E2 Strengths in $^{98}$Zr

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Aims of the Experiment

Coulex of $^{98}$Zr using GRETINA & CHICO2

- At the brink of deformation past $Z=56$; testing collectivity at $Z=58$ by measuring $E2$ to the $2_1^+$

- Weak or strong coupling? Is the mixed-symmetry one-phonon $2^+$ state excited; $B(E2)$ excitation strength will give first hint on structure

- Collective (?) structure of $^{98}$Zr already developed? Look at $B(E2)$s among higher-lying states, including low-lying $0^+$s
1) $E(2_{1}^{+})$ and $B(E2)$ Systematics

Are $N=50, 56$ and $58$ „magic“ (stabilized by $Z=40$)?

For $Z>40$ $\nu g_{7/2}$ fills and is lowered because of $\pi g_{9/2}$ -> gaps disappear

Weak coupling (p-n) was shown for $Z\sim 40, N<56$ in prev. works

Assume it here -> $E(2_{1}^{+})$ depends mainly on SPEs

$B(E2)$ will show how important correlations are!

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Simple picture: p-n 2-configuration mixing

fully p-n symmetric state:

\[ 2^+_fs = a_1 \cdot 2^+_n + b_1 \cdot 2^+_p \]

p-n mixed-symmetric state:

\[ 2^+_ms = a_2 \cdot 2^+_n - b_2 \cdot 2^+_p \]

protons and neutrons contribute about equally: good F-spin

\[ |a_i| \approx |b_i| \]

imbalance in proton and neutron contributions: broken F-spin

\[ |a_i| \neq |b_i| \]

This is „Configurational Isospin Polarization“

Based on Heyde/Sau, PRC 33, 1050 (1986)
2) (Mixed?)-p-n-Symmetry?

Magnetic Moments of both states should be sensitive to proton-neutron contents.
MS and/or Shape Coex. in $^{94}\text{Zr}$

A. Chakraborty et al., PRL 110, 032503 (2012)

„excited collective structure“
(or just proton-dominated structure)

$^{94}\text{Zr}$

$E(\text{MeV})$  

In $N>56$: Does deformation develop from a coexisting structure?  
Is there a MS 2+ state below 2 MeV?

V. Werner et al., PRC 78, 031301 (2008)
E. Elhami et al., PRC 75, 011301 (2007)
$^{98}$Zr: Relevant Levels

Known absolute strengths:

- $4_2^+$
- $3_1^-$
- $2_3^+$
- $2_2^+$
- $2_1^+$
- $0_3^+$

From fast-timing, Lohengrin @ ILL
$\tau < 11$ ps

- $\geq 6$ W.u.
- $\geq 1$ W.u.

$0_1^+$
98\textsuperscript{Zr}: Relevant Levels

Known absolute strengths:

\( \begin{array}{c}
(4_1^+) \\
7.8 \text{ W.u.} \\
0_3^+ \\
51 \text{ W.u.} \\
2_2^+ \\
\end{array} \)

From fast-timing, Lohengrin @ ILL
\( \tau < 11 \text{ ps} \)

\( \begin{array}{c}
3_1^- \\
? \\
2_3^+ \\
2_2^+ \\
0_2^+ \\
\end{array} \)

>6 W.u.

>1 W.u.
Assuming limits for the $2^+$ states, branchings are known:

- $2^+$ states
- $\tau = 0.4$ ps
- $\tau = 0.8$ ps
- $0.7 \mu_N^2$ (if M1)

- $3^-$ state
- $0.16 \mu_N^2$

- $1^+$ states
- $0.07 \mu_N^2$

- $2_1^+$ level
- $7.8$ W.u.

- $3_1^-$ level
- $51$ W.u.

- $2_2^+$ level
- $60$ W.u.

- Assume $10$ W.u.

- $1_1^+$ level
- $3$ W.u. each
Branch of $2^+_2$ states correct? Would give way too large 157 keV transition:

\[
\begin{array}{c}
(4^+_1) \\
7.8 \text{ W.u.} \\
0^+_3 \\
51 \text{ W.u.} \\
2^+_1 \\
0^+_2 \\
10 \text{ W.u.} \\
0^+_1 \\
\end{array}
\]

\[
\begin{array}{c}
4^+_2 \\
3^-_1 \\
2^+_3 \quad \tau=0.4 \text{ ps} \\
2^+_2 \quad \tau=0.8 \text{ ps} \\
7000 \text{ W.u.} \quad ?? \\
60 \text{ W.u.} \\
3 \text{ W.u. each} \\
\end{array}
\]

Assume
Different assumption could make it rotational state on top of $0_{3}^{+}$

$3^{-}$ is known to be very strong in $^{96}$Zr, here?

$\tau = 0.4$ ps
$\tau = 80$ ps

\[
\begin{align*}
(4_{1}^{+}) & \quad 3_{1}^{-} \quad 4_{2}^{+} \\
7.8 \text{ W.u.} & \quad 70 \text{ W.u.} \\
0_{3}^{+} & \quad 2_{3}^{+} \\
51 \text{ W.u.} & \quad \tau = 0.4 \text{ ps} \\
2_{1}^{+} & \quad 2_{2}^{+} \\
60 \text{ W.u.} & \quad \tau = 80 \text{ ps} \\
0_{2}^{+} & \quad 3 \text{ W.u. each} \\
10 \text{ W.u.} & \\
0_{1}^{+} &
\end{align*}
\]

assume
**Multistep Coulex**

Only possible with GRETINA and CHICO2 for proper Doppler correction
=> reasonable peak-to-background!

