Spectroscopic Factors of Ar isotopes from transfer and knock-out reactions

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

Experiment: $^{34,46}$Ar(p,d) Transfer Reactions in Inverse Kinematics
→ Comparisons to knockout results
→ Asymmetry Dependence of Neutron Correlations
Questions about spectroscopic factor measurements

*Is there a clear understanding of the uncertainties (both data and theory)?*

*Are there disagreements in the structure obtained using different reaction probes?*

*How would one get absolute SFs from transfer or is this not possible?*

*Are there specific experiments or theoretical developments that would move us forward?*
Spectroscopic Factor from experiments

Three main experimental techniques $\rightarrow$ SF(expt)

- **(e,e’p)**
  - Theory description is clear (plane-wave impulse approximation)
  - Only stable nuclei, only proton SF

- **(d,p)**
  - Stable & exotic nuclei
  - Particle- & hole-state
  - High & low energy
  - Long history (>50 years)
  - Beam intensity (>10⁴ pps)

- **Knockout reaction**
  - Exotic nuclei
  - Very low beam intensity (~ $10^2$ pps)
  - High energy (>50MeV/A)
  - So far only hole-state
SF’s Reduction and Asymmetry Dependence

J. Lee et al., PRC73, 044608 (2006)

\[ \Delta S = S_n - S_p \text{ for } n-SF \]
\[ \Delta S = S_p - S_n \text{ for } p-SF \]

\((e,e'p)\) -- nuclei near closed shell

- **Constant** \(\sim 30\text{-}50\%\) of SF reduction compared to IPM

One-nucleon knockout -- away from stability

- **Measured SF relative to LB-SM strongly depends on the asymmetry**
- **More reduction experienced by strongly bound valence nucleon**

How about Transfer Reactions?


- Constant \(\sim 30\text{-}50\%\) of SF reduction compared to IPM

\(A. \ Gade\ \text{et\ al.,
PC77, 044306 (2008)}\)

\(\n(p)\ \text{knockout}\)
Experimental SFs from transfer reactions

Spectroscopic factor (SF)

- reflects the properties of valence neutron
- independent of incident energy

Need systematic approach → consistent SFs

Past SF analysis are (mis)guided by shell-model!

Example: $1f_{7/2}$ n SF in $^{41}\text{Ca} = ^{40}\text{Ca} + n$

$d\sigma/d\Omega$ (mb/sr)

$^{14}\text{N}(d,p)^{15}\text{N}$

$E_d = 12\text{ MeV}$

J. Schiffer

J. Lee et al., PRC75, 064320 (2007)
Systematic methods for consistent spectroscopic factors

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

Johnson- Soper Adiabatic Distorted Wave (AWD) to take 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 \( r_0 = 1.25 \text{ fm} \) & \( a_0 = 0.65 \text{ fm} \); depth adjusted to reproduce experimental binding energy.

→ Compute with TWOFNR code

Johnson & Soper, PRC1,976(1970)

TWOFR from Jeff Tostevin (University of Surrey)
Quality Control of extracted SFs

80 g.s. SFs for Li to Cr (~ 430 (p,d) and (d,p) angular distributions)

\[ B(p,d)A : SF_+ ; \quad A(d,p)B : SF_- \]

Ground-state to ground-state transition

\[ \rightarrow SF_+ = SF_- \text{ (Detailed balance)} \]

18 nuclei have both $SF_+$ and $SF_-$. 

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**Associated uncertainty**

- Standard deviations
- $20\% / \sqrt{N}$

-- $SF_+ = SF_-$  \rightarrow Systematic method works
-- 20% uncertainty for each measurement
Comparisons of $(e,e'p)$ and $(p,d)$&$(d,p)$ transfer reactions


$S/(2j+1)$

Mean Field Theory

$\nu$O $^{48}$Ca $^{90}$Zr $^{7}$Li $^{12}$C $^{40}$Ca $^{208}$Pb

VALENCE PROTONS

$S/(2j+1)$ vs target mass

$SF(\text{Transfer})/SF(\text{IPM})$

J. Lee et al., PRC75, 064320 (2007)

$(e,e'p)$ -- nuclei near closed shell

- Constant $\sim 30-40\%$ of $SF$
- reduction compared to IPM

$SF_{\text{exp}}/SF_{\text{IPM}} = 1$

Pure single-particle state

$SF_{\text{exp}}/SF_{\text{IPM}} < 1$

Beyond IPM
Comparisons to IPM

Independent Particle Model (IPM)

\[ H = \sum_i \left( \frac{\vec{p}_i^2}{2m} + U(r_i) \right) \]

Magic number

\[ N=2 \]

\[ N=8 \]

\[ N=20 \]

Pure single-particle state

IPM needs refinement?
Survey of Neutron Spectroscopic Factors and Asymmetry Dependence of Neutron Correlations

Correlations between nucleons
- Mixing of particle-hole configuration near the fermi surface
- Weakening of single-particle strengths

How good the interaction in LB-SM can describe the nucleus?

