Probing nucleon-nucleon correlations in heavy ion transfer reactions

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Transfer reactions among heavy ions

- A study of multiple particle transfers.
- The transition from quasi elastic to deep inelastic processes.
- A tool for the population of neutron rich nuclei.

A study of properties near shell closure:
- Single particle states
- Coupling of the particle/hole to the collective boson

A study of the residual interaction (correlations):
- Two particle transfer (absolute values)
- Population of specific states (pairing vibration/rotation)

C.H. Dasso et al., PRL 73 (1994) 1907

Nuclear Shell Structure

B.F. Bayman et al., PRC 26 (1982) 1509
Probing correlations

How the correlations that go beyond a mean field description 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.

What will be a signature in the heavy ion transfer reactions?

HI advantages: test of correlation properties in multi-neutron and multi-proton transfer processes via simultaneous comparison of observables for ±nn/±pp/±np pairs

HI drawbacks: difficult experimental conditions (A,Z,Q-value resolutions, total efficiency) and difficult theoretical treatment (complex structure of the two interacting ions, QE and DIC processes, multistep processes, many open channels and CC effects)
Magnetic spectrometers for transfer reaction studies

Q3D, split-pole

- excited states populated in light ion transfer reactions (en. resolution ~few tenths keV)
- distribution of atomic charge states (magnetic elements of different complexity to focus momenta at the focal plane)

TOF spectrometers

- focus ions of different atomic charge states to a (small) focal plane
- good A and Z resolution, and detection efficiency, large energy dynamic range of transfer products

Large solid angle spectrometers

- simple magnetic elements and “complex” detector systems
- good A and Z resolution, detection efficiency

1980

S. Szilner et al, PRC 71 (2005) 044610

PRISMA, VAMOS, MAGNEX
coupling to large γ arrays
CLARA, EXOGAM, AGATA

2000

S. Pullanhiotan et al, NIM A 593 (2008) 343
The PRISMA spectrometer

reconstruction of the ion trajectory inside (simple) magnetic elements, ray tracing procedure: position sensitive detectors of large area

$^{90}\text{Zr} + ^{208}\text{Pb}$  
$E_{\text{lab}} = 560 \text{ MeV}$  
$\theta_{\text{lab}} = 61^\circ$

$^{82}\text{Se} + ^{238}\text{U}$  
$E_{\text{lab}} = 505 \text{ MeV}$  
$\theta_{\text{lab}} = 64^\circ$

fission  
pick-up  
Se  
stripping  
Energy [arb. units]
Properties of transfer reactions at the Coulomb barrier

- The transfer process is governed by **optimum Q-value** and nuclear structure properties.
- Nuclei are located on the left side of the charge equilibration line --> dominance of a **direct mechanism**
- For the massive proton transfer channels → the isotopic distributions drift towards lower masses (neutron evaporation)

- GRAZING model: calculates the evolution of the reaction by taking into account:
  - the relative motion (nuclear + Coulomb field), and
  - the intrinsic degrees of freedom of projectile and target (surface vibration and the single-nucleon transfer channels).
- The multinucleon transfers are described via a **multistep mechanism.**
- The model takes into account the effect of neutron evaporation.

C. H. Dasso, G. Pollarolo, and A. Winther, PRL 73 (1994) 1907
Multinucleon transfer reactions: experiment vs. theory

EXP: $^{58}\text{Ni} + ^{208}\text{Pb}$,
L. Corradi et al., PRC 66 (2002) 024606

GRAZING or CWKB, G. Pollarolo

Time Dependent Hartree-Fock theory
K. Sekizawa, K. Yabana, PRC 88 (2013) 014614

Langevin-type dynamical equations of motion
V. Zagrebaev, W. Greiner PRL 101 (2008) 122701
The shape of the yield distribution reflects the optimum Q-value. The theory describes well (0p) and (-1p) but underestimates (-2p). The contribution of a direct pair mode (“macroscopic”) both for neutrons and protons has been added in the calculations. The same strength of the form factor for neutrons and protons. The pair mode alters little the cross section for neutron transfer but is essential for the proton transfer.

\[ F_P(r) = \beta_P \frac{\partial V(r)}{\partial A} \approx \left( \frac{\beta_P R}{3A} \right) \frac{\partial V(r)}{\partial r}, \]

\( \checkmark \) The residual interaction: components responsible for the couplings (phonon - single particle), and for nucleon - nucleon correlations

\( \checkmark \) Inclusive data - difficult to have a clear signature of pair mode

L. Corradi et al., PRC 66 (2002) 024606
S. Szilner et al., PRC 71 (2005) 044610
“coupling to large γ arrays”

exp: $^{40}\text{Ar} + ^{208}\text{Pb}$

$\theta_{\text{lab}} = 46^\circ$

$54^\circ$ (grazing)

$59^\circ$

Z=18: Ar isotopes
A=38-43
Neutron transfer channels

Z=19: K isotopes
A=40-46
(+1p±xn) transfer channels

Z=17: Cl isotopes
A=37-42
(-1p±xn) transfer channels

S. Szilner et al, PRC 84 (2011) 014325

S. Szilner et al, PRC 87 (2013) 054322

Diff. and total cross sections
The character of states populated in transfer reactions

Ar isotopes: neutron transfer channels

Counts

E (keV)

$^{40}$Ar

$^{41}$Ar (+1n)

$^{42}$Ar (+2n)

$^{43}$Ar (+3n)

$^{42}$Ar

SM
The character of states populated in transfer reactions

A strong interplay between single-particle and collective degrees of freedom and the reaction dynamics

