Transfer Reactions on Argon Isotopes

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N-body problem $\rightarrow$ N 1-body problems

(Really <<N)

http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/shell.html

https://en.wikipedia.org/wiki/Nuclear_shell_model
How can we test this picture?

- One answer: **Spectroscopic Factors (SF)**
  \[ SF = \int d\vec{p} \left| \langle \Psi^{N-1} | a_{\vec{p}} | \Psi^N \rangle \right|^2 \]

- SFs are a way to quantize the occupancy of a given single particle orbital

\[ 0 \leq SF \leq 2j + 1 \]

- Can be interpreted as **probability of finding** core state \( N-1 \) within a composite state \( N \) when removing a nucleon in state \( p \)

- Example: \( SF(f_{7/2}, ^{41}\text{Ca g.s.}) = 1.01 \pm 0.06 \)

- Less single-particle like (strong influence of nucleon-nucleon correlations)

- More single-particle like (mean field is a good approximation)

Nuclear reactions can be used to extract $SF's$.
For example, consider a transfer reaction:

- Nucleon(s) transferred to/from a projectile from/to a target
- In this case, consider $A(p,d)A-1$ in inverse kinematics

Transfer Reactions To Study Nuclear Structure

- SF’s are NOT observables...but can be *extracted* from experimental data via comparison to theory
- Transfer reactions have been successfully used to extract SF’s for decades
  - Advent of radioactive ion beams opens up new sections of nuclear chart for exploration
Extracting SFs

- Calculations tell us shape of angular distribution for transfer reaction to a given state with SF = 1
Transfer vs. Knockout

- Different reaction probes of SF *should* be consistent (nuclear structure is invariant)
- **Reduction factor**: compares experimental SF with shell model prediction

\[
R_s = \frac{SF_{\text{EXP}}}{SF_{\text{SM}}}
\]

- Energy dependence of optical potential? Reaction mechanism energy dependent? Techniques/approximations unreliable at extremes of asymmetry, beam energy, cross section? Many body effects?

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- Repeat transfer measurement, but matching the beam energy for the knockout measurement

National Superconducting Cyclotron Laboratory (NSCL)

- Coupled Cyclotron Facility at the NSCL (on the campus of Michigan State University)
  - K500 and K1200 cyclotrons accelerate stable isotopes (from $^{16}\text{O}$ to $^{238}\text{U}$) up to half the speed of light
  - Smash stable beam into Be target: fragmentation produces a wide variety of nuclei, some of which are exotic
  - A1900 Fragment Separator selects particular isotopes of interest, which are delivered to experimental areas

For this experiment
Primary beams: $^{36}\text{Ar}$, $^{48}\text{Ca}$
Secondary beams: $^{34}\text{Ar}$, $^{46}\text{Ar}$

http://www.nscl.msu.edu/public/science/isotope.html
Experimental Setup

Measuring complete kinematics of $^{34,46}$Ar(p,d) at 70 MeV/u

$^{34,46}$Ar + p → d + $^{33,45}$Ar

$^{34,46}$Ar @ 70 MeV/u (from CCF at NSCL)

MCP's

Target (proton)

$^{33,45}$Ar

deuteron

Based on figure courtesy of Jenny Lee
Microchannel plates: MCPs

- Needed to calculate absolute cross section
- Allows for reactions to be localized on target (i.e. better angular resolution)

Microchannel plates: MCPs

- MCPs are each calibrated using brass mask
- With calibrations, we can get beam position at each MCP, and therefore beam position at target
S800 Spectrometer

- TOF, $\Delta E$, $\Phi$, $P$
- Heavy reaction fragment (in this case Ar residue) identification

Ar beam from CCF

S800 Spectrometer

- To calibrate, account for dependence of TOF and ΔE on focal plane coordinates (CRDC positions/angles)

- Same particle can take different trajectories, giving a different TOF and ΔE

![Diagram of S800 Spectrometer with 33Ar label and energy loss vs. TOF matrix]
High Resolution Array: HiRA

