Observation of bound $1^-$ states in $^{208}$Pb by particle spectroscopy

Andreas Heusler (Heidelberg, Germany)

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The doubly magic nucleus 208Pb

- about 300 states are known in 208Pb below the neutron threshold at $S(n)=7368$ keV
- most states below $E_x=7$ MeV are described by one-particle one-hole configurations
- the neutron pairing vibration and some octupole vibration states at $E_x \sim 5$ MeV are identified, but not yet the proton pairing vibration state
- spin, parity and dominant configuration of about 100 states below $E_x=6$ MeV (both positive and negative parity) are known in 208Pb
- above $E_x=6$ MeV only few spins are known in 208Pb
- up to $E_x=8$ MeV about twenty states are assigned spin 1-
schematic shell model predicts 16 $1^-$ states below neutron threshold

Nuclear Data Sheets (2007) and PRC 89:024322 (2014) list 16 $1^-$ states below neutron threshold

above neutron threshold more $1^-$ states are known from 207Pb(n,γ), $Eγ < 600$ keV

shell model calculations predict 12 $1^-$ states below neutron threshold

how many $1^-$ states are firmly identified?

which particle-hole components are in the $1^-$ states?

$1^-$ states in 208Pb
Particle spectroscopy with the Q3D magnetic spectrograph

- Energy resolution 1.5 keV HWHM on low Ex-side
- Peak shape is asymmetric
- Satellites from electron knockout follow each peak
- 10 keV mean spacing of states up to Ex~7.5 MeV
- Peak-to-valley ratio ~100
- Background corresponds to ~0.1 μb/sr
- Full length of spectra ~1 MeV

- 208Pb(d,d')
  - E = 16.405 MeV
  - Θ = 88°

- 208Pb(d,p)
  - E = 22 MeV
  - Θ = 20°

- 208Pb(p,p') via g9/2 IAR
  - E = 22 MeV
  - Θ = 44°

- 208Pb(p,p') via d5/2 IAR
  - E = 14.920 MeV
  - Θ = 58°

- 208Pb(p,p') via g9/2 IAR
  - E = 16.405 MeV
  - Θ = 88°
Studying 208Pb by particle spectroscopy experiments with the Q3D magnetic spectrograph

at the Maier-Leibnitz-Laboratorium (MLL) Garching

performed in 2003 - 2013

in collaboration with

T. Faestermann, G. Graw, R. Hertenberger, H.-F. Wirth (MLL, Garching, Germany),
P. von Brentano (Institut für Kernphysik, Universität zu Köln, Germany), et alii

- **energy resolution** 1.5 keV HWHM on low Ex-side *(peak shape is asymmetric)*
  (half-width at half-maximum)
- **100 eV uncertainty** in energy for Ex < 8 MeV *(for strongly excited states)*
- **peak to valley typically 100:1** *(up to 10,000:1)*
- determination of cross section from 0.1 to 1000 μb/sr in 1 hour
- determination of particle-hole components from angular distributions and excitation functions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d,d')</td>
<td>208Pb</td>
</tr>
<tr>
<td>(d,p)</td>
<td>207Pb</td>
</tr>
<tr>
<td>g 9/2</td>
<td></td>
</tr>
<tr>
<td>i 11/2</td>
<td></td>
</tr>
<tr>
<td>d 5/2</td>
<td></td>
</tr>
<tr>
<td>s 1/2</td>
<td></td>
</tr>
<tr>
<td>g 7/2, d 3/2</td>
<td></td>
</tr>
<tr>
<td>off IAR</td>
<td></td>
</tr>
</tbody>
</table>

inelastic proton scattering via isobaric analog resonances (IAR) is equivalent to a neutron pickup reaction on an excited state

- **eight different reactions** are studied
Selective excitation by different reactions

- 5245 by (d,p) three times stronger than 5292
- 5245 on s1/2 20 times weaker than 5292
- 5236, 5241, 5286 by (d,d') only
- 5276 on i11/2 only
- 5280 on s1/2 only

- E = 16.960 MeV, Θ = 84°
- E = 15.720 MeV, Θ = 84°
- E = 14.920 MeV, Θ = 108°
- E = 22 MeV, Θ = 42°
- E = 22 MeV, Θ = 30°

- j = 3−, 11+(4), 0+, 4−, 0−, 2+}

π

\[ I = 2 \]
Importance to measure weak cross sections

γ-transition from 1- and 2+ to g.s. in 208Pb(n,n'γ)

angular distribution for 5640 1− state on g9/2 fitted by g9/2 f7/2

2 μb/sr correspond to 1% s1/2 p1/2 strength

precision of Ex: δ Ex < 1 keV

10 keV mean distance, here five states within 10 keV

E = 22 MeV Θ = 25° 2 μb/sr

E = 14.920 MeV Θ = 58°

E = 16.960 MeV Θ = 48° 2 μb/sr
Selective excitation of configurations on different IARs

