Using Transfer Reactions for Nucleon Correlation Studies

One-nucleon Transfer Reactions

Survey: Extractions of Neutron Spectroscopic Factors using systematic approach → Structure Information from Transfer Reactions

Experiment: $^{34,46}$Ar(p,d) Transfer Reactions in Inverse Kinematics → Asymmetry Dependence of Neutron Correlations

Two-nucleon Transfer Reactions

Two-neutron: Systematic Calculations → Pairing properties of dilute neutron matter

Neutron-proton: Systematics of (p,$^3$He) & ($^3$He,p) Transfer in sd-shell nuclei → Baseline for np-pairing studies for N=Z nuclei
Nucleon Correlations using Direct Reactions

Truncated shell model space + effective interactions

Few active orbitals
High Occupancy

Inert Core

In reality

Short-range, tensor & collective correlations

Greater distribution of nucleons to higher energy configuration
Reduction in Occupancy

Probing the nuclear wave function

Removing nucleon from occupied orbital
→ Cross sections (probability) depend on the single-particle occupancy & overlap of many-body wave functions

Figure courtesy: J.A. Tostevin

Full Knowledge of Correlations → Complete Understanding of Nuclear Properties
Spectroscopic Factor (SF)

How much? What is the Isospin Dependence of nucleon correlations?

Cross Sections + Reaction Model
→ Spectroscopic Factors (expt)
Quantify Occupancy → Correlation Effects

How good the effective interaction in Shell Model for describing correlations?

\[
\frac{SF_{\text{exp}}}{SF_{\text{SM}}} = 1
\]
SM description is accurate

\[
\frac{SF_{\text{exp}}}{SF_{\text{SM}}} < 1
\]
Some correlations missing in the interactions?

(e,e’p) – Stable nuclei (near closed shell)
• Constant ~30-40% of SF reduction compared to theory
• Correlations missing in shell-model interactions


How about Transfer Reactions?

Transfer Reactions -- long history (>50 years) ➔ abundant data, but Problems in SF(expt)!
Experimental SF from Transfer Reactions

\[ SF = \frac{\left( \frac{d\sigma}{d\Omega} \right)_\text{EXP}}{\left( \frac{d\sigma}{d\Omega} \right)_\text{Theo}} \]

**ADWA (consistent set)**

- **Johnson-Soper (JS)**
  Adiabatic Approximation takes care of d-break-up effects

- Use global p and n optical potential with standardized parameters (CH89)

- Include finite range & non-locality corrections

- n-potential: Woods-Saxon shape \( r_o = 1.25 \) & \( a_o = 0.65 \) fm; depth adjusted to reproduce experimental binding energy

**Well-known problem**
- optical model potentials
- parameters
- reaction models

**Consistent SFs for \( ^{41}\text{Ca} \)**

**Reliable Framework → Systematic Studies**

Ground-state Spectroscopic Factors of $Z=3$-$24$

- Most extracted SFs less than IPM-plus-pairing predictions
- Absence of nucleon-nucleon correlations

\[ SF_{LB-SM} < SF_{IPM} \]


LB-SM predictions (Residual interactions $\rightarrow$ correlations)

- Remarkable 20% agreement to the large-basis shell-model calculations

LB-SM code: Oxbash, Alex Brown (MSU)
Excited-state SFs of rare nuclei:
- rp process calculations
- X-ray burst simulations

*Not available in experiment*

→ SFs from SM predictions

- SFs for excited states are very small (< 0.1)

→ Test the predictive power of Shell Model

→ Evaluate the latest interactions (USDA/USDB) in sd-shell region

\[ SF > 0.002: \text{30\% Agreement with Shell Model} \]

\[ SF < 0.002: \text{SM calculations are not accurate} \]
Neutron SFs for Ca, Ti, Cr isotopes

- Poor Shell Model predictions near $^{40}$Ca → > 10 times larger than measured
- Not $^{40}$Ca core + single particle → due to core excitation and fragmentation of states

