Structure of $^{68}\text{Ni}$:

New insights on the low-lying $0^+$ and $2^+$ states from two-neutron transfer on $^{66}\text{Ni}$ and $\beta$-decay of $^{68}\text{Co}$

IS467 and IS504 collaborations

Freddy Flavigny

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Motivation: Shell structure at Z=28 and N=40

\[\text{\textbf{3s}}_{1/2}, \text{\textbf{2d}}_{5/2}, \text{\textbf{1g}}_{9/2}, \text{\textbf{2p}}_{1/2}, \text{\textbf{1f}}_{5/2}, \text{\textbf{2p}}_{3/2}, \text{\textbf{1f}}_{7/2}\]

\[\begin{align*}
3s_{1/2} & \quad \text{Zn} \\
2d_{5/2} & \quad \text{Ni} \\
1g_{9/2} & \quad \text{Fe} \\
2p_{1/2} & \quad \text{Cr} \\
1f_{5/2} & \quad \text{Ni}
\end{align*}\]

\[\begin{align*}
3s_{1/2} & \quad \pi \\
2d_{5/2} & \quad \nu
\end{align*}\]

\[\text{\textbf{68}}\text{Ni}\]

(See also K. Wimmer’s talk on Friday, session 4A)
Motivation: Shell structure at $Z=28$ and $N=40$

Recent experimental work:

- J. Elseviers et al., to be submitted.
- F. Flavigny et al., to be submitted.
- S. Suchyta et al., PRC 89, 021301R (2013)
- F. Recchia et al., PRC 88, 041302R (2013)
- R. Broda et al., PRC 86, 064312 (2012)
- C. J. Chiara et al., PRC 86, 041304R (2012)
- A. Dijon et al., PRC 85, 031301R (2012)

- **Precise position and firm spin/parity assignment:**

  → Three 0$^+$ states and two 2$^+$ states below 2.8 MeV
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- Precise position and firm spin/parity assignment:
  Three 0\(^{+}\) states and two 2\(^{+}\) states below 2.8 MeV

State of the art shell model calculations (MCSM\([1]\), SM\([2]\))
Suggests deformed states and shape coexistence

\((0p0h + 2p2h)^{\nu}\)
\((2p2h)^{\nu} + (4p4h)^{\nu}\)

\(\rightarrow\) New picture: need to characterize these states

Experimental approach: 2 complementary data sets

- Nature of $0^+$ states in $^{68}$Ni → 2ν-2h
- Conf. Mixing of $0^+_{1}$ and $0^+_{2}$

$^{66}$Ni(t,p)$^{68}$Ni

IS504

$^{68}$Ni

3s$_{1/2}$
2d$_{5/2}$
1g$_{9/2}$
2p$_{1/2}$
1f$_{5/2}$
2p$_{3/2}$
1f$_{7/2}$

$^{68}$Ni

PhD thesis, J. Elseviers

(2$^+$) 4164
(2$^+$) 4026
2$^+$ 2743
0$^+$ 2511
2$^+$ 2033
0$^+$ 1604
0$^+$ 1604
Experimental approach: 2 complementary data sets

**IS504**
- Nature of 0\(^+\) states in \(^{68}\text{Ni}\)
- \(\rightarrow 2\nu-2\hbar\)
- Conf. Mixing of 0\(^+_1\) and 0\(^+_2\)

*PhD thesis, J. Elseviers*

\(\beta\)-decay of low-spin \(^{68}\text{Co}\) isomer

\(\beta\)-decay of \(^{66}\text{Ni}(t,p)^{68}\text{Ni}\)

**IS467 (A=68)**
- Revised decay scheme
- \(\beta-\gamma\)-E0 coincidences
- 2\(^+\) to 0\(^+\) connections
- Exp. B(E2) ratios

\(^{68}\text{Ni}\)

\(\pi\)

\(\nu\)

\(\text{N}\)

\(\text{p}\)

\(\text{d}\)

\(\text{s}\)

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β-decay studies in the $^{68}$Ni region using resonant laser ionization

