Neutron spectroscopic factors of N=27 hole-states from (p,d) transfer reactions

$^1\text{H}(^{46}\text{Ar},d) \rightarrow \text{in Inverse Kinematic: J. Lee (PhD)}$

$^1\text{H}(^{56}\text{Ni},d) \rightarrow \text{in Inverse Kinematics: A. Sanetullaev (PhD)}$

Systematics:

$^{46}\text{Ar},^{48}\text{Ca},^{50}\text{Ti},^{52}\text{Cr},^{54}\text{Fe},^{56}\text{Ni}$ (p,d) $^{45}\text{Ar},^{47}\text{Ca},^{49}\text{Ti},^{51}\text{Cr},^{53}\text{Fe},^{55}\text{Ni}$

N=28

N=27
From SD to PF shell nuclei and back

Outline

1. Introduction

2. Operational definition of experimental spectroscopic factors

3. (p,d) experiments to study the hole states in 45Ar and 55Ni, with N=27.

4. Limitations of current SM in describing the excitation from sd to pf shell.

5. Systematic of the energy and SF’s in N=27 isotones

6. Summary
From SD to PF shell nuclei and back
Overlap between microscopic and DFT require benchmark observables
From SD to PF shell nuclei and back

Overlap between microscopic and DFT require benchmark observables

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SD $\otimes$ PF (overlap CI & DFT)

PF (Configuration interaction)

DFT

SD (Ab Initio)
Systematic method (with minimal assumptions) to obtain consistent spectroscopic factors for \((p,d)\) and \((d,p)\) reactions

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

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 \(r_0=1.25\) & \(a_0=0.65\) fm; depth adjusted to reproduce experimental binding energy.

\(\rightarrow\) Compute with TWOFNR code

\[ B=A+n \]
**Quality Control**

**Textbook example:**

For the Ca isotopes, great agreement with IPM and shell model

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

Ground-state to ground-state transition

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

18 nuclei have both \( SF_+ \) and \( SF_- \)

\[ SF_+ = SF_- \rightarrow \text{Systematic method works} \]

\[ \text{-- 20\% uncertainty for each measurement} \]

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Quenching observed from \((e,e'p)\) and knockout reactions

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

\((e,e'p)\): p SF values are suppressed by ~30 compared to IPM

Asymmetry dependence of neutron correlations in knock out reactions

Correlation is beyond the residual interactions employed in the shell model

\(Gade, \text{PRL 93, 042501 (2004)}\)

\(Lee, \text{PRC73, 044608 (2006)}\)
Do transfer reactions yield absolute spectroscopic factors?

With a systematic approach, relative SF can be obtained reliably over a wide range of nuclei.
Updates on the different trends from transfer and knockout

Slide credit: Jenny Lee
Understanding Nucleon Stripping Reaction Mechanisms from Exotic Nuclei at Intermediate Energy

To study the role of core excitations and evaporation channels

Beam: $^{14}\text{O} + ^{12}\text{C}$ at 60 MeV/u
Hodoscope: Heavy residues, decayed protons, (neutrons)
Si Telescopes: Knocked-out protons
Do transfer reactions yield absolute spectroscopic factors?

With a systematic approach, relative SF can be obtained reliably over a wide range of nuclei.

For excited states, HF radii are not available.
No short term NN correlations and other correlations included in SM.

Why the agreement?

Predictions of cross-sections

Test of SM interactions

Extraction of structure information
Ground State Neutron Spectroscopic Factors for Ni isotopes

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

M. Horoi states predicted < 3MeV

- GXPF1A with full fp model space does not require $^{56}$Ni shell closure → CPU intensive
- XT interaction uses $^{56}$Ni shell closure → quick overall predictions of Ni nuclei.

**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
Experimental SF can be used to study nuclear structure and test SM interactions.
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Hole states in N=27 isotones for $^{45}$Ar, $^{47}$Ca, $^{49}$Ti, $^{51}$Cr, $^{53}$Fe, $^{55}$Ni
Z = 18, 20, 22, 24, 26, 28
via pickup reactions A+1(p,d)A
H($^{46}$Ar,d)$^{45}$Ar [MSU]
$^{48}$Ca(p,d)$^{47}$Ca [1-3]
$^{50}$Ti(p,d)$^{49}$Ti [4]
$^{52}$Cr(p,d)$^{51}$Cr [5]
$^{54}$Fe(p,d)$^{53}$Fe [6-9]
H($^{56}$Ni,d)$^{55}$Ni [MSU]

References
[8] 52 MeV Ohnuma JPSJ 32(1972)1466
$^{46}\text{Ar},^{48}\text{Ca},^{50}\text{Ti},^{52}\text{Cr},^{54}\text{Fe},^{56}\text{Ni}$ $(\text{p,d})$ $^{45}\text{Ar},^{47}\text{Ca},^{49}\text{Ti},^{51}\text{Cr},^{53}\text{Fe},^{55}\text{Ni}$

