Neutron Spectroscopic Factors from transfer reactions with rare isotopes

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

Experiment: $^{34,46}$Ar(p,d) Transfer Reactions in Inverse Kinematics
Thesis: Jenny Lee

$^{56}$Ni(p,d) & $^{56}$Ni(d, $^3$He) Transfer Reactions in Inverse Kinematics
Thesis: Alisher Sanetullaev; Tilak Ghosh (IUSSTF Fellow)
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Survey: Extractions of Neutron Spectroscopic Factors using systematic approach from Transfer Reactions

Experiment: $^{34,46}\text{Ar}(p,d)$ Transfer Reactions in Inverse Kinematics
Asymmetry of nucleon-nucleon correlations
$^{56}\text{Ni}(p,d)$ & $^{56}\text{Ni}(d, \text{^3He})$ Transfer Reactions in Inverse Kinematics
particle and hole states in $^{56}\text{Ni}$
The reaction is dominated by 1-step direct transfer.

Elastic Scattering is the main process in the entrance and exit channels.

Adiabatic Distorted Wave Approximation

\[
\frac{d\sigma}{d\Omega} = \langle \psi(B=A+1) | with |\psi(A) \rangle_{\text{core}} \otimes n(\ell j)
\]

\[
S_{l,j} = \frac{\left( \frac{d\sigma}{d\Omega} \right)_{\text{Exp}}}{\left( \frac{d\sigma}{d\Omega} \right)_{\text{ADWA}}}
\]
Systematic method (with minimal assumptions) to obtain consistent spectroscopic factors

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

Johnson- Soper Adiabatic Distorted Wave Appro. (ADWA) to take care of d-break-up effects

- Use global p and n optical potential with standardized parameters (CH89)
- n-potential : Woods-Saxon shape \( r_o = 1.25 \) & \( a_o = 0.65 \) fm; depth adjusted to reproduce experimental binding energy.

\[ A + n \]

→ Compute with TWOFNR code

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

B(p,d)A : SF⁺ ; A(d,p)B : SF⁻

Ground-state to ground-state transition → SF⁺ = SF⁻ (Detailed balance)

18 nuclei have both SF⁺ and SF⁻

-- SF⁺ = SF⁻ → Systematic method works
-- 20% uncertainty for each measurement

Single Particle Nature of Valence Nucleons

$\text{SF} =$ overlap of $|\psi (B) \rangle$ with $|\psi (A) \rangle_{\text{core}} \otimes n (\ell j)$
measures the orbital configuration of the valence nucleons

Textbook Example:
IPM (Austern, pg 291)
For $n$ even

$SF = n$

For $n$ odd

$SF = 1 - \frac{n - 1}{2j + 1}$
Single Particle Nature of Valence Nucleons

$SF = \text{overlap of } |\psi(B)\rangle \text{ with } |\psi(A)\rangle_{\text{core}} \otimes n(\ell j)$

measures the orbital configuration of the valence nucleons

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


the interaction (USDA/USDB) is well understood in sd shell

Excited-state Spectroscopic Factors of sd shell nuclei

M.B. Tsang and J. Lee et al., PRL 95, 222501 (2005)
Neutron Spectroscopic Factors for Ca Isotopes

Shell Model – closed $^{40}$Ca core: mainly single particle states

Experiment: Large fragmentation of excited states even for $^{41}$Ca

Well known problem. Can this be solved?
No short term NN correlations and other correlations included in SM. Why the agreement?

$\text{SF}_{\text{EXP}} = \text{SF}_{\text{SM}}$
Ground State Neutron Spectroscopic Factors for Ni isotopes

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

Description of Ni isotopes requires full basis with $^{40}$Ca core.
Neutron Spectroscopic Factors for Ni isotopes

**Neutron Spectroscopic Factors for Ni isotopes**

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

*Interactions for gfp shell still need improvements*

Need predictions of higher excited states

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

- **XT** interaction uses $^{56}\text{Ni}$ shell closure → quick overall predictions of Ni nuclei.
(e,e’p): Proton SF values deduced from nuclei near closed shells are suppressed by 30-40% compared to IPM.

Correlation is beyond the residual interactions employed in the shell model.

