Evolution of N = 50 shell and neutron single-particle states towards $^{78}\text{Ni}$: $^{79}\text{Zn}(d,p\gamma)^{80}\text{Zn}$

$^{79}\text{Zn}(n,\gamma)$ cross section and r-process around A = 80 mass region

Spokesperson: E. Sahin, 
*University of Oslo, Oslo, Norway*

- Location of the neutron single particle orbitals
- Size of the N=50 gap at Z=30 near $^{78}\text{Ni}$ (Z=28)
\[ \nu_{1g_{9/2}} \otimes \nu_{2d_{5/2}} \] States

- l=2 transfer (2^+, 3^+, \ldots, 7^+) from the g.s. \(^{79}\text{Zn}, 9/2^+\)
- Sensitive to changes in the N=50 shell gap due to monopole interaction
- SM calculations exist only for 5^+ and 6^+ from Z=28 to Z=36
$^1g_{9/2} \otimes ^2d_{5/2}$ States

- $l=2$ transfer ($2^+, 3^+, ..., 7^+$) from the g.s. $^{79}Zn, 9/2^+$
- Sensitive to the $N=50$ shell gap due to monopole interaction
- SM calculations exist only for $5^+$ and $6^+$

$\nu^1g_{9/2} \otimes \nu^3s_{1/2}$ States

- $l=0$ transfer ($4^+, 5^+$) from the g.s.
- Location information, $3s_{1/2}$
- No SM calculations
- **Estimated to be few hundreds keV higher than the $l=2$ states**


Location of the $s_{1/2}$ and $d_{5/2}$ states in the $N=51$ isotones
$\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}$ States

- l=2 transfer (2$^+$, 3$^+$, ... , 7$^+$) from the g.s. $^{79}$Zn, 9/2$^+$
- Sensitive to the N=50 shell gap due to monopole interaction
- SM calculations exist only for 5$^+$ and 6$^+$

$\nu 1g_{9/2}^{-1} \otimes \nu 3s_{1/2}$ States

- l=0 transfer (4$^+$, 5$^+$) from the g.s.
- Location i calculations nformation, 3s$_{1/2}$
- No SM
- Estimated to be few hundreds keV higher than the l=2 states

$\nu 1g_{9/2}^{-2} \otimes \nu 3s_{1/2}^2$ States

- l=0 transfer from the isomeric state in $^{79}$Zn
- $E_{1/2^+} = 1.05$ MeV & $t_{1/2} \geq 200$ ms
- Possible assignment as (1p-2h) excitations across N=50 (PFSDG-U int.)
- Evidence for a 0$^+$ intruder state

\[ [\text{ISOLDE: X. F. Yang et al., PRL 116, 182502 (2016).}] \]
\( \nu 1g_{9/2} \otimes \nu 2d_{5/2} \) States

- \( l=2 \) transfer \((2^+,3^+,...,7^+)\) from the g.s., \(9/2^+\)
- Sensitive to the \(N=50\) shell gap due to monopole interaction
- SM calculations exist only for \(5^+\) and \(6^+\)

\( \nu 1g_{9/2} \otimes \nu 3s_{1/2} \) States

- \( l=0 \) transfer \((4^+,5^+)\) from the g.s.
- Location i calculations information, \(3s_{1/2}\)
- No SM
- Estimated to be few hundreds keV higher than the \(l=2\) states

\( \nu 1g_{9/2} \otimes \nu 3s_{1/2}^2 \) States

- \( l=0 \) transfer from the isomeric state in \(^{79}\)Zn
- \( E_{1/2^+} = 1.05 \text{ MeV} \) & \( t_{1/2} \geq 200 \text{ ms} \)
- Possible assignment as \((1p-2h)\) excitations across \(N=50\) (PFSDG-U int.)
- Evidence for a \(0^+\) intruder state

