Neutron Single Particle Strengths in $Z = 20, 22, 24$ Isotopes

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Content

• Background knowledge:
  (1) Spectroscopic factor (SF) and its importance
  (2) Motivation of this project

• Investigation of Ca, Ti, Cr isotopes by considering (d, p) transfer reaction
  (1) Z=20, Ca41 → Ca43 → Ca45 → Ca47 evolution
  (2) Comparison of <SF_ex> and SF_sm

• Conclusion

• Appendix:
  (1) N=27, Ca47 → Ti49 → Cr51 evolution
  (2) N=29, Ar47 → Ca49 → Ti51 → Cr53 evolution
• **Spectroscopic Factor:**

  It describes the orbital configurations of valence nucleons. Since it reveals the fundamental property of nuclides, it is independent of incident energies or involved reactions.

• **Experimental Spectroscopic Factor:**

  \[
  \left( \frac{d\sigma}{d\Omega} \right)_{ex} = SF_{ex} \cdot \left( \frac{d\sigma}{d\Omega} \right)_{th}
  \]

  calculated by scattering theory, e.g. DWBA.

  obtained by systematic and consistent method.

  measured by experiment

• **Theoretical Spectroscopic Factor:**

  \[
  SF_{th} = \left[ \int \Phi(\vec{r}) \, d\tau \right]^2, \quad \text{where } \Phi(\vec{r}) = \langle \Psi^A | \Psi^A \rangle
  \]

  calculated by shell model with residual interaction included, “gx1a”.

  If \( SF_{th} \gg SF_{ex} \), our theory explains the experiments very well.

  If \( SF_{th} \gg \) or \( \ll SF_{ex} \), our theory needs modification; or experimental analysis needs revised.
Shell Model

- Some nuclei are found to be more tightly bounded than others → number of protons/neutrons 2, 8, 20, 28, 50, 82, 126 (Magic Numbers) → origin of shell model.

- Analogous to the atomic electron model which uses the Pauli principle to describe the structure of electrons in terms of energy levels developed by in 1949.

- Like the electron configuration,
  1. valence nucleons are moving in a mean field potential of the closed shell
  2. having n, l, j principle quantum numbers.

From 40Ca using shell model:

1. Assuming spherical core
2. Using pairing interaction, maximal pairing
3. Adding residual interaction

Our shell model calculation is done by Oxbash (computer program) developed by Prof. Alex Brown et al. and Prof. Horoi’s computer gx1a (full space) calculation.
Experimental Spectroscopic Factor

• To extract spectroscopic factor by using consistent and systematic method to analyze all different experimental data.

\[
\left( \frac{d\sigma}{d\Omega} \right)_{ex} = SF \cdot \left( \frac{d\sigma}{d\Omega} \right)_{th}
\]

Measured by experiment

Calculated by TwoFNR (computer program) based on DWBA and Optical Model Potential

• (1) DWBA calculation with adiabatic approximation to take d-break-up into account.

• (2) Global optical potential with global optical model parameters.

• (3) Non-local and finite range corrections.

TwoFNR developed by Prof. Jeff Tostevin

J. Lee et al, Phys. Rev. C, in press
Comparisons with shell model predictions

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


2004 SURE Talk by Jenny Lee
Excited States of sd shell nuclei

- The previous work was about ground state.
- For the excited states of sd shell nuclei, the agreement with shell model is within 30% uncertainty.
- 30% is also consistent with experimental uncertainties.

Data from Shichun Su, Jenny Lee and Betty Tsang

2006 SURE Talk by Shichun Su
Ca, Ti, and Cr isotopes

- We study three regions:
  - Fixed proton number $Z=20$, 41Ca, 43Ca, 45Ca and 47Ca
  - Fixed neutron number $N=27$, 47Ca, 49Ti and 51Cr
  - Fixed neutron number $N=29$, 47Ar, 49Ca, 51Ti and 53Cr

From www.nndc.bnl.gov/chart

<table>
<thead>
<tr>
<th>Element</th>
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Previous Ca Isotopes’ Ground State Study

• Comparison with Large-Basis Shell Model (Oxbash) and Independent Particle Model (IPM) for Ca isotopes, $^{40}$Ca – $^{48}$Ca


✓ SF’s of $^{40}$Ca–$^{48}$Ca isotopes are well described by a pairing interaction and agree very well with IPM and shell model.

✓ The $1f_{7/2}$ valance neutrons in Ca isotopes are good single particles with spherical cores.

Is this true also for excited state?
### Ca Odd Isotopes

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<th>Neutron</th>
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### Neutron States

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The NSCL is funded in part by the National Science Foundation and Michigan State University.
• For ground state, experimental results can be well explained by shell model.
• (SM) $N \uparrow \rightarrow$ excited energy $\downarrow$, SF_sm $\downarrow$; (EX) $N \uparrow \rightarrow$ can’t easily tell the change in excited energy and $<SF_{ex}>$ due to fragmentation of single particle strengths.
• (SM) $N \uparrow \rightarrow$ fragmentation $\uparrow$; (EX) even for 41Ca, as for excited state, it has a fragmentation. $\rightarrow$ Spherical core assumption can’t be well applied when talking about excited states.
Comparison Between Different Plots of Odd Ca

Only a few states can be compared in the below plot due to inability of shell model to predict these states.
The NSCL is funded in part by the National Science Foundation and Michigan State University.

