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

Proposed reaccelerated RI beam

USNDP Annual Meeting
Nov 7-9, 2006

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The National Superconducting Cyclotron Laboratory
@Michigan State University
A national user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications.

282 employees, incl. 51 undergraduate and 50 graduate students, 24 faculty

User group of over 600 CCF users

(as of March 05)
World’s first superconducting cyclotron (1982)

K500

World’s most powerful superconducting cyclotron (1989)

K1200

A1900

Coupled Cyclotron Facility (2000)
Example Fragment Separation Technique (NSCL)

100 pnA $^{86}$Kr
5 kW Beam power

8 msr
$\Delta p = 5\%$

Wedge location
D = 5 cm/\%
R = 2500 p/$\Delta p$

65% of the $^{78}$Ni is transmitted
Projectile Fragmentation

- **Fundamental science**
  - Mechanism in the production of rare isotopes
  - Study of basic properties of atomic nuclei

- **Applications**
  - Benchmark data needed to test simulation code.
    - *Beam rate estimates for RI beam facilities*
    - *Design high power accelerators*
    - *Tumor treatment*
    - *Space radiation*
    - *Nuclear waste transmutation*
Rare Isotope Production (Mocko thesis & PRC, in press)

- Nearly 2X more isotopes are produced in fragmentation of $^{48}\text{Ca}$ than $^{40}\text{Ca}$.
- Primary beams: $^{40,48}\text{Ca}$, $^{58,64}\text{Ni}$ and unstable $^{68}\text{Ni}$ and $^{69}\text{Cu}$ beams.
- Data reveal deficiencies of EPAX parameterization.
- Improvement on theoretical understanding of the RI production mechanisms.

NNDC data base for “fragmentation data”
Publication of cross-sections (Nuclear Data Sheets)
Rare Isotope Beams Produced with CCF/A1900

Sherrill (2006)
Nuclear Science at the NSCL

Where are the limits of nuclear stability?

Properties N~Z nuclei
r-p process

Role of Nuclei in the Cosmos
Nuclei Along the N=Z Line
Evolution of Nuclear Structure
Limits of Nuclear Stability
Fundamental Interactions
Reaction Mechanisms

r-process

EOS of n-rich matter

Is there physics beyond the standard model?
Mass measurements

- Mean field near stability
- Strong spin-orbit term
- Mean field for N>>Z?
- Reduced spin-orbit
- Diffuse density
- Tensor force

\[ ^{124}\text{Sn} \]
\[ ^{12}\text{Sn} \]

• Proton Number
• Neutron Number

Near stability

For N>>Z

- \( h_{9/2} \)
- \( f_{7/2} \)
- \( p_{1/2} \)
- \( f_{5/2} \)
- \( p_{3/2} \)
- \( h_{11/2} \)
- \( g_{9/2} \)
- \( d_{5/2} \)
- \( g_{7/2} \)
- \( d_{9/2} \)
- \( s_{1/2} \)
- \( d_{9/2} \)
- \( g_{7/2} \)
- \( d_{9/2} \)

\( 124\text{Sn} \)
\( 12\text{Sn} \)
Experimental Areas at NSCL

215 Fast/slow pixels
55 Bragg counters
ISOTOPE SCIENCE FACILITY AT MSU
Developing Plans for the Future (10-Year Horizon)
ISF@MSU

Large intensity gains (factors of 100-100,000) over current capability rare isotope beams with energies between 0 and 200 MeV/nucleon
ISF Upgrade Options

Modular, expandable capacity to meet future science needs

- Multi-user capability, flexible science-driven selection of upgrade elements
  - Energy/nucleon: 400 MeV $^{238}$U, 539 MeV $^{129}$Xe, 864 MeV $^3$He, 1122 MeV $^1$H
  - Power 400 kW
Extracting spectroscopic factors from 40 years of (p,d) and (d,p) data

Magic number

N=20

N=8

N=2

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

$^{42}\text{Ca}$
Properties of Single Particle

\[ S_{gs} = \frac{\frac{d\sigma}{d\Omega}}{\frac{d\sigma}{d\Omega}}_{RM} \]