Expt: Large Fragmentation of States
Shell-Model: Mainly Single Particle States

• sd-pf model space with new interactions is needed

Ground-state Neutron SFs for Ni isotopes

- IPM
- Auerbach interaction (’60)
- JJ4PNA : T=1 effective interaction (derived for heavy Ni isotopes)

$^{40}$Ca core, in fp model space

$^{56}$Ni core

$^{56}$Ni is not a good closed core

Description of Ni isotopes requires $^{40}$Ca core

• IPM
• Auerbach interaction (’60)
• JJ4PNA : T=1 effective interaction (derived for heavy Ni isotopes)

$^{56}$Ni is not a good closed core

GXFP1A with full fp model space does not require $^{56}$Ni shell closure → CPU intensive


SF values agree to factor of 2 → cannot distinguish between two interactions

Data uncertainties: 20-30% → Interactions for fpg shell still need improvements

M.B. Tsang and J. Lee et al., Phys. Rev. Lett. 102, 062501 (2009)

Survey of Spectroscopic Factor (Transfer Reactions)

Reaction Model: CH89 + ro=1.25 fm with minimum assumption ➔ consistent SF(expt) with Shell Model

Ni isotopes -
Ground states

USDA/USDB
Excited states

GXPF1A
Excited states

GXPF1A
Full Basis
Confirmation of Spin Assignment from Systematics

$J^\pi$ assignment

$^{27}$Mg (NNDC):

$(3/2, 5/2)^+$

Survey of Spectroscopic Factor (Transfer Reactions)

\[ \frac{SF_{\text{exp}}}{SF_{\text{theory}}} \approx 1 \]

Do we understand all the correlations?
Suppression of SFs in Transfer Reactions

Microscopic Input in Reaction Model

- \( CH89 + r_o=1.25 \text{ fm} \) with minimum assumption
  \( \rightarrow \) consistent SF(expt) with Shell Model

- \( JLM \) potential & Hartree-Fock (SK20)

Global CH89 \( \rightarrow JLM + HF \) densities

Constant \( \sim 30\% \) reduction in SFs

Constant ~30% reduction in SFs

\[ \Delta S = S_n - S_p \]
\[ \Delta S (\text{MeV}) \]

\[ \text{SF(expt)/SF(SM)} \]


Different sets of consistent parameters \( \rightarrow \) different normalizations

Transfer reactions do not yield absolute SF; Systematic approach \( \rightarrow \) relative SF can be obtained reliably over a wide range of nuclei

Nuclear structure purpose \( \rightarrow \) Relative normalized SFs
Isospin Dependence of Neutron Correlations

\[ ^{34,36,46}\text{Ar} + p \rightarrow d + ^{33,35,45}\text{Ar} \]

Inverse kinematics at 33MeV/A

\[ ^{34}\text{Ar} : ^{36}\text{Ar} 150\text{MeV/A} + ^9\text{Be} 1480 \text{ mg/cm}^2 \]

\[ ^{46}\text{Ar} : ^{48}\text{Ca} 140\text{MeV/A} + ^9\text{Be} 1763 \text{ mg/cm}^2 \]

Beam PID: Time-of-flight of the extended focal plane and radio-frequency (RF) of K1200 cyclotron

Coupled Cyclotron Facility (CCF) +A1900 fragment separator

I2-Dispersive Plane

Al wedge (375 mg/cm\(^2\))
Isospin Dependence of Neutron Correlations

$^{34,36,46}\text{Ar} + p \rightarrow d + ^{33,35,45}\text{Ar}$

Inverse kinematics at 33MeV/A

Goal: neutron spectroscopic factors

Observables: deuteron differential cross sections

1. High Resolution Array
2. S800 Spectrograph
3. Micro-Channel Plates

✓ Complete kinematics measurement
✓ First transfer reaction experiment using HiRA with S800 + MCP at NSCL
Experimental Setup

