Physics

Quantum entanglement in nuclear Cooper-pair tunneling with γ rays

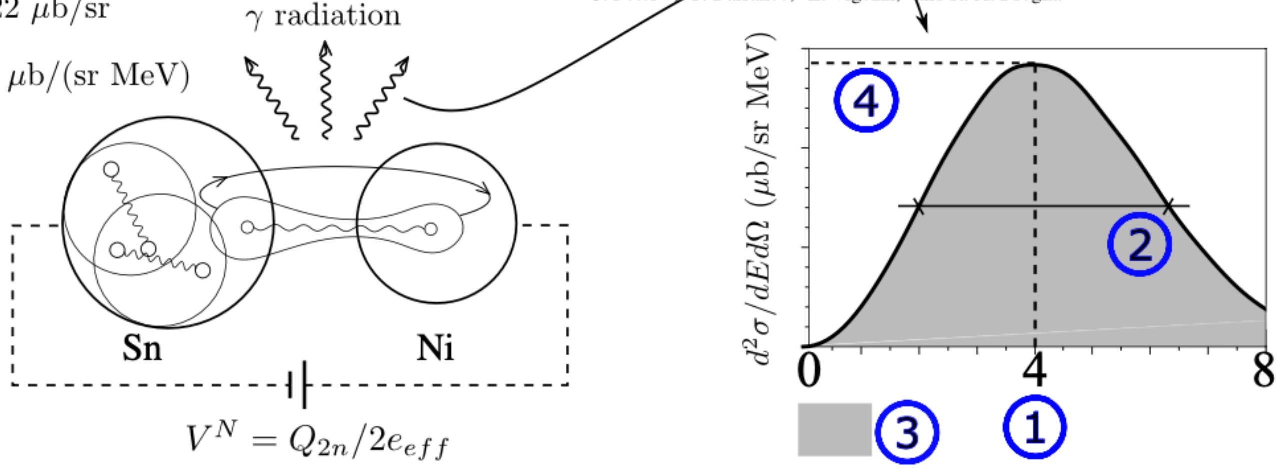
G. Potel,[1] F. Barranco,[2] E. Vigezzi,[3] and R. A. Broglia[4,5]

(1) centroid: 4 MeV

(2) width: 4 MeV

(3) integral: 5.22 μb/sr

(4) max. : 1.42 μb/(sr MeV)



nuclear superconducting "circuit"

calculated γ-strength function

- The *Q*-value of the reaction acts as a "battery", providing an equivalent potential V^N.
- The finite collision time, as well as recoil effects, provides a width ($\Delta E \sim \hbar/\tau_{coll}$).

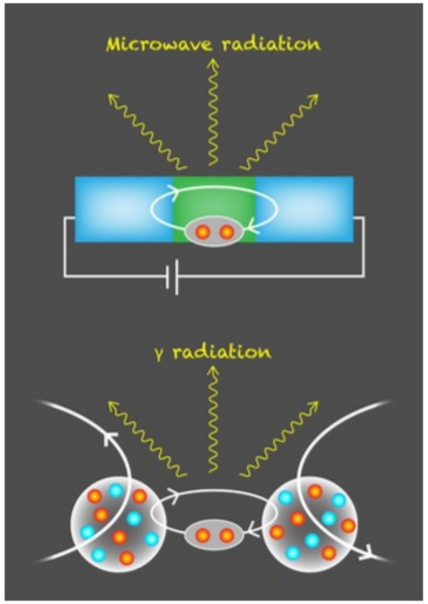
Nuclear superconductivity?

Physics VIEWPOINT

The Tiniest Superfluid Circuit in Nature

A new analysis of heavy-ion collision experiments uncovers evidence that two colliding nuclei behave like a Josephson junction—a device in which Cooper pairs tunnel through a barrier between two superfluids.