Do transfer reactions yield absolute spectroscopic factors?
Deduced Spectroscopic factors constrained by Hartree-Fock calculations

1. Change the rms radius of the transferred neutron

   No a priori justification to adopt fixed geometry for n-bound states with $r_o=1.25$ fm and $a_o=0.65$ fm

   ➔ Constrain the transferred neutron orbital rms radii with Hartree-Fock (HF) calculations

   ➔ 15 % reduction in the spectroscopic factors

2. Adopt the global potentials derived from nuclear matter effective nucleon-nucleon potential (JLM)

   ➔ Constrain the geometry of the nucleon optical potential with the target by HF calculations through target density

   ➔ Another 15 % reduction in the spectroscopic factors
Quenching observed from \((e,e'p)\) reactions

\[ G.J.\text{Kramer et al., Nucl. Phys. A 679, 267 (2001)} \]

\[ J.\text{Lee et al, Phys. Rev. C 73 \textbf{,} 044608 (2006)} \]

\((e,e'p)\): Proton SF values deduced from nuclei near closed shells are suppressed by 30-40\% compared to IPM.

As long as a systematic approach is used, relative SF can be obtained reliably over a wide range of nuclei.

\[ \rightarrow \] Correlation is beyond the residual interactions employed in the shell model.
Suppression of Spectroscopic Factors in Transfer Reactions

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

Overall ~30% reduction in SFs

Procedure has not been applied to excited states because of difficulties in calculating the HF geometry and density for excited states.

JLM optical potential + bound n- radii constrained with HF geometry → Overall ~30% reduction in SFs
Asymmetry dependence of neutron correlations in knock out reactions

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

(Jenny Lee, 2009)
$p^{(46}\text{Ar},d)^{45}\text{Ar}$

**Kinematics**

- $\text{E}_{\text{level}} (\text{keV})$  
  - 0.0 5/2-, 7/2-
  - 542.1  $^6$ 1/2-, 3/2-
  - 1339.9  $^8$
  - 1416.1  $^{12}$ 1/2-, 3/2-
  - 1660  50 ?
  - 1734.7  $^9$
  - 1770.3  $^8$
  - 1876  1/2-, 3/2-
  - 1911  5
  - 2420  50
  - 2510  1/2-, 3/2-
  - 2757.0  $^{12}$ ?
  - 3230
  - 3294.8  $^8$
  - 3718
  - 3949.7  $^{12}$ ?
  - 4280
  - 4326.1  $^9$
  - 4800
  - 5773

**Q-values**

- $1^{\text{st}}$ e.x. = 0.476 MeV (FWHM: 489 keV)
- g.s. (FWHM: 494 keV)
- 1.34–1.91 MeV
- 2.42–2.76 MeV
- 3.23–3.29 MeV
- 3.72–4.33 MeV
Errors in Reaction theories using Feddeev Calculations

Discrepancy in trends

Equivalent reaction theory errors should be obtained in knockout reactions using the 3-body Feddeev calculations
Single Nucleon Knockout of $^{36}$Ca

Rebecca Shane – Wash U results

Knockout Cross Sections

<table>
<thead>
<tr>
<th>Residue</th>
<th>$\sigma_{\text{exp}}$ (mb)</th>
<th>$\sigma_{\text{thy}}$ (mb)</th>
<th>$R_s = \frac{\sigma_{\text{exp}}}{\sigma_{\text{thy}}}$</th>
<th>$SF_{\text{knock}}$</th>
<th>$SF_{\text{DOM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{35}$K ($d_{3/2}$)</td>
<td>51.1 ± 2.6</td>
<td>64.6</td>
<td>0.83</td>
<td>0.75</td>
<td>0.7-0.8</td>
</tr>
<tr>
<td>$^{35}$Ca ($s_{1/2}$)</td>
<td>5.03 ± 0.46</td>
<td>22.22</td>
<td>0.24</td>
<td>0.21</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Results are consistent with prior knockout analyses
Very different SF from DOM fits
Neutron correlations in N=28 isotones (add more protons)

$^{54}\text{Fe}$; n’s feel the effect most strongly when 2 p’s are removed
Nuclear structure study with \((p,d)\) reactions

Spin assignments from Systematics

\(J^\pi\) assignment

\(^{27}\text{Mg} \text{ (NUDAT)}:\)

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

Expt

SM

5.627, 3/2

5.454, 3/2

5.404, 5/2
Nuclear structure study with (p,d) reactions
Spin assignments from Systematics

Only about 30% of the states with extracted SF can be matched to states from SM calculations.
Corrections for beam positions and beam angles using MCP are important to improve the energy resolutions of the data.
Angular Distributions

$p^{(56}\text{Ni}, d)^{55}\text{Ni}; E/A \sim 37 \text{ MeV}$

Need theoretical predictions for 3.18 MeV state.