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Angle (°)</th>
<th>(d,p) Configuration</th>
<th>(d,d') Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>20</td>
<td>d 5/2</td>
<td>g 9/2, i 11/2</td>
</tr>
<tr>
<td>16.495</td>
<td>48</td>
<td>d 5/2</td>
<td>s 1/2, g 7/2, d 3/2</td>
</tr>
<tr>
<td>16.960</td>
<td>115</td>
<td>s 1/2</td>
<td>g 7/2, d 3/2</td>
</tr>
<tr>
<td>17.720</td>
<td>84</td>
<td>g 7/2, d 3/2</td>
<td>off IAR</td>
</tr>
</tbody>
</table>

- Resolution of two states in < 2 keV distance
- Peak to valley 200:1

Strong excitation on s1/2 and weak by (d,p) yields s1/2 p3/2

E = 22 MeV Θ = 20°

2 μb/sr

E = 16.495 MeV Θ = 48°

15 μb/sr

E = 16.960 MeV Θ = 115°

70 μb/sr

E = 17.720 MeV Θ = 84°

30 μb/sr

? 1^- 6^- 3^- other spins 1^- 7^- are unknown 1^- 8^-
Spin assignment: 6076 not $1^-$ and 6086 not $1^-$

- Spin $2^-$: from distribution of $d^{3/2} p^{1/2}$ strength by $(d,p)$
- Spin $3^-$ from excitation on $s^{1/2}$, weak excitation by $(d,p)$, and natural parity from $(\alpha,\alpha')$: $s^{1/2} f^{5/2}$
- Spin $2^-$ from absence on $s^{1/2}$, $(d,p)$: $L=2$ and polarization asymmetry

**Peak to valley ratios**:
- peak to valley 400: 1 for 6086
- peak to valley 20: 1 for 6076

### Energy and Angle Values

- $E = 18.040 \text{ MeV}$, $\theta = 138^\circ$
- $E = 16.405 \text{ MeV}$, $\theta = 88^\circ$
- $E = 16.960 \text{ MeV}$, $\theta = 84^\circ$
- $E = 18.040 \text{ MeV}$, $\theta = 138^\circ$

**Labels and Notations**
- $(d,d')$, $(d,p)$, $s^{1/2}$, $g^{7/2}$, $d^{5/2}$, off IAR
- Spin assignment and excitation modes:
  - $4^+$
  - $?$
  - $2^-$
  - $2^- 3^-$
  - $? 3^-$
  - $? ?$

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**Diagrams**

- Energy and angular distribution for different incident energies and angles.
- Peaks and valleys indicated with different colors and labels.
- Example energy levels and transitions marked for analysis.

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**Additional Notes**

- Spin and parity assignments based on experimental data and theoretical models.
- Importance of angular distribution in nuclear spectroscopy.
- Correlation between spin assignments and excitation mechanisms.

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**Interpretation**

The spin assignments are crucial for understanding the nuclear structure and reactions.

- The $(d,p)$ reaction is a powerful tool for measuring spin and parity of excited states.
- Angular distributions provide insights into the transition probabilities and selection rules.
- The peak to valley ratios help in identifying the dominant excitation pathways.
Particle spectroscopy above the neutron threshold

- Precision of $E_x$: $\delta E_x < 1$ keV if the states are resolved
- $E_x = S(n) + E_y (207^{\text{Pb}} + n)$
- $S(n) = 7367.9$ keV

$E = 22$ MeV
$\Theta = 32^\circ$

$E = 16.500$ MeV
$\Theta = 138^\circ$

$E = 17.300$ MeV
$\Theta = 138^\circ$

$E_y = 41.3$

$E_y = 101.8$

$E_y = 181.5$

$E_y = 209.4$
Structure of $1^{-}$ states of $^{208}$Pb from cross sections

Strong on $s_{1/2}$, weak (d,p): $s_{1/2} \, p_{3/2}$

Strong on $s_{1/2}$ or strong on $d_{3/2}$ and strong (d,p): $s_{1/2} \, p_{1/2}$ or $d_{3/2} \, p_{1/2}$

Particle from IAR, hole from comparison to s.p. widths

Configuration from comparison to DWBA calculations

Relative cross section on any IAR

Particles and holes indicated by color and symbol.
Strengths of particle-hole configurations in $1^-$ states of $^{208}$Pb

- Dominant strength determined from $^{208}$Pb(p,p') via IAR in $^{209}$Bi and from $^{207}$Pb(d,p) configuration mixing from angular distributions $^{208}$Pb(p,p') via IAR in $^{209}$Bi where particle is determined from excitation functions.
- Components of particle $\times$ p1/2 from $^{207}$Pb(d,p).

The diagram shows the states of $^{208}$Pb with configurations and IARs indicated. The g7/2 and d3/2 IARs are a doublet.
Bound and unbound $1^-$ states in $^{208}$Pb

Schematic shell model predicts 16 $1^-$ states below neutron threshold.

Below neutron threshold, 14 $1^-$ states are confirmed.

Above neutron threshold, $1^-$ states observed by $^{207}$Pb(n,γ) are confirmed.

Four $1^-$ states contain more than 80% of a single configuration.

More $1^-$ states among ~200 states below neutron threshold are expected.

Shell model calculations predict 12 $1^-$ states below neutron threshold.
thank you for your attention