**Facility:** ISOLDE (p (1.4GeV) → UC$_x$)  
*thick & hot target*

- Pure Mn sources
  - Z selection: Laser ionisation (RILIS)
  - A/Q selection: Spectrometer (HRS)

- **A=68**
  - Previous exp. : 2 isomers in $^{68}$Co
    - $(7^-)$ $T_{1/2} = 0.23(3)$ s
    - $(1^+, 3^+)$ $T_{1/2} = 1.6(3)$ s
  - ISOLDE: Selectivity of $^{68}$Fe$_{gs}$ (0$^+$) decay

<table>
<thead>
<tr>
<th>Z = 28</th>
<th>$^{60}$Ni stable</th>
<th>$^{61}$Ni stable</th>
<th>$^{62}$Ni stable</th>
<th>$^{63}$Ni stable</th>
<th>$^{64}$Ni stable</th>
<th>$^{65}$Ni</th>
<th>$^{66}$Ni</th>
<th>$^{67}$Ni</th>
<th>$^{68}$Ni$^*$</th>
<th>$^{69}$Ni</th>
<th>$^{70}$Ni$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>$^{60}$Co 1925 d</td>
<td>$^{61}$Co 1.650(5) h</td>
<td>$^{62}$Co 1.50(4)m</td>
<td>$^{63}$Co 27.4(5) h</td>
<td>$^{64}$Co 0.30(3) s</td>
<td>$^{65}$Co$^*$ 1.20(6) s</td>
<td>$^{66}$Co 0.18(1) s</td>
<td>$^{67}$Co 0.23(3) s</td>
<td>$^{67}$Co 0.27(5) s</td>
<td>$^{68}$Co 0.23(3) s</td>
<td>$^{69}$Co 0.27(5) s</td>
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<tr>
<td>26</td>
<td>$^{60}$Fe 1.5E6 a</td>
<td>$^{61}$Fe 5.98(6) h</td>
<td>$^{62}$Fe 68(2) s</td>
<td>$^{63}$Fe 6.1(6) s</td>
<td>$^{64}$Fe 2.0(2) s</td>
<td>$^{65}$Fe$^*$ 1.07(12) s</td>
<td>$^{66}$Fe 0.17(3) s</td>
<td>$^{67}$Fe 0.17(3) s</td>
<td>$^{68}$Fe 0.17(3) s</td>
<td>$^{69}$Fe 0.17(3) s</td>
<td>$^{70}$Fe 0.17(3) s</td>
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<tr>
<td>25</td>
<td>$^{58}$Mn 3.0(1) s</td>
<td>$^{60}$Mn 0.28(2) s</td>
<td>$^{61}$Mn 623(10) ms</td>
<td>$^{62}$Mn 671(5) ms</td>
<td>$^{63}$Mn 0.29(2) s</td>
<td>$^{64}$Mn 50(4) ms</td>
<td>$^{65}$Mn 88(4) ms</td>
<td>$^{66}$Mn 47(2) ms</td>
<td>$^{67}$Mn 28(4) ms</td>
<td>$^{68}$Mn 14(4) ms</td>
<td>$^{69}$Mn 14(4) ms</td>
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</table>

$\beta$-decay  
* studied at LISOL  
□ studied at ISOLDE
LISOL $\beta-\gamma$ detection setup at ISOLDE

**MINIBALL**: 5.8% photo-peak efficiency at 1.332 MeV

**3 plastic detectors**: 50% beta efficiency

**DGF system**: digital read-out on event-by-event basis

**Polyethylene-borax-lead-brass shielding**
Feeding of $0^+_{2}$ state in $^{68}$Ni : $\beta$-$\gamma$-E0 coincidences

Top view:

$^{68}$Co

$^{68}$Ni

$\beta$

$\gamma$

$\gamma$ (1139 keV)

$\gamma$ (55% conv. e, 45% pair cr.)