34, 36, 46 Ar Beams

HiRA

State-of-the-art detectors
excellent particle identification

16 HiRA telescopes –
efficiency ~30-40%

✓ 1024 pixels (2mm x 2mm)
✓ 0.16° at 35 cm setup
Experimental Results

Isospin Dependence of Nucleon Correlations

$\Delta S = S_n - S_p$

Transfer Reactions:

- Neutron-rich
- Proton-rich

Follow the established systematics (e.g. $^{40-49}$Ca isotope chain)

Dispersive Optical Model (DOM)
(elastic-scattering & bound-level data for $^{40-49}$Ca)

JLM-HF, n-transfer

DOM results

Isospin Dependence of Nucleon Correlations

Q: Isospin Dependence?

Transfer reactions: Weak
\[ p(^{34,36,46}Ar,d) \text{ at } 33 \text{ MeV/A} \]

Knockout reactions: Yes & Strong

Systematic difference between two probes!

\[ \text{Inconsistency} \rightarrow \text{Incomplete understanding in underlying reaction mechanism} \]

Transfer Reaction
\[ \checkmark \quad ^{34,46}Ar(p,d) \text{ at } 70 \text{ MeV/A @ MSU (approved – MSU)} \]
- same energy as knockout reactions
- same SF from transfer at higher energy? (reliability and applicability of model)

Energy-Degraded Beam
\[ \rightarrow \text{compromise: beam quality & statistics – determines beam energy used} \]

Knockout Reaction?
\[ \rightarrow \text{Experiments proposed} \]
Transfer Reactions – Experimental Challenges

- Small reaction cross sections (~ 1 mb)
  - Intensity required ~ $10^3 - 10^4$ s$^{-1}$

- Cross sections drop rapidly with energy
  - Low Energy reactions

⇒ limit the experimental reach of transfer reactions

Energy-degraded intense beams

⇒ Large energy spread of the beams

Sensitivity to what part of nucleon correlations ⇒ Reaction energy
Summary I : One-Nucleon Transfer

Analyzed > 2000 measured angular distributions systematically using CH89 potential and conventional n-bound state parameters → Spectroscopic Factors

88 g.s. & 565 excited-state SFs → Compare to shell model (Oxbash) to test the residual interactions

Benchmark and Essential framework to understand structure information using transfer reactions

p(^{34}\text{Ar},d)^{33}\text{Ar} & p(^{46}\text{Ar},d)^{45}\text{Ar}

n-SF -- No strong dependence of neutron correlations on asymmetry

Intriguing questions:
Reaction mechanisms of transfer and knockout reactions
Pairing Correlations Using Transfer Reactions

**Two-like nucleon Transfer Reaction**

**Similarity between pairing field and 2-body transfer operator**

Two-nucleon transfer reactions like (t,p) or (p,t) $\rightarrow$ specific tool to probe $T=1$ pair correlations

Ground-state composed of BCS pairs, two-nucleon transfer cross sections enhanced


$^{76}\text{Ge}$ & $^{76,78}\text{Se}(p,t)$ strength: predominately to the ground states $\rightarrow$ simple BCS paired states

How to get more quantitative + systematic knowledge of *nn-pairing*?
**nn-pairing in Sn Isotopes**

Pair Transition density – Skyrme HFB + QRPA approach

M. Matsuo et al., PRC 82, 024318 (2010)
H. Shimoyama, M. Matsuo, paper submitted

**How to see & interpret these nn-pairing structure in Transfer Reaction?**

Insight → First Step: Systematic Reaction Calc.

- **One-step transfer + QRPA Form Factor**

Planned: Two-step Calculations

**TWOFNR, M. Igarashi et al.,**
Calc: D.Y. Pang (Peking), Y. Aoki (Tsukuba)

**Structure Calc.**
Pair Transfer Strength from QRPA Form Factor

**(p,t) to resonance states → Width**

Another useful observables?

