Extracting spectroscopic factors from 40 years of (p,d) and (d,p) data

Magic number

N=20

Spectroscopic Factors: measure the single particle nature of the valence nucleons.

Why measure SF

provide rigorous tests to shell model parameters.

Affect the reaction rates in nuclear reactions in astrophysical models (nucleosynthesis, X-ray burst models...)

42Ca
Properties of Single Particle

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

Scattering theory:
e.g. DWBA with many parameters

Inconsistency and uncertainties in measurements

\( SF_{EXP} \xrightarrow{\text{SF}_{SM}} \) Information on single particle wave-functions
SF compilations with values > 0.01 are not consistent to LBSM calculations to better than factor of 2.
X-ray burst light curves from GS 1826-24

Change in light curve if rate of $^{27}\text{P}(p,\gamma)^{28}\text{S}$ is changed by factor of 2.
Consistent analysis yields 20% agreement with SM for g.s. n-SF

What about excited states? They have smaller values but are more important for nuclear astrophysics?
Magnitude of SF decreases with excited states. For astrophysics, excited states SF are important.
Analysis of SF from excited states of $^{17-18}O$, $^{21}Ne$, $^{24}Na$, $^{25-27}Mg$, $^{29,31}Si$, $^{33,35}S$ show that agreement with shell model is better than 30% for SF\_exp>0.05. The mirror nuclei of above isotopes are of astrophysical interest.
Spin assignment from Systematics with SM

- $5.627;3/2^+$
- $3.491;3/2^+$
- $4.15;5/2^+$
- $5.172;3/2^+$
- $5.172;5/2^+$ (wrong $l$

Need more case studies
Interactions for gfp shell still needs improvements. SF values agree to factor of 2.
Summary

1. Last SF review was done by Endt in 1977. A new review of SF values is overdue with more data, better reaction models and better SM calculations; → gives directions for rare-isotope research.

Summer Undergraduate Research Experience, Chinese University of Hong Kong, (SURE) students

Jenny Lee (2004, ground states)

Shi Chun Su (2006, excited states)
Without evaluations, published spectroscopic factors show large fluctuations from analysis to analysis.
Properties of Single Particle

Experimental SF:

\[
S_{gs} = \frac{\frac{d\sigma}{d\Omega}^{\text{EX}}}{\frac{d\sigma}{d\Omega}^{\text{RM}}}
\]

⇒ **Spectroscopic factor (SF)** measures the orbital configuration of the valence nucleons.

⇒ **Importance**

- Provide rigorous tests to shell models.
- Affect the reaction rates in nuclear reactions in astrophysical models (nucleosynthesis, X-ray burst models).
Spectroscopic Studies from (p,d) & (d,p) transfer reactions

Pros:
✓ We know the exact state of the nucleon transferred.
✓ Good understanding of the experimental technique and reaction theory (DWBA) & beyond
✓ Lots of data from past 40 years (NSR).

Cons:
✗ Do we measure the “absolute” spectroscopic factors?
✗ Data appear to give inconsistent results

SF is one of the important properties to understand the structure of the rare nuclei.
Goss, PRC12,1730 (1975)  
\[ E_d = 14 \text{ MeV} \]

\[ \text{SF} = 0.88 \]

Cecil, NPA255,345 (1975)  
\[ E_d = 17 \text{ MeV} \]

\[ \text{SF} = 0.99 \]

Murillo, NPA579, 125 (1994)  
\[ \text{SF} = 1.03 \]

The data differ by factor of 2 but SF’s are nearly the same by varying the input parameters!!
Discrepancies between data sets

*Quoted experimental uncertainties are 6-20%*

![Graph showing data sets for 
\[ {^{11}}\text{B}(d,p)^{12}\text{B} \] and 
\[ {^{12}}\text{C}(d,p)^{13}\text{C} \] reactions.]


**Quality control from independent measurements**
**TWOFNR** (Tostevin)

**Soper-Johnson Adiabatic Approximation**

To take care of $d$-break-up effects.

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

- $n$-potential: Woods-Saxon shape $r_o=1.25$ fm & $a_o=0.65$; depth adjusted to experimental binding energy.