States populated by $(\text{p,d})$ transfer reactions

$2p\ 3/2$ \hspace{2cm} $2p\ 3/2$ \hspace{2cm} $2p\ 3/2$ \hspace{2cm} $2p\ 3/2$

$2s\ 1/2$ \hspace{2cm} $1d\ 3/2$ \hspace{2cm} $1f\ 7/2$ \hspace{2cm} $1d\ 3/2$

$1d\ 3/2$ \hspace{2cm} $1f\ 7/2$ \hspace{2cm} $1f\ 7/2$ \hspace{2cm} $1f\ 7/2$

$2s\ 1/2$ \hspace{2cm} $N=28 \ \text{gap}$ \hspace{2cm} $N=20 \ \text{gap}$ \hspace{2cm} $N=20 \ \text{gap}$

$1d\ 3/2$ \hspace{2cm} $N=28 \ \text{gap}$ \hspace{2cm} $N=20 \ \text{gap}$ \hspace{2cm} $N=20 \ \text{gap}$

$2p\ 3/2$ \hspace{2cm} $1s\ 1/2$ \hspace{2cm} $2s\ 1/2$ \hspace{2cm} $2d\ 3/2$

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 States populated by $(\text{p,d})$ transfer reactions

g.s. $7/2^-$ \hspace{1cm} 1$^\text{st}$ excited states $p3/2^-$ \hspace{1cm} $s1/2^+, \hspace{1cm} d3/2^+$

(often come as doublets)
$^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni}$
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Complete Kinematics
Worse angular (energy) resolution with large beam spot
2 mm strips $\rightarrow$ $\pm 0.16$ deg
10 mm $\rightarrow 0.8$ deg
Require beam position and angle corrections

$^{56}$Ni beam
Beam position and angle determination with MCP
Beam position and angle corrections with MCP
\[ ^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni} \]
Angular Distributions: spin & parity assignments

\[ \frac{d\sigma}{d\Omega} \text{ (mb/sr)} \]

\[ \theta_{c.m.} \text{ (deg)} \]

\[ H^{56}\text{Ni},^2\text{H}^{56}\text{Ni} \]

\[ \text{g.s.} \]

\[ f_{7/2}^- \]

\[ 2.09\text{MeV} \]

\[ P_{3/2}^- \]

\[ S_{1/2}^+ \]

\[ 3.18\text{MeV} \]

\[ d_{3/2} \]

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

(Jenny Lee, 2009)
States that have substantial cross-sections from (p,d) transfer reactions are g.s. ($7/2^-$), 1$^{st}$ excited states ($p3/2^-$) state (very small c.s.), $s_{1/2}^+$, and $d_{3/2}^+$ (often come as doublets).
Angular Distributions: spin & parity assignments

![Graph showing angular distributions with labels for different energy levels (0.542 MeV, 1.75 MeV, 3.95 MeV) and quantum numbers (s, d, p)].

- g.s. $f_{7/2}$
- ADWA
- $\sim 1.75\text{MeV}$
- $\sim 0.542\text{MeV}$
- $p_{3/2}$
- $l=0$
- $d_{3/2}$

$\frac{d\sigma}{d\Omega}$ (mb/sr)

$\theta_{\text{c.m.}}$ (deg)
Hole states in N=27 isotones for $^{45}$Ar, $^{47}$Ca, $^{49}$Ti, $^{51}$Cr, $^{53}$Fe, $^{55}$Ni
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States with substantial cross-sections from (p,d) transfer g.s. $(7/2^-)$, 1st excited states $(p3/2^-)$, $s1/2^+$, $d3/2^+$ (often come as doublets)

States with substantial cross-sections from (p,d) transfer g.s. $(7/2^-)$, 1st excited states $(p3/2^-)$, $s1/2^+$, $d3/2^+$ (often come as doublets)

Well described by standard Shell models

SM problems reflect the importance of SD⊗PF
Agreement with shell model for g.s. and $p_{3/2}$ states
Predictions before measurements
Predictions from SCGF

$^{55}$Ni hole states

$^{57}$Ni particle states

PRC 79, 064313 (2009)
Data:
$s_{1/2}$ and $d_{3/2}$ hole states occur around 2-4 MeV
Theory (SCGF)
$s_{1/2}$ and $d_{3/2}$ hole states occur around $\sim$15 MeV
Comparisons between Data and shell models

Mihai Horoi’s talk
Wanted: Models to describe systematics

![Diagram with energy levels and isotopes]
Wanted: Models to describe systematics

SF values of 1 & 2 correspond to 50% occupation.
Data available to test state of the art coupled SD&PF interactions
Summary

1. The experimental spectroscopic factors are not dead. They should be extracted in a consistent manner.
2. $S_{\text{Fexp}}$ that agree with the state of the art shell models
   a. Provide regions of accuracy of the calculations.
   b. Provide structural information of states populated by direct reactions
   c. Provide benchmark tests for SM residual interactions especially in the PF shell regions.
3. The $s1/2$ and $d3/2$ deep hole states in $N=27$ isotones allow us to explore the couplings of the SD and PF shells and provide data to test the development of SM to describe the emergence of the SD shell to PF shell.
4. Models must describe the systematic trends, not just individual nucleus.
Physics with 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)

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Indiana University  Romualdo deSouza, Sylvie Hudan,
INFN, Milan  Arialdo Moroni
Western Michigan University  Mike Famiano,
ORNL  Dan Shapira
Physics with

Theory Support for 55Ni hole states

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University of Tokyo  T. Otsuka
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Nihon University  T. Suzuki