**E(0^+) \approx 2 \text{ MeV} \ \nu(2p-2h)**

\[ \begin{align*}
\text{E(0^+)} & \approx 2 \text{ MeV} \\
\nu(2p-2h) & \approx 2 \text{ MeV}
\end{align*} \]

\[ \text{80Zn } \nu(2p-2h) \]

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

**References:**

$\nu_{g_{9/2}}^{-1} \otimes \nu_{2d_{5/2}}^{1}$ States

- l=2 transfer (2$^+$, 3$^+$, ..., 7$^+$) from the g.s., 9/2$^+$
- Sensitive to the N=50 shell gap due to monopole interaction
- SM calculations exist only for 5$^+$ and 6$^+$

$\nu_{g_{9/2}}^{-1} \otimes \nu_{3s_{1/2}}^{1}$ States

- l=0 transfer (4$^+$, 5$^+$) from the g.s.
- Location i calculations information, 3s$$_{1/2}$
- No SM
- Estimated to be few hundreds keV higher than the l=2 states

$\nu_{g_{9/2}}^{-2} \otimes \nu_{3s_{1/2}}^{2}$ States

- l=0 transfer from the isomeric state in 79Zn
- $E_{1/2}= 1.05$ MeV & $t_{1/2} \geq 200$ ms
- Possible assignment as (1p-2h) excitations across N=50 (PFSO-DG-U int.)
- Evidence for a 0$^+$ intruder state

RIKEN inelastic scattering and proton removal: $^9$Be($^{80}$Zn,$^{80}$Zn) and $^9$Be($^{81}$Ga,$^{80}$Zn):
Y. Shiga et al., PRC 93 024320 (2016).

5$^+$, 6$^+$: K. Sieja and F. Nowacki, PRC85 051301(R) (2012)
DWBA Calculations via FRESCO

Parabola similar to $^{90}$Zr & $^{88}$Sr

Setup and Experiment

\( ^{79}\text{Zn}(d,p\gamma)^{80}\text{Zn} \) inverse kinematics

Beam energy (\( ^{79}\text{Zn} \))

395 MeV (5 MeV/nuc)

Beam intensity on MINIBALL

4x10^4 pps \( \rightarrow \) 4x10^3 pps

Target thickness (CD_2)

1 mg/cm^2 \( \rightarrow \) 2 mg/cm^2

Cross sections

DWBA via FRESCO

Isolde Database: 10^6 pps/µC UCx

Suggested value from the earlier records: ~5.10^5 pps/µC UCx

1.6 µC total proton intensity + 5% transmission eff. \( \rightarrow \) 4x10^4 pps at MINIBALL

Rb/Ga contamination: 4x10^3 pps recommended by TAC.
• TREX angular coverage: 60%
• MINIBALL efficiency on average 6% at 1MeV
• Average cross section for $\nu_1 g_{9/2}^{-1} \otimes \nu_2 d_{3/2}^{1/2}$ states: 20 mb
• Average cross section for $\nu_1 g_{9/2}^{-1} \otimes \nu_3 s_{1/2}^{1}$ states: 28 mb

**Beam time request**

TOTAL: 21 shifts for physical runs + 3 shifts for beam preparation
to \( \sigma \) with increasing spin while from \( \approx 25 \) to \( \approx 35 \) \( \text{mb} \) for the \( l=0 \) states, shown in Fig. 2b. Figure 2c shows the calculated differential cross sections as a function of proton scattering angle in the center of mass for both multiplets. The obtained single-particle and differential cross sections as well as gamma-decay patterns given in Fig. 1b are used as input in the Geant4 simulations in the next section. A spectroscopic factor of 1 is assumed in the DWBA calculations.

Identification of states in the worst scenario:

Low-spin states have lower cross section and energy behaviour also follows a certain trend (parabola).

One can use gamma-tagged proton angular distributions and see how this compares with the expected trends of the excitation energy and the s.p. cross sections.

