Probing nucleon-nucleon correlations in heavy ion transfer reactions

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How the pairing correlations can be probed (static and dynamics properties and effects)?

- **Binding energies**: the ground states → description in terms of superfluid condensates, in which the pairs of nucleons form the Cooper pairs
- **Significantly different behavior at medium to high spins of rotational bands**
- **Enhanced probability to add or remove a nucleon-nucleon pair.**
Delayed alignments in the N=Z nuclei $^{84}\text{Mo}$ and $^{88}\text{Ru}$

The np pairing interaction may be the cause of the delayed rotational alignments in the even-even N=Z nuclei (A~80); different pairing fields (nn, pp, and np) respond differently to the Coriolis forces (the enhancement of the np interaction in N=Z nuclei has in general an effect to sustain the pairing field under rotation).

Real situation is rather complex:

$\rightarrow$ the spin alignment may also be influenced by deformation (shapes).

$\rightarrow$ different strengths of quadrupole interaction (np QQ) may mimic the experimental bending
The structure of the ground-state wave-function of 92Pd in the spin-aligned np paired phase can be viewed as a system of deuteron-like np hole pairs with respect to the 100Sn ‘core’.

The SM calculated spectra for 92Pd with “full neutron–proton interactions” (calculations of the pure T=0 and pure T=1 neutron–proton interaction contributions).
Two-nucleon transfer constitute the specific probe in the study of pairing in nuclei:

STRUCTURE: The pairing interaction induces particle-particle correlations that are essential in defining the properties of finite quantum many body systems in their ground and neighboring states. These structure properties may influence in a significant way the evolution of the collision of two nuclei.

DYNAMICS: which degrees of freedom describe the evolution of the reaction from the quasielastic to the deep inelastic regimes and to fusion.
Probing correlations in transfer reactions

Two-particle transfer processes induced by light and heavy ions are an ideal tool to study the dynamical aspects of pairing correlations.

Theoretical treatment: the structure information is entangled with the reaction mechanism (complex structure of the two interacting ions, QE and DIC processes, many open channels).

Light ion induced transfer reactions, (t,p), (p,t), (3He,n), (4He,d):
Advantages: shape defines L transferred, population of the specific final state
Drawbacks: as one uses different probes the reaction mechanism may differ in two-particle transfer reactions involving different reaction participants

Heavy ion transfer reactions:
HI advantages: test of correlation properties in transfer processes via simultaneous comparison of ±n and ±p, and ±nn/±pp/±np pairs; transfer of “many” pairs
HI drawbacks: limited A,Z, energy resolutions.

B.F. Bayman et al., PRC 26 (1982) 1509
Enhancement coefficients:
the ratio of the actual cross section to the prediction of models using uncorrelated states which provide a direct measurement of the correlation of the populated states.

Experimental extraction by comparison of one- and two-particle transfer probabilities as a function of the distance of closest approach (W. von Oertzen and coworkers)

Drawbacks:
all existing studies involve inclusive cross sections (energy resolution) at energies higher than the Coulomb barrier (many open channels) and at angles forward of the grazing (complex reaction mechanism)
Absolute cross sections for two-nucleon transfer reactions induced by light ions

\( \text{Sn(p,t)}^{116,118,120,122}\text{Sn} \)

\( \text{Sn(p,t)}^{118,120,122,124}\text{Sn} \)

\( \text{(p,t) reactions : absolute cross sections} \)

recently performed calculations for two neutron transfer reactions match the experimental data with high accuracy

Absolute cross sections for one and two-nucleon transfer reactions

\[ ^{208}\text{Pb}(^{16}\text{O},^{18}\text{O}_{\text{g.s.}})^{206}\text{Pb} \]

Informations about correlations are extracted when experimental absolute cross sections are compared with a microscopic theory which beside correlations includes also the coupling between relative motion (reaction) and intrinsic motion (structure).

\[ \begin{array}{ccc}
\text{full quantum-mechanical} & \text{semi-classical} & \text{full quantum-mechanical} \\
\end{array} \]


G. Potel et al, PRL 105 (2010) 172502
Above the barrier:
→ many open channels, transfer of 5-10 protons and neutrons governed by optimum Q-value
→ large TKEL, onset of DIC components
→ secondary processes: evaporation, transfer induced fission

Wilczynski plots
heavy ions: to deal with limited energy resolutions and with the presence of both QE and DIC components