Large Basis Shell Model (LB-SM)

\[ H = \sum_i \left( \frac{\vec{p}_i^2}{2m} + U(r_i) \right) + \sum_{i<j} V_{NN}(\vec{r}_i - \vec{r}_j) - \sum_i U(r_i) \]

Mean field  Residual interactions

Some correlations missing in the interactions?

\[ \frac{SF_{\text{exp}}}{SF_{\text{LB-SM}}} < 1 \]

LB-SM description is accurate

\[ \frac{SF_{\text{exp}}}{SF_{\text{IPM}}} < SF_{\text{LB-SM}} \]
Ground-state Spectroscopic Factors of Z=3-24

IPM + Maximal pairing

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

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

LB-SM predictions (Residual interactions)
20% agreement

LB-SM code: Oxbash, Alex Brown (MSU)

M.B. Tsang and J. Lee et al., PRL 95, 222501 (2005)
Predictive power of transfer reaction cross sections

M.B. Tsang and J. Lee et al., PRL 95, 222501 (2005)

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

Ni isotopes -
Ground states

\~SF(LB-SM)
from good
interactions in
Hilbert spaces

CH89
approach in ADWA model

\[ SF_{\text{ADWA}} \]

\[ SF_{\text{LB-SM}} \]

\[ SF_{\text{SM}} \]

\[ SF_{\text{ADWA}} \]

USDA/USDB
Excited states

GXPF1A
Full Basis

Excited states

\[ SF_{\text{ADWA}} \]

\[ SF_{\text{LB-SM}} \]
Suppression of Spectroscopic Factors in Transfer Reactions

Global CH89 + \( r_0 = 1.25 \text{ fm} \) with minimum assumption \( \rightarrow \) consistent SF with LB-SM

Predictive power for experimental x-sections & Astrophysics rates!

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

\(~SF(\text{LB-SM})\) from good interactions in Hilbert spaces

\( r_0 = 1.25 \text{ fm} \) \( \rightarrow \) HF rms radius

Global CH89 \( \rightarrow \) microscopic nucleon-nucleon JLM + HF densities

JLM optical potential + bound n-radii constrained with HF geometry \( \rightarrow \) Overall \( \sim 30\% \) reduction in SFs
Neutron transfer reactions for neutron rich and proton rich Ar isotopes

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

Inverse kinematics at 33MeV/u

NSCL Expt 05133 (Oct 19-30, 2007)

Thesis (2010)
Jenny Lee

\( n(p) \) knockout

\( ^{34}\text{Ar} \)

\( ^{46}\text{Ar} \)
L-matching—desirable but not necessary

\[ L \approx Q \cdot R = |K_{in} - K_{out}| \cdot R \]

Condition is well-matched \( \rightarrow \) transferred momentum is bound by the condition to \( \sim \pm 1 \)

- nucleon-transfer probability to that particular state would be relative large
- contributions from other reaction channels are negligible
- simple one-step DWBA description to the data is valid
Asymmetry dependence of neutron correlations – Transfer Reactions

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

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

Beam from A1900

Focal Plane

Target Chamber

S800

Experimental Setup

Focal Plane

Target Chamber

S800

Experimental Setup

Focal Plane

Target Chamber

S800

Experimental Setup

Focal Plane

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Focal Plane

Target Chamber

S800
High Resolution Array (HiRA)

16 HiRA telescopes  
- efficiency ~40%

1.5mm Si

65μm Si  

- 1024 pixels (2mm x 2mm)
- 0.16° at 35 cm setup

Energy resolution:
DE ~50 keV; EF ~70keV
The observed resolutions are reproduced by GEANT4 simulations (finite beam spot, energy + angular straggling, detector resolutions).

J. Lee et al., PRL104, 112701 (2010).
Transfer SF’s depend less strongly on the neutron-proton asymmetry than do those measured in knockout reactions.
Results indicate that
\[ \frac{d\sigma}{d\Omega}_{\text{Exp}} = SF_{\text{LB-SM}} \cdot \frac{d\sigma}{d\Omega}_{\text{ADWA}} \]

Important for astrophysical applications
Systematics can be used to test SM interactions & spin assignments confirmations.

Summary I: Predictive power of transfer reaction cross-sections
Summary II: SF’s depends on choice of OMP and bound state geometry.

J. Lee, J.A. Tostevin et al., PRC 73, 044608 (2006)

J. Lee et al., NSCL Thesis (2010)
Are there specific experiments or theoretical developments that would move us forward?

Charity:
Application of the DOM to \((p,d)\) and \((d,p)\) reactions.

HiRA
Perform \(34\text{Ar}(p,d)\) at \(E/A=70\text{ MeV}\); \(32\text{Ar}\)?

Theory development: Ron Johnston & others

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Jeff Tostevin (University of Surrey)
Mihai Horoi (Central Michigan University)
Ming-chung Chu(朱明中), Shi Chun Su(蘇士俊), Jiayan Dai(戴家琰)(Chinese University of Hong Kong)