By Piotr Magierski



Velocity of the transferred (nuclear) Cooper pair: Depairing velocity .

$$v_c = \frac{\hbar s_c}{m} = \frac{2\Delta}{m v_F} = \frac{\hbar}{m\xi}$$

$\xi = \hbar\, v_F / 2\,\Delta$, coherence length of the superfluid

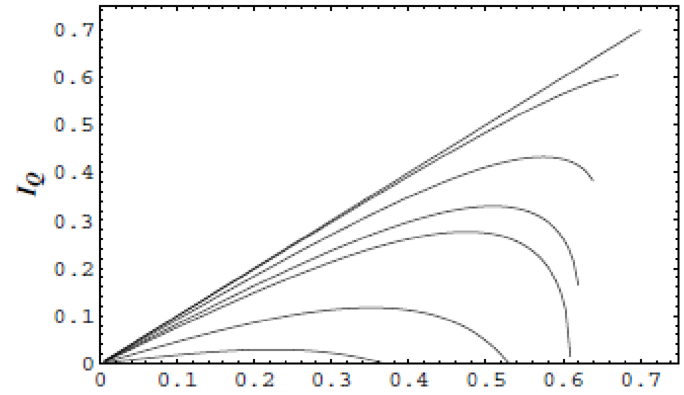


FIG. 5: Supercurrent I_Q (in units of I_Q^0) vs. superfluid velocity v (in unit of v_L) for various temperatures. From top to bottom: $T = (0.1, 0.25, 0.4, 0.5, 0.556, 0.75, 0.9)\, T_c^0$. The curves terminate at the critical velocities $v_c(T)$ appropriate to these temperatures. The maximum supercurrent for a particular curve determines the value of the critical current at that temperature.

Revisiting the critical velocity of a clean one-dimensional superconductor

Tzu-Chieh Wei

Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, ON N2L 3G1, Canada[*]

Paul M. Goldbart

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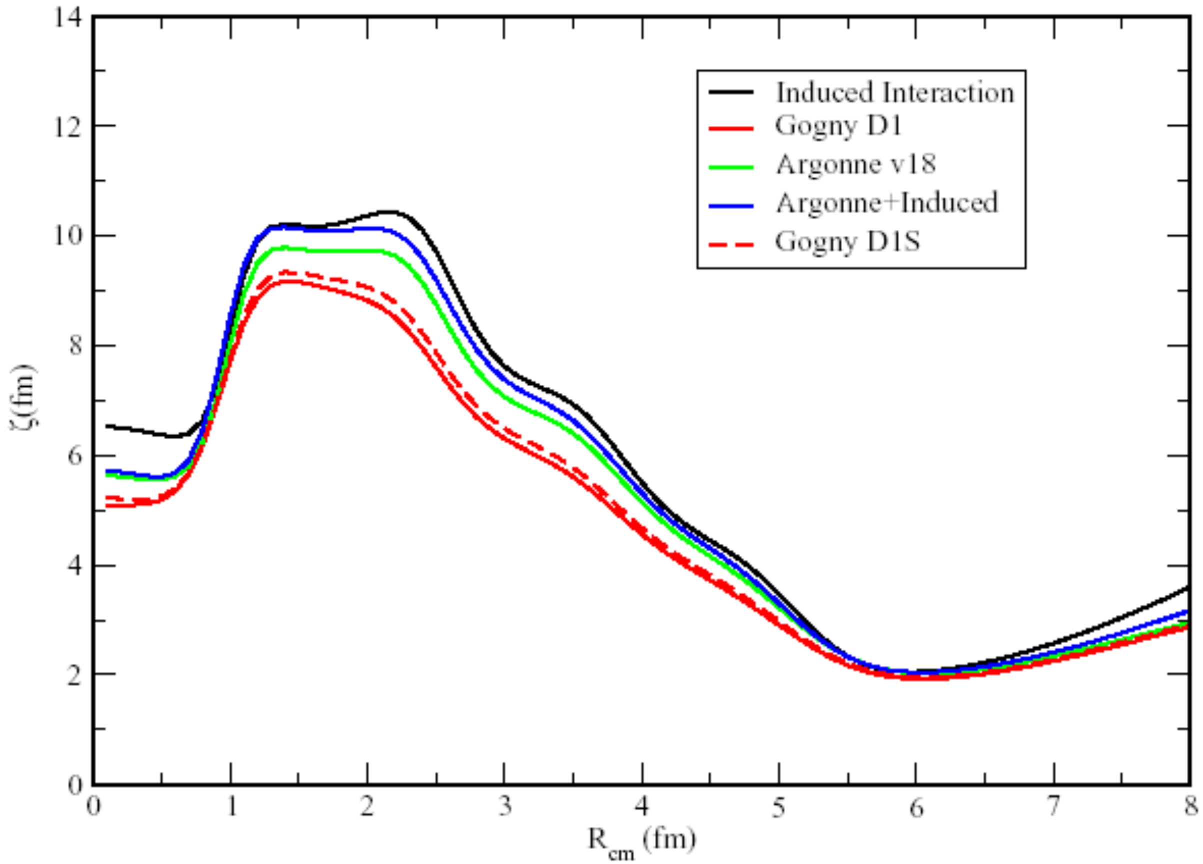
Extension of the Cooper pair in an isolated nucleus
: almost the same for different forces.
It is constrained by the nuclear mean and field is much smaller than the nuclear matter estimate h $v_F /\pi\Delta$ (~ 20 fm)

