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:

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

N=28

N=27

Betty Tsang
From nuclear structure to particle-transfer reactions and back
Nov 5-8-13, 2013 Trento, Italy
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
Systematic method (with minimal assumptions) to obtain consistent spectroscopic factors for \((p,d)\) and \((d,p)\) reactions

\[
\frac{d\sigma}{d\Omega}_{\text{EXP}} = SF_{\text{EXP}} \frac{d\sigma}{d\Omega}_{\text{RM}}
\]

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.

→ Compute with \textit{TWOFNR} code \(B=A+n\)

\(40\text{Ca}(d,p)^{41}\text{Ca}\)

\[\begin{array}{c}
\text{4.69} \\
\text{5} \\
\text{6} \\
\text{7} \\
\text{7.2 MeV} \\
\text{11.8 MeV} \\
\text{56 MeV}
\end{array}\]

\[\begin{array}{c}
\text{8} \\
\text{9} \\
\text{10} \\
\text{11} \\
\text{12} \\
\text{12.8} \\
\text{14.3}
\end{array}\]

\[\begin{array}{c}
J. Lee et al., PRC75, 064320 (2007)
\end{array}\]

\textit{TWOFNR} from Jeff Tostevin (University of Surrey)

Johnson & Soper, PRC1,976(1970)
Quality Control

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

Ground-state to ground-state transition
\[ \rightarrow SF_+ = SF_- \quad (\text{Detailed balance}) \]

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

Textbook example:

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

\[ 18 \text{ nuclei have both } SF_+ \text{ and } SF_- \]

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

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

\[ J. \text{Lee et al, Phys. Rev. C75 (2007) 064320} \]

\[ M.B. \text{Tsang, et al, PRL95, 222501 (2005).} \]
Quenching observed from \((e,e’p)\) and knockout reactions

\(\langle e,e’p \rangle\): 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
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.

\[ r_0 = 1.25 \text{ fm} + \text{CH89} \]
SF_{EXP} = SF_{SM}

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

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

$^{56}$Ni core

- $^{40}$Ca core, in fp model space
- GXPF1A – complete basis
  ➔ CPU intensive
Neutron Spectroscopic Factors for Ni isotopes

SF values agree to factor of 2 \( \Rightarrow \) cannot distinguish between two interactions

Interactions for gfp shell still need improvements

Need predictions of higher excited states

\textit{• GXFP1A with full fp model space does not require} \textit{\textsuperscript{56}Ni shell closure} \textit{\( \Rightarrow \) CPU intensive}

\textit{• XT interaction uses} \textit{\textsuperscript{56}Ni shell closure} \textit{\( \Rightarrow \) quick overall predictions of Ni nuclei.}
Experimental SF can be used to study nuclear structure and test SM interactions.
Experimental SF can be used to study nuclear structure and test SM interactions.
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
$^{46}$Ar, $^{48}$Ca, $^{50}$Ti, $^{52}$Cr, $^{54}$Fe, $^{56}$Ni (p,d) $^{45}$Ar, $^{47}$Ca, $^{49}$Ti, $^{51}$Cr, $^{53}$Fe, $^{55}$Ni

States populated by (p,d) transfer reactions

g.s. $^7/2^-$

1$^\text{st}$ excited states
$p^3/2^-$

$s^{1/2}^+$, $d^{3/2}^+$

(often come as doublets)
$^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni}$
Complete Kinematics

$^{56}\text{Ni} + p \rightarrow d + ^{55}\text{Ni}$

1.5mm Si

65μm Si

Csl(Tl)
Worse angular (energy) resolution with large beam spot
2 mm strips → +−0.16 deg
10 mm → 0.8 deg
Require beam position and angle corrections
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

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

\( \theta_{c.m.} \) (deg)

\( g.s. \)

\( f_{7/2}^{-} \)

\( 2.09 \text{MeV} \)

\( d_{3/2} \)

\( p_{3/2}^{-} \)

\( 3.18 \text{MeV} \)

\( s_{1/2}^{+} \)

\( H^{(56\text{Ni},^2\text{H})^{56}\text{Ni}} \)

--- 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

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

- **a)**
  - g.s.
  - \( f_{7/2} \)
  - ADWA

- **b)**
  - 0.542 MeV
  - \( p_{3/2} \)

- **c)**
  - \( \sim 1.75 \text{MeV} \)
  - \( s_{1/2} \)
  - \( d_{3/2} \)

- **d)**
  - \( \sim 3.95 \text{MeV} \)
  - \( l=0 \)

\[ \theta_{\text{c.m.}} \text{ (deg)} \]
Hole states in N=27 isotones for
$^{45}\text{Ar}$, $^{47}\text{Ca}$, $^{49}\text{Ti}$, $^{51}\text{Cr}$, $^{53}\text{Fe}$, $^{55}\text{Ni}$
$Z = 18, 20, 22, 24, 26, 28$
via pickup reactions $A+1(p,d)A$
$H(^{46}\text{Ar},d)^{45}\text{Ar} \ [\text{MSU}]$
$^{48}\text{Ca}(p,d)^{47}\text{Ca} \ [1-3]$
$^{50}\text{Ti}(p,d)^{49}\text{Ti} \ [4]$
$^{52}\text{Cr}(p,d)^{51}\text{Cr} \ [5]$
$^{54}\text{Fe}(p,d)^{53}\text{Fe} \ [6-9]$
$H(^{56}\text{Ni},d)^{55}\text{Ni} \ [\text{MSU}]$

References
[8] 52 MeV Ohnuma JPSJ 32(1972)1466
States with substantial cross-sections from (p,d) transfer
g.s. \((7/2^-)\), 1\textsuperscript{st} excited states \((p3/2^-)\),
s\(1/2^+, \, d3/2^+\) (often come as doublets)

Well described by standard Shell models

SM problems reflect the importance of SD\(\otimes\)PF
Agreement with shell model for g.s. and $p_{3/2}$ states
Angelo Signoracci and B. Alex Brown, PRL 99, 099201 (2007)

Predictions before measurements

First excited state (p3/2)
Predictions from SCGF

$^{55}$Ni hole states  $^{57}$Ni particle states

**Figure**: Energy level diagrams showing $^{55}$Ni hole states and $^{57}$Ni particle states, with labels for different energy levels and states such as $p_{1/2}$, $p_{3/2}$, $f_{5/2}$, $f_{7/2}$, $d_{3/2}$, and $s_{1/2}$, along with the Fermi level ($E_F$) indicated.
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 energy systematics
Wanted: Models to describe the SF 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. SF_{exp} 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 s{1/2} and d{3/2} 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.
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Theory Support for 55Ni hole states

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