48Ti + 208Pb - energy distributions
A smooth transition between QE and DIC

Below the barrier Q-values get very narrow and without DIC components:
1) $E > E_b$ large number of open channels, DIC components / evaporation effects
2) $E < E_b$ narrow Q-value distributions (concentrated at “one state”)

$L. Corradi et. al., PRC 84 (2011) 034603$
$D. Montanari et. al., PRL 113 (2014) 052501$
$D. Montanari et. al., PRC 93 (2016) 054623$

$^{96}\text{Zr}(^{40}\text{Ca},^{42}\text{Ca})$ $Q_{gs} = +5.6 \text{ MeV}$

$^{116}\text{Sn}(^{60}\text{Ni},^{62}\text{Ni})$ $Q_{gs} = +1.3 \text{ MeV}$
$^{116}\text{Sn} + ^{60}\text{Ni}: \text{detection of (light) target-like ions in inverse kinematics with PRISMA}$

Excitation function:
\[ E_{\text{beam}} = 410 \text{ MeV} - 500 \text{ MeV} \]
(D ~ 12.3 to 15.0 fm)

Excellent channel separation at D ~ 15 fm

Beam direction 20°
\(^{116}\text{Sn} + ^{60}\text{Ni}: \text{neutron pair transfer far below the Coulomb barrier}\)

Transfer strength very close to the g.s. to g.s. transitions

\[ P_{tr} \propto e^{-2\alpha D} \quad \alpha = \sqrt{\frac{2mB}{\hbar^2}} \]


\[
P_{tr} = \frac{d\sigma_{tr}}{d\sigma_{Ruth}}
\]

\[
D = \frac{Z_a Z_A e^2}{2E_{c.m.}} \left(1 + \frac{1}{\sin(\theta_{c.m.}/2)}\right)
\]
$^{116}\text{Sn} + ^{60}\text{Ni}$: two particle transfer
(semiclassical theory, microscopic calculations, $2^{nd}$ order Born app.)

3 terms: simultaneous, orthogonal and successive

only the successive term contributes to the transfer amplitude (simultaneous component is canceled out by the nonorthogonality correction)

Only 0+ to 0+ transitions are included (BCS).

\[
(c_\beta)^{\text{succ}} = \frac{1}{\hbar^2} \sum_{a_1,a'_1} B^{(A)}(a_1a_1;0)B^{(a)}(a'_1a'_1;0)2 \frac{(-1)^{j_1+j'_1}}{\sqrt{2j_1+1}\sqrt{2j'_1+1}} \sum_{m_1m'_1} (-1)^{m_1+m'_1}
\]

\[
\times \int_{-\infty}^{+\infty} dt f_{m_1m'_1}(\mathcal{R})e^{i[(E_\beta-E_\gamma)t+\delta_\beta(t)+\delta_\gamma(t)-\hbar(m'_1-m_1)]\Phi(t)/\hbar}
\]

\[
\times \int_{-\infty}^{t} dt f_{-m_1-m'_1}(\mathcal{R})e^{i[(E_\gamma-E_\alpha)t+\delta_\gamma(t)-\hbar(m'_1-m_1)]\Phi(t)/\hbar}
\]
A measure of the sensitivity of two-nucleon transfer reactions to pairing correlations is provided by the “enhancement” of the calculated cross sections with respect to pure configurations.

Character of pairing correlations manifests itself equally well in simultaneous and successive transfers due to the correlation length.
The experimental transfer probabilities are well reproduced, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon correlations:

- a consistent description of (1n) and (2n) channels
- the formalism for (2n) incorporates the contribution from both the simultaneous and successive terms (only the ground-to-ground-state transition has been calculated)
Two particle transfer (semiclassical theory, microscopic calc.)
3 terms: simultaneous, orthogonal and successive (only the successive term contributes to the transfer amplitude)

- to obtain $P_{tr}$: summed over all possible transitions that can be constructed from the single particle states in projectile and target - the set of single particle states covers a full shell below the Fermi level for $^{96}$Zr and a full shell above for $^{40}$Ca

L. Corradi et. al., PRC 84 (2011) 034603
$^{60}\text{Ni} + ^{116}\text{Sn}$: PRISMA+AGATA measurement

$^{40}\text{Ca} + ^{96}\text{Zr}$: PRISMA + CLARA measurement

$^{60}\text{Ni} + ^{116}\text{Sn}, ^{40}\text{Ca} + ^{96}\text{Zr}$: detection of beam-like ions (direct kinematics) with PRISMA, coincident gamma with CLARA/AGATA