Some rate estimates for above assumptions, 2400 pps $^{98}$Zr @ 464 MeV, $^{196}$Pt target (*relative measurement*), CHICO2 forward shell for safe Coulex,

\[
\begin{align*}
2^+_1 & \rightarrow 0^+_1 : 10 \text{ W.u.} \quad \sim 300 \text{ counts/day} \\
2^+_2 & \rightarrow 0^+_1 : 3 \text{ W.u.} \quad \sim 30 \text{ counts/day} \\
2^+_3 & \rightarrow 0^+_1 : 3 \text{ W.u.} \quad \sim 10 \text{ counts/day} \\
2^+_3 & \rightarrow 2^+_1 : 0.16 \mu^2 \quad \sim 11 \text{ counts/day} \quad \text{(indirect M1: if E2 it could be)} \\
4^+_1 & \rightarrow 2^+_1 : 11 \text{ W.u.} \quad \sim 5 \text{ counts/day} \\
0^+_3 & \rightarrow 2^+_1 : 51 \text{ W.u.} \quad \sim 40 \text{ counts/day}
\end{align*}
\]

Assuming 50 W.u. Excitation strength for the $3^-$:

\[
3^-_1 \rightarrow 2^+_1 : \sim 16 \text{ counts/day}
\]

Primary goal: measure E2 strength of $2^+_1$ \text{ few days}

Test the nature of the $2_{2,3}^+$ states \text{ ~ 1 week for 50-100 counts}
Shape coexistence around $^{100}$Zr

- until today: $\tau(2^+_1)$ in $^{98}$Zr is unknown ($<11$ ps)
- models (shell model, IBM) predict 1 – 5 ps
  (Bettermann et al., PHYSICAL REVIEW C 82, 044310 (2010))

**Possible experiment:**
- $^{98}$Zr beam provided by CARIBU (340mCi)
  - $l=2400$ pps
  - $E=464$ MeV (~88% of Coul. barrier)
- $^{196}$Pt (2mg/cm$^2$)

- Using CHICO2 (forward shell)
- Using GRETINA for measurement of $\gamma$ rays

- Estimated yield of target excitation ($^{196}$Pt):
  - 3500 cpd in $2^+_1 \rightarrow 0^+_1$ transition

- Estimated lifetimes:
  - $2^+_2$: 0.8ps
  - $2^+_3$: 0.4ps

  To normalize to GS transitions of ~3 W.u.

- Include multipole mixing ratio of $2^+_3 \rightarrow 2^+_1$ transition of 0.2(1)

### Transition Table

<table>
<thead>
<tr>
<th>Transition</th>
<th>$E_y$ [keV]</th>
<th>$B(EL)$</th>
<th>Counts/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{98}$Zr in</td>
<td>w/o funny</td>
<td>w/ funny</td>
<td></td>
</tr>
<tr>
<td>$2^+_1 \rightarrow 0^+_1$</td>
<td>1223</td>
<td>E2</td>
<td>311</td>
</tr>
<tr>
<td>$4^+_1 \rightarrow 2^+_1$</td>
<td>621</td>
<td>E2</td>
<td>11(5)</td>
</tr>
<tr>
<td>$0^+_3 \rightarrow 2^+_1$</td>
<td>213</td>
<td>E2</td>
<td>51(5)</td>
</tr>
<tr>
<td>$^{196}$Pt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^+_2 \rightarrow 0^+_1$</td>
<td>1591</td>
<td>E2</td>
<td>3</td>
</tr>
<tr>
<td>$2^+_2 \rightarrow 0^+_3$</td>
<td>155</td>
<td>E2</td>
<td>(7k)</td>
</tr>
<tr>
<td>$2^+_2 \rightarrow 2^+_1$</td>
<td>368</td>
<td>M1</td>
<td>(0.04)</td>
</tr>
<tr>
<td>$2^+_2 \rightarrow 0^+_2$</td>
<td>737</td>
<td>E2</td>
<td>(16)</td>
</tr>
<tr>
<td>$2^+_3 \rightarrow 0^+_1$</td>
<td>1744</td>
<td>E2</td>
<td>(3)</td>
</tr>
<tr>
<td>$2^+_3 \rightarrow 2^+_2$</td>
<td>153</td>
<td>E2</td>
<td>(18k)</td>
</tr>
<tr>
<td>$3^+_1 \rightarrow 2^+_1$</td>
<td>580</td>
<td>E3</td>
<td>(50)</td>
</tr>
<tr>
<td>$2^+_3 \rightarrow 2^+_1$</td>
<td>522</td>
<td>M1/E2</td>
<td>(0.09)</td>
</tr>
<tr>
<td>$2^+_3 \rightarrow 0^+_2$</td>
<td>890</td>
<td>E2</td>
<td>(19)</td>
</tr>
</tbody>
</table>

### E$_\gamma$ and W.u. with Funny Transitions

<table>
<thead>
<tr>
<th>Transition</th>
<th>Estimated B(EL)</th>
<th>$E_{\gamma}$</th>
<th>$W.u.$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{196}$Pt $2^+_1 \rightarrow 0^+_1$</td>
<td>356</td>
<td>E2</td>
<td>40.6(2)</td>
</tr>
<tr>
<td>$2^+_2 \rightarrow 2^+_1$</td>
<td>333</td>
<td>E2</td>
<td>57.7(8.8)</td>
</tr>
<tr>
<td>$4^+_1 \rightarrow 2^+_1$</td>
<td>521</td>
<td>E2</td>
<td>60.0(9)</td>
</tr>
</tbody>
</table>
Assuming limits for the $2^+$ states, branchings are known:

- $2_1^+ \rightarrow 3^- \rightarrow 4_2^+$: $0.16 \mu_N^2$, $\tau = 0.4$ ps
- $2_2^+ \rightarrow 2_3^+$: $0.07 \mu_N^2$, $\tau = 0.8$ ps

Assume $3$ W.u. each.