Ar isotopes

\[ \nu p_{1/2}, \nu p_{3/2}, \nu f_{7/2}, \nu f_{5/2} \rightarrow 1/2^-, 3/2^-, 5/2^-, 7/2^- \]

\[ 2^+ \otimes \nu f_{7/2} \rightarrow 11/2^-, 9/2^-, ..., 3/2^- \]

odd: excitation of states of single-particle character

a significant population of a stretched configuration of the valence neutron coupled to the vibration quanta

SDPF-U SM calculations
"yrast" states; "fermion-boson" coupling

**40Ca** + **96Zr** reaction:
95Zr: a strong population of the "yrast" states (up to 16+ at 7.4 MeV)


**90Zr** + **208Pb** reaction:
92Zr: a strong population of the "yrast" states (up to 16+ at 7.4 MeV)


**48Ca** + **64Ni** reaction:
49Ca: a strong population of "boson-fermion" multiplets

D. Montanari et al., PLB 697, 288 (2011); PRC 85 (2012) 044301

Fe: S. Lunardi et al, PRC 76 (2007) 034303
Ar: D. Mengoni et al, PRC 82 (2010) 024308
S. Bhattacharyya et al, PRL 101 (2008) 03501 ...
open reaction channels are those compatible with the optimum Q-value window (kinematical condition).

This window has its origin in the matching of the orbits before and after the transfer process.
The $^{40}$Ar+$^{208}$Pb system

Z- M distribution

Wilczynski plots

$^{40}$Ar + $^{208}$Pb ($E_{LAB}$=260 MeV)

EXP vs. GRAZING: the (+np)
channel – factor 5
The $^{40}$Ar+$^{208}$Pb system

Quasi-elastic processes

Deep-inelastic processes

Wilczynski plots, (+1p+xn) channels

Angular distributions (integrated over energy: TOTAL, QE, DIC)
EXP vs. GRAZING (quasi-elastic): the (+np) channel – factor 2.5

PRELIMINARY

A smooth transition between QE and DIC processes

Below the barrier Q-values gets very narrow and without DIC components:
1) $E > E_b$ large number of open channels, DIC components
2) $E < E_b$ narrow Q-value distributions: no evaporation effects

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

$^{96}$Zr($^{40}$Ca,$^{42}$Ca) $Q_{gs} = +5.6$ MeV
$^{116}$Sn($^{60}$Ni,$^{62}$Ni) $Q_{gs} = +1.3$ MeV
$^{60}\text{Ni} + ^{116}\text{Sn}$: 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
Experimental transfer probabilities

$slopes$ of $P_{tr}$ $vd$ $D$ are $as$ $expected$ $from$ $the$ $binding$ $energies$ $(tail$ $of$ $the$ $formfactor)$

*a bare phenomenological analysis shows an “enhanced” pair transfer, $P_{2n} \sim 3 \left( P_{1n}^2 \right)$ and $P_{3n} \sim P_{1n} \left( P_{2n} \right) \sim 3 \left( P_{1n}^3 \right)*$

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

(Semiclassical theory, microscopic calculations, 2nd order Born app.)

3 terms: simultaneous, orthogonal and successive
Only the successive term contributes to the transfer amplitude
Only $0^+$ to $0^+$ transition can be reduced to a simple expression

\[
(c_\beta)_{\text{succ}} = \frac{1}{\hbar^2} \sum_{a_1, a'_1} B^{(A)}(a_1 a_1; 0) B^{(a)}(a'_1 a'_1; 0) 2 \frac{(-1)^{j_1 + j'_1}}{\sqrt{(2j_1 + 1)} \sqrt{(2j'_1 + 1)}} \sum_{m_1 m'_1} (-1)^{m_1 + m'_1} \]
\[
\times \int_{-\infty}^{+\infty} dt f_{m_1 m'_1}(R) e^{i[(E_\beta - E_\gamma)t + \delta_{\beta \gamma}(t) + \hbar (m'_1 - m_1) \Phi(t)]/\hbar}
\times \int_{-\infty}^{t} dt f_{-m_1 - m'_1}(R) e^{i[(E_\gamma - E_\alpha)t + \delta_{\gamma \alpha}(t) - \hbar (m'_1 - m_1) \Phi(t)]/\hbar}.
\]
Comparison between experimental and theoretical transfer probabilities

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
$^{60}\text{Ni} + ^{116}\text{Sn}$: neutron pair transfer far below the Coulomb barrier

The experimental transfer probabilities are well reproduced, for the first time with heavy ion reactions, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon correlations.

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

Absolute cross sections for one and two-nucleon transfer reactions

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

- - - - - - simultaneous

successive + simultaneous

**full quanto-mechanical**

**semi-classical**

**full quanto-mechanical**


G. Potel et al, PRL 105 (2010) 172502
Sub-barrier transfer: TDHF or TDHF+BCS

$^{16}\text{O} + ^{208}\text{Pb}$

$^{40}\text{Ca} + ^{96}\text{Zr}$


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

C. Simenel, PRL105(2010)192701

M. Evers et al, PRC84(2011)054614

G. Scamps et al., EPJ Web Conf. 86 (2015) 00042
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 fine details of such processes.

- The total, differential cross sections and individual state yield distribution reflect a strong interplay between single-particle and collective degrees of freedom and the reaction dynamics: transfer reactions are sensitive to the transferred angular momentum (good matching), the nuclear matrix element contains the spectroscopic information (both of the projectile and target).

- The importance of components responsible for the couplings (phonon-single particle), and for particle correlations (residual interaction)

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

OUTLOOK:
gamma-particle coincidences
proton transfer channels at large D
proton rich nuclei (np correlations)
neutron rich nuclei (density dependent forces)
very heavy systems
microscopic calculations for high multipolarity states
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