$<SF_{ex}>$ vs. $SF_{sm}$ only g.s.

$<SF_{ex}>$ vs. $SF_{gx1a}$ only g.s.

- $41Ca$
- $43Ca$
- $45Ca$
- $47Ca$
- $49Ca$
- $47Ti$
- $49Ti$
- $51Ti$
- $51Cr$
- $53Cr$
- $55Cr$
• Why there are points whose \(<SF_{\text{ex}}\) is much less than corresponding SF_{\text{gx1a}}?
• These states contain fragmentation while the corresponding states calculated in shell model mainly reflect single particle states.
The NSCL is funded in part by the National Science Foundation and Michigan State University.

<SF_ex> vs. SF_sm without g.s.

<SF_ex> vs. SF_gx1a without g.s.

- 41Ca
- 43Ca
- 45Ca
- 47Ca
- 49Ca
- 47Ti
- 49Ti
- 51Ti
- 51Cr
- 53Cr
- 55Cr
Conclusion

- From $<\text{SF}_{\text{ex}}>$ vs. SF_sm plot, we can see the agreement between experiment and theory overall is good, but not as good as sd shell.

- For $^{41}\text{Ca}$, it used to be considered as a perfect spherical core according to the ground state data; but concerning to experimental work, it is found that excited state of $^{41}\text{Ca}$ has much more fragmentation, far from single particle state.

- Also for other odd Ca isotopes, the states turn out to be more fragmented than predicted theoretically.
Acknowledgement

• Many thanks to Prof. Tsang for her instructions with a lot of physics insights and her guidance on which direction I should follow.

• Many thanks to Jenny Lee for her always warm-hearted helps and being patient to provide me a lot of explanations.

• Many thanks to Prof. Horoi for his help with the theoretical calculations on Ti, and Cr.

• Many thanks to Prof. Brown and his student to give some time to attend the meeting to offer precious insights and comments.
Thank you very much!
Appendix: Ti and Cr involved
The NSCL is funded in part by the National Science Foundation and Michigan State University.

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<th>Neutron</th>
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- For ground state, $\langle SF_{ex} \rangle$ can be well explained by $SF_{sm}$.
- For excited state of $^{47}\text{Ca}$, $\langle SF_{ex} \rangle$ turns out to be smaller than $SF_{sm}$.
- For $^{51}\text{Cr}$, experimental results have more fragmentation than shell model predicted.
- Only two states are shown due to insufficient experimental information.
- Theoretically, more states can be calculated. Here fpd6pn reaction was used to do the calculation. Experimentally, more states can also be measured.
The NSCL is funded in part by the National Science Foundation and Michigan State University.

\[ N=29 \]

<table>
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<td>_<em><strong>16O</strong></em>_</td>
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The NSCL is funded in part by the National Science Foundation and Michigan State University.
• The trend shown in experimental results is similar as predicted in shell model.
• From 49Ca to 53Cr, we observe that when Z=20 increase to Z=24, 53Cr is more fragmented.
Comparison Between Different Plots of $N=27$ and $N=29$

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Comparison Between Different Plots of $N=27$ and $N=29$
• For N=27 and N=29 (except for 47Ar), when proton number increases, the excited energy level decreases, and corresponding spectroscopic factor decreases.

• 47Ar’s first excited energy compared with 49Ca is even lower, is because it doesn’t have a closed core.

• For N=27 and N=29, when proton number increases, excited state is more fragmented, e.g. 51Cr, 53Cr.
Appendix

- IPM assumption:
  - (1) $^{40}\text{Ca}$ is a spherical core
  - (2) Pairing interaction, maximal pairing

$$S = n \quad \text{for even } n$$
$$S = 1 - \frac{n - 1}{2j + 1} \quad \text{for odd } n$$
Previous Experimental Spectroscopic Factor

Example: If $\frac{7}{2}$ neutron SF in $^{41}$Ca = $^{40}$Ca+n
Data from Jenny Lee

\[
\left( \frac{d\sigma}{d\Omega} \right)_e = SF_{ex} \cdot \left( \frac{d\sigma}{d\Omega} \right)_{th}
\]

Depending on experimental data analysis

- Do all the experiments using the same method to analyze their data?

No. Why?

They used different parameters to obtain spectroscopic factor.

So, what shall we do?
After Adopting Consistent Method

Consistent spectroscopic factors for $^{41}$Ca

- For incident energy less than 10 MeV, compound nuclear effect are dominant.

- Extracted spectroscopic factors for $^{41}$Ca ground state in different experiments are much more consistent with each other, and match well with prediction by shell model.

It provides a more reliable link between theory and experiments.

$^{40}$Ca(d,p)$^{41}$Ca

$SF = 1.01 \pm 0.06$

$SF(SM) = 1.00$

$J. Lee et al, Phys. Rev. C, in press$
ENSDF (Evaluated Nuclear Structure Data File, www.nndc.bnl.gov/ensdf) is a database which contains evaluated nuclear structure and decay information for over 2900 nuclides. It’s updated on a continuous basis.

(1) <SF_ex> in general matches with SF_ensdf → reasonable result.

(2) More experiments used vs. Only one or two adopted

(3) Consistent and systematic method vs. Directly using paper values