Plus shell model calculations might be helpful.
<table>
<thead>
<tr>
<th></th>
<th>This proposal</th>
<th>Accepted proposal Spokesperson: R. Orlandi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam intensity</td>
<td>$^{79}\text{Zn}(d,p\gamma)^{80}\text{Zn}$</td>
<td>$^{80}\text{Zn}(d,p\gamma)^{81}\text{Zn}$</td>
</tr>
<tr>
<td>Target thickness</td>
<td>$5 \times 10^4$ pps/$\mu$C at UCx $4 \times 10^3$ pps at MINIBALL</td>
<td>$3 \times 10^4$ pps/$\mu$C at UCx $2.3 \times 10^3$ pps at MINIBALL</td>
</tr>
<tr>
<td>Required beam time</td>
<td>7 days</td>
<td>7 days</td>
</tr>
<tr>
<td>Expected yield</td>
<td>$300 \text{ p}\gamma / 30 \text{ p}\gamma\gamma$ events for one $l=2$ state $400 \text{ p}\gamma / 40 \text{ p}\gamma\gamma$ events for one $l=0$ state</td>
<td>$350 \text{ p}\gamma$ events for the $l=0$ state, $1/2^+$</td>
</tr>
</tbody>
</table>

Future perspective: New neutron converter will increase expected yield as indicated in IS556. Test has been done Ref: J.P. Ramos et al., NIMB 463, 357 (2020).

Alternative solution could be dropping the neutron converter (UCx + neutron converter + quartz line + RILIS)

Special thanks to Sebastian Rothe
Thank you
Additional slides
**Shell gap from mass is correlated.**

SM approach:
K. Sieja and F. Nowacki, PRC85 051301(R) (2012)
F. Nowacki et al., PRL 117, 272501 (2016)
A. Welker et al., PRL 119, 192502 (2017).

Mean-field approach:
M. Bender et al. PRC78, 054312 (2008)

Correlation effects can be explored and help theory
Momentum matching in transfer reactions

$^{60}\text{Ni}(\alpha,^3\text{He})$: $Q_{\text{g.s.}} = -12.8 \text{ MeV} \rightarrow \text{high momentum transfers}$

$^{60}\text{Ni}(d,p)$: $Q_{\text{g.s.}} = 5.6 \text{ MeV} \rightarrow \text{low momentum transfers}$

$^{79}\text{Zn}(d,p)^{80}\text{Zn}$

$Q_{\text{g.s.}} = 4.064 \text{ MeV}$

(example borrowed from C. Hoffman)
TABLE V. Summary of \((d,p)\) results for levels in \(^{88}\)Sr.

<table>
<thead>
<tr>
<th>Level No.</th>
<th>(E^*) (keV)</th>
<th>(l)</th>
<th>(G_{ij}^e)</th>
<th>(l)</th>
<th>(G_{ij}^{88})</th>
<th>(G_{ij}^{88}) (assumed)</th>
<th>(J^+)</th>
<th>(S_{ij}^{88})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1836)</td>
<td>2</td>
<td>0.126</td>
<td>2</td>
<td>(0.13)</td>
<td>2+</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4032</td>
<td>2</td>
<td>0.279</td>
<td>2</td>
<td>0.35</td>
<td>2+</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4294</td>
<td>2</td>
<td>0.376</td>
<td>2</td>
<td>0.53</td>
<td>4+</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4413</td>
<td>2</td>
<td>0.875</td>
<td>2</td>
<td>1.18</td>
<td>[5]+</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>(4450)</td>
<td>2</td>
<td>0.083</td>
<td>(2)</td>
<td>(−0.10)</td>
<td>[4]+</td>
<td>(0.11)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>4514</td>
<td>2</td>
<td>1.080</td>
<td>2</td>
<td>1.31</td>
<td>[6]+</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>4633</td>
<td>2</td>
<td>0.564</td>
<td>2</td>
<td>0.68</td>
<td>[3]+</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>4744</td>
<td>2</td>
<td>0.805</td>
<td>2</td>
<td>0.14</td>
<td>5.86</td>
<td>[4]+</td>
<td>0.28(0.16)</td>
</tr>
<tr>
<td>17</td>
<td>5094</td>
<td>2</td>
<td>1.040</td>
<td>2</td>
<td>1.33</td>
<td>[7]+</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>4873(c)</td>
<td>0</td>
<td>0.230</td>
<td>0</td>
<td>0.24</td>
<td>4+ (e)</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>5416</td>
<td>0</td>
<td>0.105</td>
<td>0</td>
<td>0.13</td>
<td>5(e)</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>5466</td>
<td>0</td>
<td>0.563</td>
<td>0</td>
<td>0.61</td>
<td>4+ (e)</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>(5506)</td>
<td>0</td>
<td>0.027</td>
<td>(0)</td>
<td>&lt;0.01</td>
<td>5(e)</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>5729</td>
<td>0</td>
<td>0.789</td>
<td>0</td>
<td>0.94</td>
<td>5(e)</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>(5780)</td>
<td>0</td>
<td>0.405</td>
<td>0</td>
<td>0(±0.03)</td>
<td>1.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>(6214)</td>
<td>0</td>
<td>0.031</td>
<td>(0)</td>
<td>(−0.03)</td>
<td>2.150</td>
<td>1.95</td>
<td></td>
</tr>
</tbody>
</table>