- Modular array of Si + CsI charged particle detectors
- Measures energy, position information
- Energy loss in a “thin” detector vs. a “thick detector” yields particle identification (PID)

High Resolution Array: HiRA

• Need two stages of PID (due to kinematics)

Kinematics for $^{46}$Ar(p,d)$^{45}$Ar Gated on S800

$^{45}$Ar

d

ΔE (65μm) E (1.5mm) CsI(Tl)

Lab Energy (MeV)

Lab Angle (Degrees)
Beam Spot Reconstruction for $^{46}\text{Ar}(p,d)^{45}\text{Ar}$

- Beam spot large at target position

\(~300 \text{ mm}^2\) beam spot

\(4 \text{ mm}^2\) per pixel

Reconstructed Target Position

U.S. Department of Energy Office of Science
National Science Foundation
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J. Manfredi, SSGF Annual Review
6/22/2017, Slide 19
Kinematics Comparison

Kinematics Without MCP

Lab Energy (MeV)

Lab Angle (Degrees)

34 32 30 28 26 24 22 20 18 16 14 5 10 15 20 25 30 35 40

Kinematics With MCP

Lab Energy (MeV)

Lab Angle (Degrees)

34 32 30 28 26 24 22 20 18 16 14 5 10 15 20 25 30 35 40
Example Excitation Energy Spectrum

- In the center-of-mass frame:
  - Deuteron energy → Q-value → Excitation Energy of $^{45}$Ar
- Use the number of counts in a given angular range to get cross section
Example Angular Distribution

- Correct for geometrical efficiency
- $^{46}\text{Ar}(p,d)^{45}\text{Ar}_{\text{g.s.}}$
Conclusions

• Spectroscopic factors are an important tool in studying nuclear structure
• Nuclear reactions can be used to probe nuclear structure via extraction of spectroscopic factors
  • Discrepancy between transfer and knockout reactions
• High energy transfer reactions on proton-rich ($^{34}$Ar) and neutron-rich ($^{46}$Ar) argon isotopes were measured at the NSCL
• Next step: perform theoretical calculations, compare to data, and extract spectroscopic factors
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Analysis Progress: HiRA Si Calibration

- 5-point calibration with $^{228}$Th alpha source

![Telescope 5, E Front, Summed 1D Thorium Spectrum](image)
HiRA Efficiency
Bethe Bloch Equation

\[- \frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right] \]

\[\beta \gamma = \frac{p}{E m} = \frac{p}{m}\]

A: atomic mass of absorber
\[K_A = 4\pi N_A r_e^2 m_e c^2 / A = 0.307075 \text{ MeV g}^{-1} \text{cm}^2, \text{ for } A = 1 \text{ g mol}^{-1}\]
z: atomic number of incident particle
Z: atomic number of absorber
I: characteristic ionization constant, material dependent
\(T_{max}\): max. energy transfer (see previous slide)
\(\delta(\beta \gamma)\): density effect correction to ionization energy loss
(p,d) vs. (d,p)

• Masses with both measurements range from 11 to 53
• Good check for consistency of transfer
Deriving SF relation

- Fermi’s golden rule
- DWBA Approximations:
  
  Approximations: one step direct process, reaction weak enough to use 1st order perturbation theory, adiabatic approximation (deuteron breakup), distorted waves

- Assuming single particle states...
Evaluation of transfer theory

- Nunes, et al claim transfer data corroborates knockout data
- Quantified errors in reaction theory from optical potential by performing exact three-body Faddeev calculation
- But...large (20%) divergence between Faddeev and ADWA results
- PRC 83, 034610
Woods-Saxon Potential

\[ V = -\frac{V_0}{1 + \exp\left(\frac{r-R}{a}\right)} \]

- Plus spin orbit:

\[ V = V(r) - f(r) \vec{l} \cdot \vec{s} \]
Ion Chamber Energy check

- Energy loss calculations performed with LISE++
Knockout vs (e, e’ p)
CRDCs