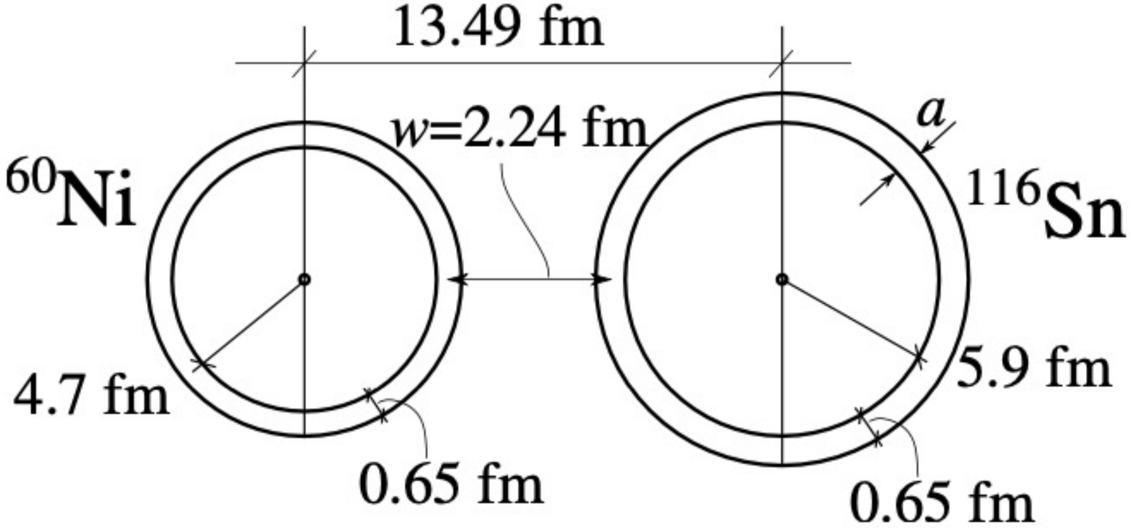
$$\xi(R_{CM}) = \left(\frac{\int d^3 r_{12} \, |\kappa(R_{CM}, r_{12})|^2 r_{12}{}^2}{\int d^3 r_{12} |\kappa(R_{CM}, r_{12})|^2} \right)^{1/2}$$



M. Matsuo, Phys. Rev. C56 (2007) 3054
N. Pillet, N. Sandulescu, P. Schuck, Phys. Rev. C76 (2007)24310
K. Hagino, H. Sagawa, J. Carbonell, P. Schuck, PRL 99 (2007)22506

The nucleon pair is transferred due to the mean field acting twice.
The amplitude due to the action of the pairing force is about one order of magnitude weaker
D.R. Bes and O. Civitarese, Nucl. Phys. A 983 (2019) 53

Coherence length during the reaction: possibly, a somewhat different concept
The two nucleons remain correlated even when they are separated by the distance of closest approach



PIAVE-ALPI ACCELERATOR

Search for a Josephson-like effect in the $^{116}Sn+^{60}Ni$ system

PRISMA + AGATA experiment

Spokesperson(s): L. Corradi, S. Szilner
(GLIMOS: L. Corradi)

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