270(5) ns

0$^+$

Time difference: $t_\beta - t_{E0}$

$T_{1/2} = 235(23)$ ns

Counts / 100 ns

Count rate decreases over time.
Feeding of $0^+_{2}$ state in $^{68}\text{Ni}$: $\beta$-$\gamma$-E0 coincidences

- Top view: $^{68}\text{CO}$ beam $\rightarrow$ $\beta$ $\rightarrow$ $2^+$ $\rightarrow$ $\gamma$ (1139 keV) $\rightarrow$ $0^+$ $\rightarrow$ $^{68}\text{Ni}$
- Time difference: $t_{\beta} - t_{E0} = 2743 \pm 1604$ ns
- Coincident $\gamma$ rays
  - 590 events
    - Highly selective signal
    - 1139 and 2421 keV feeding $0^+_{2}$
    - $E(0^+_{2}) = 1603.6(6)$ keV in agreement
      - 1603.5(3) in [1]
      - 1605(3) in [2]
    - $I_{rel}(0^+_{2} \rightarrow 0^+_{1}) = 19(8)$ %

References:
**β-γ coincidences**

- Time condition: \( t_\beta - t_{PP} \) in [350,2200] ms

  → to avoid \(^{68}\text{Mn}\) decay (\(T_{1/2} = 28(3)\) ms)

- Clean \(^{68}\text{Co}\) low-spin spectrum
  - Low bkg (shielding)
  - Laser ionisation (RILIS)
  - Mass separation (HRS)
  - Selectivity of the \(^{68}\text{Fe}_{gs}\) (0+) decay

- Grand daughter decay
  - 1/3 statistics previous LISOL studies [1]

- Beta-delayed n branches

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![Graph showing β-γ coincidences](image-url)
Revised decay scheme

- **New:**
  - 710 keV intensity (clean, no high spin)
  - 1139 and 2421 keV placement
  - Removed 694 keV (after β-delayed n)
  - 814 keV intensity - 5⁻ isomer
  - \( I_{rel}(0^+ \rightarrow 0^+_1) = 19(8) \% \)

- **Upper limits:**
  - \( I_{rel}(0^+_3 \rightarrow 0^+_2) < 2(1)\%
  - \( I_{rel}(0^+_3 \rightarrow 0^+_2), I_{rel}(0^+_3 \rightarrow 0^+_1) < 4(1)\%

---

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  - 710 keV intensity (clean, no high spin)
  - 1139 and 2421 keV placement
  - Removed 694 keV (after β-delayed n)
  - 814 keV intensity - 5⁺ isomer
  - $I_{\text{rel}}(0^+\rightarrow 0^+_1) = 19(8)\%$

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  - $I_{\text{rel}}(0^+_3\rightarrow 0^+_2)$
  - $I_{\text{rel}}(0^+_3\rightarrow 0^+_1) < 4(1)\%$

- **Int. balance: test of completeness in the full A=68 chain**
  - Determination of missed feeding:
    - Direct β feeding of gs
    - Direct β-del.n feeding to gs or isomeric state
    - Missed E0 decay
    - Missed γ ray feeding to gs or isomeric states

  **Missed feeding: 42(10)\%**

  -> No conclusion on spin assignment from β-feeding

Exp. VS SM calculations:

1. Using the LNPS interaction [1]
2. Monte-Carlo shell model calculations [2]

$$R = \frac{B(E2, 2^+_i \rightarrow I^+)}{B(E2, 2^+_i \rightarrow 0^+_1)}$$

Main results:

- $2^+_1 \rightarrow 0^+_2$
  - $I_{rel} < 0.7(2) \% \rightarrow R < 17$
  - Th: $R=12$ (MSCM), 4 (LNPS)

[3] δ(E2/M1)≈-1.5^{0.9}_{-1.2} from C.J. Chiara et al, PRC86 041304R (2012)
B(E2) ratios

From experiment:

\[
\begin{align*}
(2^+) & \rightarrow \text{4164} \\
(2^+) & \rightarrow \text{4026} \\
(2^+) & \rightarrow \text{2743} \\
(2^+) & \rightarrow \text{2511} \\
0^+ & \rightarrow \text{2033} \\
0^+ & \rightarrow \text{1604} \\
\end{align*}
\]

Exp. VS SM calculations:
1. Using the LNPS interaction [1]
2. Monte-Carlo shell model calculations [2]

\[
R = \frac{B(E2, 2_i^+ \rightarrow I^+)}{B(E2, 2_i^+ \rightarrow 0_1^+)}
\]