**Reaction Calc: 0^+_2 & 2^+_1 (in progress)**
Advanced 2n Transfer Calculations

Calculation of **absolute** \((p,t)\) cross sections:
- Proper pairing interaction
- Multistep & All Terms


<table>
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<tr>
<th>(\sigma(\mu b))</th>
<th>5.11 MeV</th>
<th>6.1 MeV</th>
<th>10.07 MeV</th>
<th>15.04 MeV</th>
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<tr>
<td>total</td>
<td>1.29 (\times) (10^{-17})</td>
<td>3.77 (\times) (10^{-8})</td>
<td>39.02</td>
<td>750.2</td>
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<tr>
<td>successive</td>
<td>9.48 (\times) (10^{-20})</td>
<td>1.14 (\times) (10^{-8})</td>
<td>44.44</td>
<td>863.8</td>
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<tr>
<td>simultaneous</td>
<td>1.18 (\times) (10^{-18})</td>
<td>8.07 (\times) (10^{-9})</td>
<td>10.9</td>
<td>156.7</td>
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<tr>
<td>non–orthogonal</td>
<td>2.17 (\times) (10^{-17})</td>
<td>7.17 (\times) (10^{-8})</td>
<td>22.68</td>
<td>233.5</td>
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<tr>
<td>non–orth.+sim. pairing</td>
<td>1.31 (\times) (10^{-17})</td>
<td>3.34 (\times) (10^{-8})</td>
<td>3.18</td>
<td>17.4</td>
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<tr>
<td></td>
<td>1.01 (\times) (10^{-19})</td>
<td>6.86 (\times) (10^{-10})</td>
<td>0.97</td>
<td>14.04</td>
</tr>
</tbody>
</table>

\(^{132}\text{Sn}(p,t)^{130}\text{Sn}\)

Q: Best reaction energy for 2N-transfer expt.? 
Energy region \(\rightarrow\) large cross sections & good control of reaction mechanism (calculation).

Q: Other probe \((^{18}\text{O},^{16}\text{O})\) etc \(\rightarrow\) Structure ?

Ans: from Reliable Reaction Calc.
In nuclei: 4 types of Pairs

Isovector (T=1, S=0) nn, pp, np pair  
*np should be similar to nn & pp*

Isoscalar (T=0, S=1) np pair (deuteron-like)  
→ new phase of nuclear matter

Theoretical & experimental efforts  
since 60’s → Contradicting opinions & results!

**Neutron-Proton Pair Correlations**

- **Isovector (T=1) np-pairing**  
  Well defined from the Isospin Symmetry

- **Isoscalar (T=0) np-pairing**  
  A lot of uncertainties !!

N=Z unique system  
for np-pairing studies!
Previous Observables for np-pairing

Extra Binding Energy of N=Z nuclei
“Wigner Energy”

T(T+1) – simple symmetry energy

Change Experimental Observables from static properties → dynamic counterparts!
Neutron-Proton Transfer Reactions

Interacting Boson Model (IBM-4)

**Deuteron Transfer in N = Z Nuclei**

P. Van Isacker, D. D. Warner, and A. Frank

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(Received 14 September 2004; published 29 April 2005)

**T=0 (T=1) pairing:**

*enhanced transfer probabilities* \(0^+ \rightarrow 1^+ (0^+ \rightarrow 0^+)\) states

Measure the np transfer cross section to T=1 and T=0 states

Absolute \(\sigma(T=1)\) and \(\sigma(T=0)\) – character and strength of the correlations

\(\sigma(T=1) / \sigma(T=0)\) – interplay of T=1 and T=0 pairing modes

**Reactions**

- (p, \(^3\)He), (\(^3\)He,p) \(\Delta T=0,1\)
- (d,\(\alpha\)), (\(\alpha\),d) \(\Delta T=0\)
- (\(\alpha\), \(^6\)Li), (\(^6\)Li,\(\alpha\)) \(\Delta T=0\)
**np-Transfer Reactions using Radioactive Beams**