Include finite range & non-locality corrections

**Application**

Apply the technique to a large data set

\[ ^{12}\text{C}(d,p)^{13}\text{C}_{gs} \]


SF=0.75±0.10; SF(SM) = 0.62
### Ground state n-spectroscopic factors for 80 nuclei

<table>
<thead>
<tr>
<th>$Z$</th>
<th>Element</th>
<th>$n$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Li</td>
<td>6, 7, 8, 9</td>
</tr>
<tr>
<td>4</td>
<td>Be</td>
<td>9, 10, 11</td>
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<tr>
<td>5</td>
<td>B</td>
<td>10, 11, 12</td>
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<tr>
<td>6</td>
<td>C</td>
<td>12, 13, 14, 15</td>
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<tr>
<td>7</td>
<td>N</td>
<td>14, 15, 16</td>
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<td>8</td>
<td>O</td>
<td>16, 17, 18, 19</td>
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<tr>
<td>9</td>
<td>F</td>
<td>19, 20</td>
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<tr>
<td>10</td>
<td>Ne</td>
<td>21, 22, 23</td>
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<tr>
<td>11</td>
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<td>12</td>
<td>Mg</td>
<td>24, 25, 26, 27</td>
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<tr>
<td>13</td>
<td>Al</td>
<td>27, 28</td>
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<tr>
<td>14</td>
<td>Si</td>
<td>28, 29, 30, 31</td>
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<tr>
<td>15</td>
<td>P</td>
<td>32</td>
</tr>
<tr>
<td>16</td>
<td>S</td>
<td>32, 33, 34, 35, 37</td>
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<tr>
<td>17</td>
<td>Cl</td>
<td>35, 36, 37, 38</td>
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<td>18</td>
<td>Ar</td>
<td>36, 37, 38, 39, 40</td>
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<tr>
<td>19</td>
<td>K</td>
<td>39, 40, 41, 42</td>
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<tr>
<td>20</td>
<td>Ca</td>
<td>40, 41, 42, 43, 44, 45, 47, 48, 49</td>
</tr>
<tr>
<td>21</td>
<td>Sc</td>
<td>45, 46</td>
</tr>
<tr>
<td>22</td>
<td>Ti</td>
<td>46, 47, 48, 49, 50, 51</td>
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<tr>
<td>23</td>
<td>V</td>
<td>51</td>
</tr>
<tr>
<td>24</td>
<td>Cr</td>
<td>50, 51, 52, 53, 55</td>
</tr>
</tbody>
</table>

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**Jenny Lee, 2004**

**SURE student**
<table>
<thead>
<tr>
<th>Process</th>
<th>Nuclei</th>
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</thead>
<tbody>
<tr>
<td>$S_n$</td>
<td>80</td>
</tr>
<tr>
<td>$(p,d) : S_+$</td>
<td>47</td>
</tr>
<tr>
<td>$(d,p) : S_-$</td>
<td>56</td>
</tr>
<tr>
<td>$(p,d) &amp; (d,p)$</td>
<td>18</td>
</tr>
</tbody>
</table>

- **Equivalent processes** $S_+ = S_-$
- **18 nuclei**

$A+p \rightarrow B+d$  
$B+d \rightarrow A+p$  

$\Rightarrow$ **Self consistency checks**

$\Rightarrow$ **Assign uncertainties**

---

**Quality Control?**

80 nuclei from Li to Cr (~ 430 angular distributions)

20% uncertainties for each measurement
Comparison with Endt’s (Atomic Data and Nuclear Tables 19, 23 (1977)) best SF values in A=21-44 region

**Endt’s SF:**
- **uncertainty :** 25% [(p,d), (d,p), (d,t), (^3He, α)]
- 50 % for (d,p) and (p,d) reactions only
- removal of normalization uncertainties
- mainly based on communication with authors

**Our SF :**
- **uncertainty :** < 20 %
- re-analysis by consistent method and parameters
- can be applied to other data.
Measurements of Spectroscopic Factors

Lapikas, NPA 553, 297c (1993)

Gade, PRL 93, 042501 (2004)

Tsang et al, PRL 95, 222501 (2005)

Mean Field Theory

$S/(2j+1)$

$(e,e'p)$

Nucleon knockout

Ion Energy [MeV]

$S_F$ (Transfer)

$S_F$ (Shell)

Tsang et al, PRL 95, 222501 (2005)
SF values and trends should be the same independent of measurement methods, i.e. \((e,e'p)\), nucleon knockout and transfer reactions should give same SF values.

Measurements of Spectroscopic Factors

Approved experiments: 
\[ p(^{46}\text{Ar}, d)^{45}\text{Ar}; p(^{34}\text{Ar}, d)^{33}\text{Ar} \] – to study possible quenching effects in strong and weakly bound neutrons in rare isotopes.