Main results:

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  \(\lambda_{rel} < 0.7(2)\% \rightarrow R < 17\)
  Th.: R=12 (MSCM), 4 (LNPS)

- \(0^+_3 \rightarrow 2^+_1\)
  Th. partial \(T_{1/2}\) of 108 and 1.5 ns (MSCM,LNPS)
  *Big difference: lifetime measurement needed.*
B(E2) ratios

From experiment:

\[ \frac{B(E2, 2^+_i \rightarrow I^+)}{B(E2, 2^+_i \rightarrow 0^+_1)} \]

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- \( 0^+ \rightarrow 2^+_1 \)
  Th. partial T\(_{1/2}\) of 108 and 1.5 ns (MCSM, LNPS)
  Big difference: lifetime measurement needed.

- \( 2^+_2 \rightarrow 2^+_1 \)
  \( I_{rel} = 11(2) \% \rightarrow R = 448^{+185}_{-311} \) using [3]
  Higher than published values [4]
  \( R = 29 \) and 278 (MCSM, LNPS)

[3] \( \delta(E2/M1)=-1.5^{+0.9}_{-1.2} \) from C.J. Chiara et al, PRC86 041304R (2012)
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  $I_{rel} = 11(2)\% \rightarrow R = 448^{+185}_{-311}$ using [3]

  *Higher than published values [4]*

  $R = 29$ and $278$ (MCSM, LNPS)

- $2^+_3$ and $2^+_4$

  *Qualitative agreement for (2^+_4)*

  *Significant discrepancies for (2^+_3)*

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**Exp. VS SM calculations:**

1. Using the LNPS interaction [1]
2. Monte-Carlo shell model calculations [2]

$$R = \frac{B(E2, 2^+_i \rightarrow I^+_f)}{B(E2, 2^+_i \rightarrow 0^+_1)}$$

---

**From experiment:**

Two-neutron transfer reaction: $^{66}\text{Ni}(t,p)^{68}\text{Ni}$
$^{66}\text{Ni}(t,p)^{68}\text{Ni}$: Experimental Setup

Resonant Laser Ion Source
- Z-selectivity

Mass separation
- A/Q-selectivity

Post-acceleration (REX-ISOLDE)

$^{66}\text{Ni}(t,p)^{68}\text{Ni}$

- Beam energy: 2.6 MeV/u
- Intensity \( \approx 2.0 \times 10^6 \) pps
- Beam purity \( >86\% \)
- Target: 500 mg/cm\(^2\)
  \( ^3\text{H} \) loaded Ti (40 mg/cm\(^2\) \( ^3\text{H} \))
- Measurement time: \( \approx 100h \)

• **Proton detection in T-REX:**
  - Identification
  - Energy
  - Angular distribution

• **\( \gamma \) detection in Miniball:**
  - Energy
  - Angular distribution (Doppler correction)

- 8 DE-E\(_{\text{rest}}\) Barrel det.
- 1 DE-E\(_{\text{rest}}\) CD detectors
- 8 Miniball triple (HPGe) clusters
- Crystals: 6-fold segmented
- 5% efficiency at 1.33 MeV
\( ^3\text{H}(^{66}\text{Ni},p)^{68}\text{Ni} : \text{Results} \)

**Proton - gamma coincidences**

**Energy of all Cluster, rough doppler corrected prompt with protons (no pID 11)**

- \( 4_1^+ \rightarrow 2_1^+ \rightarrow 1115\text{keV} \)
- \( 2_1^+ \rightarrow 0_1^+ \rightarrow 2033\text{keV} \)
- \( 2_2^+ \rightarrow 0_1^+ \rightarrow 2744\text{keV} \)

\( ^{68}\text{Ni}(^{3}\text{H},^{1}\text{H})^{68}\text{Ni} \)

**Q = 5.12 \text{MeV}**

- 615
- 243
- 139
- 709
- 478
- 2033
- 2511
- 1604

**270(5) ns**

**Proton-gated**

- \((t,p) E_{ex} = 0 \text{ MeV}\)
- \((t,p) E_{ex} = 6 \text{ MeV}\)