- Proof of Principle (LBNL) – successfully completed  
  $^3\text{He}(^{44}\text{Ti},p)$ @ 4.5 AMeV at ATLAS

- Approved experiments at ISAC2  
  $^{48}\text{Cr}, ^{72}\text{Kr}$ – ($^3\text{He},p)$  
  **LBNL, ANL, TRIUMF**

- Plan: ReA3/NSCL using AT-TPC (LBNL)

- Approved experiments at GANIL  
  $^{48}\text{Cr, }^{56}\text{Ni}$ -- (d, $\alpha$) @ ~30 AMeV

Insight / physics of np-pairing?  
Methodology / framework established?  
Physics from light $N=Z$ stable nuclei?
Systematics of $T=0$ & $T=1$ \textit{np}-pairing in $sd$-shell

Ratio of cross section ($T=1/ T=0$)
- reducing systematic effects of absolute normalization

from A. Macchiavelli (LBNL)

Shiro Yoshida, NP 33, 685 (1962)

\[ \text{Superfluid limit } \sim (2\Delta_{T=1}/G)^2 \]

\[ \text{Single-particle estimate } \sim (\text{spin})x(3\text{He,p})x(LS \rightarrow jj) \]

\textbf{Inconsistencies in the trends ($sd$-shell):}

- Closed-shell nuclei $^{16}\text{O}$, $^{40}\text{Ca}$ NOT follow single-particle estimate?
- No intuitive understanding – $^{20}\text{Ne}$, $^{24}\text{Mg}$ follow single-particle prediction?
- Doubtful increase of $> a$ factor of 10 from $^{24}\text{Mg}$ to $^{28}\text{Si}$?

Need systematic measurements dedicated to \textit{np}-pairing studies!
Systematics of $T=0$ & $T=1$ np-pairing in sd-shell

Systematic measurements spanning sd-shell nuclei – approved RCNP E365

$^{24}$Mg($^3$He,p), $^{32}$S($^3$He,p) – Oct, 2011

$^{24}$Mg(p,$^3$He), $^{28}$Si(p,$^3$He) & $^{40}$Ca(p,$^3$He)

Framework & Baseline -- studies of np pairing in heavier $N=Z$ nuclei (RI Beams)
Systematics of $T=0$ & $T=1$ $np$-pairing in $sd$-shell

$N=Z$ nuclei in $sd$-shell

$^{24}$Mg($^{3}$He,p) @ 25 MeV

Online Results

Comparison at $0^\circ$

(online results – very preliminary)

Also one-nucleon transfer data

$^{24}$Mg($^{3}$He,p) @ 25 MeV

Intermediate States
np-Transfer Reactions – Stable \(N=Z\) nuclei

New Structure of \(np\)-pairing:
- transfer amplitudes from SM / pair operators
- matrix elements from spherical/ projected SM
- formulating \(np\)-pairing using QRPA
- including \(T=0\) \(np\)-pairing based on MF / SLAP

Structure Input:
many-body wave functions & transition matrix density

\[\begin{array}{c}
\text{I.J. Thompson (LLNL): Full one-step & two-step} \\
\text{transfer reaction calculations (FRESCO)}
\end{array}\]

\[\begin{array}{c}
\text{Framework / Baseline -- studies of np pairing in heavier N=Z nuclei (RI Beams)}
\end{array}\]
Summary II : Two-Nucleon Transfer

\( ^{\text{ASn}}(p,t) \) Reaction Calc.

Reliable Calculations
→ Experimental planning
(eg. Best reaction energy)

\( 2n \)-transfer → Sensitivity to pairing properties of dilute neutron matter

\( np \)-transfer → Dynamical Effects of np-pairing

Systematic measurements in \( sd \)-shell nuclei

Benchmark & Baseline of \( np \)-pairing research

\( N=Z \) nuclei in \( sd \)-shell

\( ^{32}\text{S}(\text{new}) \)

\( ^{24}\text{Mg}(\text{new}) \)

\( ^{3}\text{He},p \)