Alisher Sanetullaev, Thesis: 2011
Comparison of proton and neutron spectroscopic factors in $^{56}\text{Ni}$

MSU + VECC collaboration

E/A = 37 MeV
$^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni}$

E/A = 80 MeV
$^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni}$

$^{56}\text{Ni} + d \rightarrow ^3\text{He} + ^{55}\text{Co}$

Upcoming Results

MSU + VECC collaboration

E/A = 37 MeV
$^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni}$

E/A = 80 MeV
$^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni}$

Comparison of proton and neutron spectroscopic factors in $^{56}\text{Ni}$

MSU + VECC collaboration

E/A = 80 MeV
$^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni}$

$^{56}\text{Ni} + d \rightarrow ^3\text{He} + ^{55}\text{Co}$
Proton Spectroscopic Factor:

\[ ^3\text{He} + A(N,Z) \rightarrow B(N,Z+1) + d \]
\[ d + A(N,Z) \rightarrow B(N,Z+1) + n \text{ (n is difficult to detect)} \]

\[ SF = \text{overlap of } |\psi (B=A+1)\rangle \text{ with } |\psi (A)\rangle_{\text{core}} \otimes p(\ell j) \]

The reaction is dominated by 1-step direct transfer. Elastic Scattering is the main process in the entrance and exit channels.

Distorted Wave Born Approximation (DWBA)

\[ S_{\ell,j} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Expt}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{DWBA}}} \]

Need Optical Model potentials for \(^3\text{He}, d & n\)

\(^3\text{He} \text{ potential: Becchetti-Greenlees (B-G); GDP08; microscopic} \]

\(d \text{ potentials: Daehnick} \]

\(p \text{ potentials: Woods-Saxon, } ro=1.25 \text{ fm, } ao=0.65 \text{ fm} \]
Fits to $^3$He+(A-p)→d+A

Lee & Pang
The p SF-systematics is not as consistent as the n-SF systematics.

Extracted SF are larger than SM(SF).

Different potentials have different normalization factors \( \pm 50\% \) fluctuations.

Lee, Pang & Yan

Theoretical input and collaborations are welcome.
Physics with HiRA

HiRA core collaboration
Bill Lynch, Betty Tsang, Zibi Chajecki, Daniel Coupland, Tilak Ghosh, Rachel Hodges, Micha Kilburn, Jenny Lee, Fei Lu, Andy Rogers, Alisher Sanetullaev, Jack Winkelbauer, Mike Youngs (Mark Wallace, Frank Delaunay, Marc VanGoethem)

WU in St. Louis  Bob Charity, Jon Elson, Lee Sobotka
Indiana University  Romualdo deSouza, Sylvie Hudan,
INFN, Milan  Arialdo Moroni
Western Michigan University  Mike Famiano,
ORNL  Dan Shapira
Homework Problems—Summary of questions/requests

1. Can SF for excited states in nuclei near closed shell nuclei be predicted with better accuracy?
2. Are there explanations why the SFs extracted using the “standard parameter” set with AWDA agree with LBSM predictions?
3. Better residual interactions are needed for gfp shell in predicting the SFs of the excited states. We also need predictions for higher excited states for the gfp shell nuclei.
4. We need a procedure to apply the HF geometry constraints for the excited states.
5. Is there explanation for the consistent discrepancies between knockout and transfer reactions?
6. Where are the missing strength of the states strongly quenched in knock out reactions?
7. We need errors in knockout reaction theories using the 3-body Feddeev calculations as in PRC83, 034610(2011).
8. Typically, only a small number of states predicted by the shell model can be matched to the experimental results. Can this situation be improved?

10. For proton-SF, we need better theoretical guidance in choosing or deriving $^3$He OM parameters.

11. Can a model similar to AWDA approach be developed for ($^3$He,d) & ($^3$H,d) reactions?
Is elastic scattering data for individual data set the best way to get the optical model potential parameters?

Different sets of parameters were used for the same reaction yield different results.

Need systematic approach including global OM potentials