Lee, PRC73, 044608 (2006); Gade, PRL 93, 042501 (2004)
### $^{31}$Si (mirror nuclei: $^{31}$Cl)  \ T=3/2  \ Sn= 6.587 MeV

#### Experiment: $^{31}$Si (NUDAT)

<table>
<thead>
<tr>
<th>Energy</th>
<th>State</th>
<th>( \frac{\hbar}{2} )</th>
<th>( \frac{\hbar}{2} )</th>
<th>( \frac{\hbar}{2} )</th>
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<tbody>
<tr>
<td>3.54 MeV</td>
<td>3/2-</td>
<td>1.5</td>
<td>0.458</td>
<td></td>
</tr>
<tr>
<td>3.14 MeV</td>
<td>7/2-</td>
<td>1.5</td>
<td>0.620</td>
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</tr>
<tr>
<td>2.79 MeV</td>
<td>5/2+</td>
<td>1.5</td>
<td>0.033</td>
<td>0.048</td>
</tr>
<tr>
<td>2.32 MeV</td>
<td>3/2+</td>
<td>1.5</td>
<td>0.054</td>
<td>0.027</td>
</tr>
<tr>
<td>1.70 MeV</td>
<td>5/2+</td>
<td>1.5</td>
<td>0.012</td>
<td>0.019</td>
</tr>
<tr>
<td>0.76 MeV</td>
<td>1/2+</td>
<td>1.5</td>
<td>0.237</td>
<td>0.219</td>
</tr>
<tr>
<td>0 MeV</td>
<td>3/2+</td>
<td>1.5</td>
<td>0.54</td>
<td>0.58</td>
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</table>

#### Oxbash: $^{31}$Si

<table>
<thead>
<tr>
<th>Energy</th>
<th>State</th>
<th>( \frac{\hbar}{2} )</th>
<th>( \frac{\hbar}{2} )</th>
<th>( \frac{\hbar}{2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 MeV</td>
<td>3/2+</td>
<td>1.5</td>
<td>0.54</td>
<td>0.58</td>
</tr>
<tr>
<td>0.76 MeV</td>
<td>1/2+</td>
<td>1.5</td>
<td>0.219</td>
<td>0.219</td>
</tr>
<tr>
<td>0.82 MeV</td>
<td>1/2+</td>
<td>1.5</td>
<td>0.82 MeV 1/2+</td>
<td></td>
</tr>
<tr>
<td>1.61 MeV</td>
<td>5/2+</td>
<td>1.5</td>
<td>1.61 MeV 5/2+</td>
<td></td>
</tr>
<tr>
<td>2.30 MeV</td>
<td>3/2+</td>
<td>1.5</td>
<td>2.30 MeV 3/2+</td>
<td></td>
</tr>
<tr>
<td>2.87 MeV</td>
<td>5/2+</td>
<td>1.5</td>
<td>2.87 MeV 5/2+</td>
<td></td>
</tr>
<tr>
<td>3.83 MeV</td>
<td>3/2+</td>
<td>1.5</td>
<td>3.83 MeV 3/2+</td>
<td></td>
</tr>
</tbody>
</table>
Evidence for Shell Breaking at $^{56}$Ni

Small magnetic moment of $^{57}$Cu ground state suggests that $^{56}$Ni is not a good doubly-magic core in $^{57}$Cu

Minamisono et al., PRL 96, 102501 (2006)
Sensitivity to different interactions – structure of $^{56}$Ni core

Approved experiments to probe the n & p hole-states in $^{56}$Ni

$p(^{56}$Ni,d)$^{55}$Ni; $d(^{56}$Ni,${}^3$He)$^{55}$Co
Transfer reactions of RI nuclei with Inverse kinematics
The High Resolution Array (HiRA)

Future plans: S2 reconfiguration

- A program of neutron, proton measurements in the S2 vault was favorably reviewed by the program advisory committee at its latest meeting.
- Objectives are to constrain $S(\rho)$, $m^*_{n}$, $m^*_{p}$, $\sigma_{pp}$ and $\sigma_{np}$.
Summary

1. Last SF review was done by Endt in 1977. A new review of SF values is overdue with more data, better reaction models and better SM calculations; \( \rightarrow \) gives directions for rare-isotope research.

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Summary/Suggestions

1. Last SF review was done by Endt in 1977. A new review of SF values is overdue with more data, better reaction models and better SM calculations; gives directions for rare-isotope research.

2. Include projectile fragmentation cross-sections in NuDat as in spallation cross-sections.

3. Publications in Nuclear Data Sheets?

4. Direct inclusion of large sets of data from PRC, NP etc.

5. Search, search, search …incorporate google search engine in the data base?
In near future, transfer reactions will become an important and unique tool to understand structure and reaction mechanism.
Endt:


^{21-23}Ne, \ ^{24}Na, \ ^{25-27}Mg, \ ^{28}Al, \ ^{30-31}Si, \ ^{32}P, \ ^{33-35}S, \ ^{36}Cl, \ ^{37}Ar.

ENSDF


^{21,23}Ne, \ ^{24}Na, \ ^{26-27}Mg, \ ^{32}P, \ ^{33,35}S, \ ^{36}Cl, \ ^{37}Ar.

MSU


^{17-18}O, \ ^{21}Ne, \ ^{24}Na, \ ^{25-27}Mg, \ ^{29-31}Si, \ ^{32}P, \ ^{33,35}S, \ ^{36}Cl, \ ^{37}Ar.