\(\text{FIG. 8. Measured differential cross sections and DWBA fits for } l=2 \text{ transitions. All fits are based on NLFR calculations using } L/B \text{ parameters.}\)
Equivalent of $5^+,6^+$ states in $^{82}$Ge is found to be $13/2^-,15/2^-$ in $^{83}$As

SM Calculations:
Interaction: JJ4B + SDI
Model spaces: $pfg9+sdg$
Inert Core nucleus: $^{56}$Ni
Tensor interactions are included

The SPEs relative to the $^{56}$Ni core have been derived from the SPEs with respect to the doubly-magic $^{78}$Ni core.

<table>
<thead>
<tr>
<th>Model Space</th>
<th>Single-Particle Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pfg$</td>
<td>$E(f_g/3)$  $E(2p_{3/2})$  $E(2p_{1/2})$  $E(1g_{9/2})$</td>
</tr>
<tr>
<td>$sdg$</td>
<td>$E(d_{5/2})$  $E(3s_{1/2})$  $E(1g_{7/2})$</td>
</tr>
<tr>
<td></td>
<td>-1.19440  -0.16800  0.2700</td>
</tr>
</tbody>
</table>

$E(\nu d_{5/2} - \nu g_{9/2}) = \text{parameter}$
Weak r-process

Sensitivity study to the n-capture process in the context of neutron-rich supernova and collapsar accretion disk winds.

weak $r$ process—a rapid neutron capture process that forms a solar-type $A \sim 80$ $r$-process peak and potentially nuclei up to the $A \sim 130$ peak.

Nuclear data relevant to $r$-process calculations are (parity assignments, excitation energies, spectroscopic factors and can be extracted from transfer reactions, such as (d, p).

R. Surman et al., AIP Advances 4, 041008 (2014)
Experiment at ISOLDE (IS559): $^{66}\text{Ni}(d,p)^{67}\text{Ni}$

Oslo method in inverse kinematics
$^{86}\text{Kr}(d,p)^{87}\text{Kr}$ iThemba
V. W. Ingeberg, Master thesis 2016

V. Ingeberg, to be submitted to PRC, Feb 2022.
V. Ingeberg, PhD thesis to be submitted, Feb 2022
Aim: \((n,\gamma)\) cross section for \(^{79}\text{Zn}(d,p\gamma)\)

\[ N_A(\sigma/v) = 10^4 \text{ cm}^2 \text{s}^{-1} \text{ mol}^{-1} \]

- 6 different NLD models
- 5 different gSF models
- 30 combinations in total

Temperature \((10^9 \text{ K})\)

Exp: \(^{79}\text{Zn}(d,p\gamma)\)

Calculations by A.C. Larsen, Univ. of Oslo

A.C. Larsen et al., PRC 97, 054329 (2018)