**KU LEUVEN**
$^3\text{H}(^{66}\text{Ni},p)^{68}\text{Ni}$: Backward CD

**CD data only**

- **Population of $0_2^+$ and $2_1^+$ states**
  
  $E = 1621(28)$ keV - 4.8(16) % of gs  
  $E = 2033(10)$ keV - 28(4) % of gs

- **Non-observed direct population of $0_3^+$, $2_2^+$ and $2_3^+$ states**
  
  $0^+_3$ (2512 keV) < 2% based on 478 keV transition  
  $2^+_2$ (2744 keV) < 4% based on 709 keV transition  
  $2^+_3$ (4026 keV) < 3% based on 1515 keV transition
**Parameters of our calculations:**

- Finite-range DWBA (code FRESCO\(^1\) )
- Glob. Pot.: \(^3\)H+\(^{66}\)Ni and \(^1\)H+\(^{68}\)Ni
- **Two nucleon overlap amplitudes (TNA’s)**
  - Code: NUSHELL (A. Brown, MSU) \(^2\)
  - Interaction jj44pna from \(^3\)
  - Model space: \(f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}\)
  - Calculated \(^{68}\)Ni energies
    
    \[ E(0^+_{2}) = 1593 \text{ keV}, E(2^+_{1}) = 2077 \text{ keV} \]
Two-neutron transfer:

Direct + Sequential

$^{66}\text{Ni}$

$^{67}\text{Ni}$

$^{67}\text{Ni}$

$^{68}\text{Ni}$

Parameters of our calculations:

- Finite-range DWBA (code FRESO$^1$)
- Glob. Pot.: $^3\text{H}+^{66}\text{Ni}$ and $^1\text{H}+^{68}\text{Ni}$
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  - Interaction jj44pna from $^3$
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  - Calculated $^{68}\text{Ni}$ energies

$E(0^+_2) = 1593 \text{ keV}, E(2^+_1) = 2077 \text{ keV}$

Neutron occupation numbers

Proton occupation numbers

Average number of neutrons in a given state:

<table>
<thead>
<tr>
<th>jj44pna</th>
<th>$f_{5/2}$</th>
<th>$p_{3/2}$</th>
<th>$p_{1/2}$</th>
<th>$g_{9/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{66}\text{Ni}$ gs</td>
<td>4,53</td>
<td>3,34</td>
<td>1,07</td>
<td>1,06</td>
</tr>
<tr>
<td>$^{68}\text{Ni}$ gs</td>
<td>5,19 +0,66</td>
<td>3,59 +0,25</td>
<td>1,73 +0,66</td>
<td>1,49 +0,43</td>
</tr>
<tr>
<td>$^{68}\text{Ni}$ $0^+_2$</td>
<td>5,01 +0,48</td>
<td>3,44 +0,10</td>
<td>1,14 +0,07</td>
<td>2,41 +1,35</td>
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Conclusions:

- Reasonable agreement th/exp for $0_{1,2}^+$ states
  
  ![Graph](image)

- No scaling of theory to experiment

- Shape very sensitive to intermediate state properties

First exp. evidence that $0_{2}^+$ in $^{68}$Ni is a neutron excitation above N=40
Outlook

- Future experiments at HIE-ISOLDE in the region of $^{68}$Ni:
  - $^{80}$Zn(d,p)$^{81}$Zn, [R. Orlandi et al., INTC-2012-051 P-352]
  - $^{70}$Ni(d,p)$^{71}$Ni, [J.J Valiente Dobon et al., INTC-2012-050 P-351]
  - $^{68}$Ni(d,p)$^{69}$Ni, [accepted]
    - $d_{5/2}$ single particle strength above N=50
  - Coulomb excitation of $^{68}$Ni, $^{70}$Ni
    - Absolute B(E2) values
  - Decay of $^{68}$Mn with the new ISOLDE Decay Station [accepted]
    - Lifetime of $0^+_3 \rightarrow 2^+_1$ transition (478 keV)