$^{60}\text{Ni} + ^{116}\text{Sn}$: angular distributions measurement:

$E_{\text{beam}} = 245 \text{ MeV}$ at $70^0$

($D \sim 14.5 \text{ fm}$)

AGATA demonstrator (four triple cluster modules): at 16.5 cm from the target covering angular range: $130^0 - 170^0$

simulated full-absorption efficiency: 2.64% for 1.3 MeV
states with relatively high angular momentum
states with non-natural parity
comparison between experimental and theoretical transfer probabilities: the two-nucleon transfer reaction does not populate only 0+ states; more complicated two-particle correlations have to be taken into account.
\[ ^{60}\text{Ni} + ^{116}\text{Sn} \rightarrow ^{62}\text{Ni} + ^{114}\text{Sn} \text{ (2n channel)} \]

- No gamma in \(^{114}\text{Sn}\), few gamma in \(^{62}\text{Ni}\) compatible with \(2^+ \rightarrow 0^+\) transitions.
$^{60}\text{Ni} + ^{116}\text{Sn}: \text{PRISMA+AGATA measurement}$

$^{60}\text{Ni}$:
- $1333\text{ keV}$, $2^+_1 \rightarrow 0^+$
- $826\text{ keV}$, $2^+_2 \rightarrow 2^+_1$
- $1173\text{ keV}$, $4^+_1 \rightarrow 2^+_1$

$^{116}\text{Sn}$:
- $1293\text{ keV}$, $2^+_1 \rightarrow 0^+$
- $972\text{ keV}$, $3^- \rightarrow 2^+_1$
- $1097\text{ keV}$, $4^+_1 \rightarrow 2^+_1$

$^{61}\text{Ni}$:
- $283\text{ keV}$, $1/2^- \rightarrow 3/2^+$

$^{115}\text{Sn}$
- $489\text{ keV}$, $5/2^+ \rightarrow 3/2^+$
- $497\text{ keV}$, $3/2^+ \rightarrow 1/2^+$

$^{62}\text{Ni}$:
- $1173\text{ keV}$, $2^- \rightarrow 0^+$

$T_{1/2} = 3.3\ \mu s\ (7/2^+)$

$= 159\ \mu s\ (11/2^-)$
The strengths (normalized to $2^+ \rightarrow 0^+$ in $^{60}$Ni) of the most important transitions, corrected for the contributions of the feeding and for their relative detection efficiency in AGATA.

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<tbody>
<tr>
<td>$^{116}$Sn$(2^+)$</td>
<td>$0.792 \pm 0.160$</td>
<td>0.720</td>
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<tr>
<td>$^{116}$Sn$(4^+)$</td>
<td>$0.042 \pm 0.011$</td>
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<td>$^{60}$Ni$(4^+)$</td>
<td>$0.060 \pm 0.013$</td>
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<td>$0.018 \pm 0.003$</td>
<td>0.037</td>
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<td>$^{61}$Ni$(1/2^-)$</td>
<td>$0.014 \pm 0.003$</td>
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<tr>
<td>$^{62}$Ni$(2^+)$</td>
<td>$&lt; 0.00145$</td>
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- the direct population of states can be compared with any reaction code
- DWBA, coupled channels, tabulated deformations, spectroscopic factors
- a direct check on the one-particle form factors (+1n), and of potential
The transitions to the excited states in (2n) channels contribute to the total strength: <24%

\[ \sigma_R - \sigma_{el} = \sigma(2^+, ^{60}\text{Ni}) + \sigma(2^+, ^{116}\text{Sn}) \]

\[ \sigma_R \left(1 - \frac{\sigma_{el}}{\sigma_R}\right) = \sigma(2^+, ^{60}\text{Ni}) \left(1 + \frac{\sigma(2^+, ^{116}\text{Sn})}{\sigma(2^+, ^{60}\text{Ni})}\right) \]

\[ \frac{\sigma_{el}}{\sigma_R} = 0.64 \]

\[ \sigma_{2n} = \sigma_R P_{2n}, \quad P_{2n} = 0.0012 \]

\[ \frac{\sigma_{2n}}{\sigma(2^+, ^{60}\text{Ni})} = 0.006 \]

Next step: to estimate the fraction of total cross section of the (2n) channel, $^{62}\text{Ni}$, going into $2^+$

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Heavy ion transfer reactions