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

Independent Particle Model (IPM), SF represents how good can we describe the nucleus as a single particle plus a core.

\[ \frac{S_{exp}}{S_{IPM}} = 1 \]

Orbital description is accurate

\[ \frac{S_{exp}}{S_{IPM}} < 1 \]

Valence nucleon occupies more than one orbit \( \rightarrow \) LBSM.
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.*
Published spectroscopic factors show large fluctuations from analysis to analysis.
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%


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

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>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
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<td>V</td>
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<tr>
<td>24</td>
<td>Cr</td>
<td>50, 51, 52, 53, 55</td>
</tr>
</tbody>
</table>

Jenny Lee, 2004
SURE student

Tsang et al, PRL 95, 222501 (2005)
Quality Control?

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

- \( S_n \): 80 nuclei
- \((p,d) : S_+\): 47 nuclei
- \((d,p): S_-\): 56 nuclei
- \((p,d) \& (d,p)\): 18 nuclei

\[ A + p \rightarrow B + d \quad S_+ \]
\[ B + d \rightarrow A + p \quad S_- \]

Equivalent processes \( S_+ = S_- \)

18 nuclei

\( \Rightarrow \) Self consistency checks

\( \Rightarrow \) Assign uncertainties

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% \([(p,d), (d,p), (d,t), (^3\text{He}, \alpha)]\)
- 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.
Compare with LB-Shell Model (Oxbash, B.A. Brown)

Good agreement with most isotopes

Austern’s values were predicted 40 years ago

Measurements of Spectroscopic Factors

**Nucleon knockout**

- Lapikas, NPA 553, 297c (1993)
- Gade, PRL 93, 042501 (2004)
- 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.

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.
SF’s of excited states for $^{27}\text{Mg}$, $^{30}\text{Si}$, $^{31}\text{Si}$, $^{35}\text{S}$ & $^{36}\text{Cl}$

- The (unstable) mirror nuclei $^{27}\text{P}$, $^{30}\text{S}$, $^{31}\text{Cl}$, $^{35}\text{K}$ & $^{36}\text{K}$ are of astrophysical importance in nucleosynthesis processes.

- No experimental (SF) data exist so reaction rates (and energy levels) rely on shell model calculations.

- Important to establish the accuracies of these calculations by comparing SF data to predictions.

*Shi Chun Su, 2006  
SURE student*
$^{31}$Si (mirror nuclei: $^{31}$Cl)  \( T=3/2 \)  \( S_n=6.587 \) MeV

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

- 3.54 MeV 3/2$^-$
  - $^T_5$ $^N_3$ 0.458
- 3.14 MeV 7/2$^-$
  - $^T_5$ $^N_3$ 0.620
- 2.79 MeV 5/2$^+$
  - $^T_5$ $^N_3$ 0.033
- 2.32 MeV 3/2$^+$
  - $^T_5$ $^N_3$ 0.054
- 1.70 MeV 5/2$^+$
  - $^T_5$ $^N_3$ 0.012
- 0.76 MeV 1/2$^+$
  - $^T_5$ $^N_3$ 0.237
- 0 MeV 3/2$^+$
  - $^T_5$ $^N_3$ 0.54

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

- 3.83 MeV 3/2$^+$
  - $^T_5$ $^N_3$ 0.044
- 2.87 MeV 5/2$^+$
  - $^T_5$ $^N_3$ 0.048
- 2.30 MeV 3/2$^+$
  - $^T_5$ $^N_3$ 0.027
- 1.61 MeV 5/2$^+$
  - $^T_5$ $^N_3$ 0.019
- 0.82 MeV 1/2$^+$
  - $^T_5$ $^N_3$ 0.219
- 0.00 MeV 3/2$^+$
  - $^T_5$ $^N_3$ 0.58
Comparisons to LB-SM (oxbash, B.A. Brown) calculations

Well-known states to establish systematic
Spin assignment from Systematics with SM

Need more case studies
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)

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)
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.