Transfer reactions with light nuclei

$^{60}\text{Ni} + ^{116}\text{Sn}$

$^{122}\text{Sn}(p,t)^{120}\text{Sn}$

D. Montanari et. al., PRL 113 (2014) 052501

D. Montanari et. al., PRC 93 (2016) 054623


\[ D = \frac{Z_a Z_A e^2}{2E_{\text{c.m.}}} \left(1 + \frac{1}{\sin(\theta_{\text{c.m.}}/2)}\right) \]
Sub-barrier transfer: TDHF or TDHF+BCS

\[ ^{40}\text{Ca} + ^{96}\text{Zr} \]

EXP (1n) and (2n);
(1n) c.c.; (2n) (g.s. → g.s.)
(g.s. → 0+ at ~6MeV)

L. Corradi et. al., PRC 84 (2011) 034603
G. Scamps et al., EPJ Web Conf. 86 (2015) 00042
Sub-barrier transfer: TDHF or TDHF+BCS

\[ {^{16}\text{O}} + {^{208}\text{Pb}} \]

\[ (2\text{n}) \text{ TDHF} \]
\[ (1\text{n}) \text{ TDHF} \]

\[ {^{40}\text{Ca}} + {^{46}\text{Ca}} \]

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C. Simenel, PRL105(2010)192701
M. Evers et al, PRC84(2011)054614

G. Scamps and D. Lacroix, PRC87(2013)014605
One- and two-neutron transfer

$^{40}\text{Ca} + ^{116,124,130}\text{Sn}$

$^{18}\text{O} + ^{28}\text{Si}, \; ^{18}\text{O} + ^{11}\text{B}, \; ^{18}\text{O} + ^{12,13}\text{C}$

**Calculations:** constrained molecular dynamics
**Exp:** MAGNEX

Summary

✓ The comparison between data and theory: elementary modes of the complex mechanism can be probed.

✓ “large” spectrometers coupled to “large” gamma arrays are powerful tools to study the correlations.

✓ Sub-barrier transfer reaction measurement (nuclei interact at large distances): good probe for pair correlations

✓ The information about correlations are extracted when experimental absolute cross sections are compared with a microscopic theory which beside correlations includes also the coupling between relative motion (reaction) and intrinsic motion (structure).

Outlook

→ very heavy systems
→ proton transfer channels at large D
→ (np) correlations
in the collision between very heavy ions, population of final states with high excitation and angular momenta may significantly change the transfer strength for the g.s. to g.s. transitions.

“Q-value matching”: the heavy semi-magic combination with closed proton shells and open neutron shells and the g.s. to g.s. Q-values close to Q-optimum whether and to what extent the effect of neutron-neutron correlations in the evolution of the reaction is modified in the presence of high Coulomb fields.
Kinematics of $^{206}$Pb+$^{118}$Sn

$\theta_{\text{lab}} = 35^\circ$ is close to the limiting angle for Pb-like ions, so one can safely control the correct geometry of the experiment.

With PRISMA at $\theta_{\text{lab}} = 35^\circ$ Sn-like ions have kinetic energies $\sim 750$ MeV at $E_{\text{lab}} = 1200$ MeV, so one expects good A, Z resolutions.

INFN – LNL, PRISMA spectrometer, February, 2018, L. Corradi, S. Szilner: Nucleon-nucleon pairing correlations probed in the $^{206}$Pb+$^{118}$Sn transfer reaction at far sub-barrier energies.
The $^{197}\text{Au} + ^{130}\text{Te}$ multinucleon transfer reaction: Te-like in PRISMA

Mass distribution for the Te isotopes obtained after ion trajectory reconstruction in PRISMA.

$^{197}\text{Au} + ^{130}\text{Te}$ at $E(^{197}\text{Au}) = 1097$ MeV, $\theta_{\text{PRISMA}} = 37^\circ$

The mass-mass correlations in multinucleon transfer reaction
A gas detection system for fragment identification in low-energy heavy-ion collisions
E. Fioretto et al. NIM A, in press
Few data are available, but for small D's, where absorption plays an important role, the analysis done via the interpretation of the enhancement factors at the phenomenological level.

The proton transfer processes in a heavy-ion collisions are much less understood (large modification in the trajectories of entrance and exit channels are involved due to the modification of the Coulomb field). The single-particle level density for protons is less studied and the corresponding single-particle form factors are less known (even the one-proton transfer cross sections are not very well described in the DWBA).

R.Kunkel et al., PLB 208 (1988) 355

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