Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Probing the structure of yrast states in even-even $^{214,216,218}$Po through fast-timing measurements following the $\beta$-decay of $^{214,216,218}$Bi

Spokespersons:

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A.N. Andreyev, University of York (UK)
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• Physics motivation
  • Previous studies of isomeric states/seniority scheme in even-even Po
  • Recent shell-model calculations
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• Experimental description
  • Beam production
  • Fast-timing measurements at the ISOLDE Decay Station
  • Rate estimations

• Beamtime request
Physics motivation

- Po isotopes
- Text-book example for studying the seniority scheme
- Presence of $\pi(h_{9/2})$ 8$^+$ isomers in the even-even Po
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  - presence of $\pi(h_{9/2})$ $8^+$ isomers in the even-even Po
- Po isotopes with $N>126$
  - shell-model test using $^{208}\text{Pb}$ as an inert core
  - study the filling of the $\nu g_{9/2}$ orbital

$\rightarrow \alpha + ^{208}\text{Pb}$ cluster configurations in $^{212}\text{Po}$
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$^{214,216,218}\text{Po}$
  - Lack of experimental data for the heavier Po isotopes due to difficulties in producing them using stable beams

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$^{214,216,218}$Po

- Lack of experimental data for the heavier Po isotopes due to difficulties in producing them using stable beams
- Recent measurement by Astier et al. [1] of the $8^+_1$ state half-life $T_{1/2} = 13(1)$ ns in $^{214}$Po indicating a similar excitation mechanism as for $^{210}$Pb, one-neutron-pair breaking

$^{214}$Po

- $z$: 84 $n$: 130
- $T_{1/2}$: 164.3 ms 2.0
- $\beta$: 99.9977% 2.3E-4%
- $\alpha$: 100%

$^{216}$Po

- $z$: 84 $n$: 132
- $T_{1/2}$: 0.145 ± 0.002
- $\beta$: 95%
- $\alpha$: 100%

$^{218}$Po

- $z$: 84 $n$: 134
- $T_{1/2}$: 0.012
- $\beta$: 99.80%
- $\alpha$: 0.20%

$^{214}$Bi

- $z$: 83 $n$: 130
- $T_{1/2}$: 45.59 m 0.06
- $\beta$: 97.80%
- $\alpha$: 2.20%

$^{216}$Bi

- $z$: 83 $n$: 132
- $T_{1/2}$: 7.6 m 0.2
- $\beta$: 100%

$^{218}$Bi

- $z$: 83 $n$: 134
- $T_{1/2}$: 3.088 m 0.012
- $\beta$: 71.8%
- $\alpha$: 28.2%
Physics motivation

We updated the B(E2) figure with known experimental data for Po isotopes (ENSDF + Kocheva et al. [1,2])

→ A staggering can be noticed around $^{210}$Po for the $8^+ \rightarrow 6^+$ transition probability (present also for the $6^+$, $4^+$, $2^+$ cases?)

→ The large value measured in $^{212}$Po was proposed to be due to the $\alpha + ^{208}$Pb cluster structures [A. Astier et al., Eur. Phys. J. A46, 165-185 (2010)]

→ The first four excited states measured in $^{216,218}$Po have similar excitation energies to those known in $^{214}$Po, indicating a structural similarity (needs to be confirmed by B(E2) values in $^{216,218}$Po)

Physics motivation

Shell model calculations were recently performed for selected transitions in the Po isotope chain for two model spaces and interactions: [H. Grawe, Private Communication, Oct 2017]

\[ \pi(h_{9/2}, f_{7/2}, i_{13/2}) \nu(p, f_{5/2}, i, g_{9/2}, j_{15/2}) \] - denoted by \( hfi \rightarrow gij \), with interaction PBPKH [1].

\[ \pi(h_{9/2}, f, i_{13/2}, p) \nu(h_{9/2}, p, f, i, g, d, s_{1/2}, j_{15/2}) \] - denoted by \( r5i \rightarrow r6j \), with interaction PBKH7 [2].

- Non-truncated calculations were performed for \(^{208-212}\text{Po}\). For the other, truncation must be applied, which requires tuning of the pairing part of the interaction.
- Excitations across the \(^{208}\text{Pb}\) shell closure were blocked.
- Transition rates were calculated with effective operators [3]

\[ e_p=1.5 \; e; \; e_n=0.85 \; e; \; g_s=0.6 \; g_s^{\text{eff}}; \; g_m=1.115; \; g_v=0 \]

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  \[ e_p = 1.5 \; e; \; e_n = 0.85 \; e; \; g_f = 0.6 \; g^{\text{free}}; \; g_m = 1.115; \; g_{\pi} = 0 \]

Observations:

- For $N > 126$ the importance of truncation and the low-spin N=6 orbits is clearly visible in contrast to earlier statements that a single- or two-orbit model space for protons and neutrons is appropriate [4].
- The importance of precise new lifetime measurements for $^{212-218}$Po $6^+$ and $8^+$ states is clearly exhibited in the figure.

\[ \pi(h_{9/2}, f_{7/2}, i_{13/2}) \nu(p, f_{5/2}, i, g_{9/2}, j_{15/2}) \]  - denoted by $hfi-gij$, with interaction PBPKH [1].

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**Conclusion:**

$B(E2)$ values in the Po chain will be decisive to verify shell model interactions and disentangle the correlation of model space and interaction. A staggering except when crossing the N=126 shell closure is not really supported by shell model calculations.

β-decay studies of $^{214,216,218}$Bi at ISOLDE

$^{214}$Bi
- HFS recently studied at ISOLDE (IS608: MR-ToF 2016 and IDS 2017)
- direct identification and spectroscopy of an $8^+$ isomer using RILIS+IDS
  (including HFS/isomer shift measurements, spin, decay pattern and half-life)

IDS 2017

MR-ToF 2016 – Ground state

Energy Gated Alpha (cps)

$^{214}$Bi

$^{214}$Bi$^g$ hfs
$^{214}$Bi$^m$ hfs
(new)
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Time distributions between the emissions of γ rays of $^{214}$Po showing either prompt coincidences [curves in red and green, panel (a)] or delayed ones corresponding to the decay of the 1583-keV state [curves in blue, panels (b), (c), and (d)].

$T_{1/2} = 13(1) \text{ ns using HPGe detectors}$ [1]

→ can be re-checked using fast-timing detectors

→ $B(E2; 8^+ \rightarrow 6^+) = 0.54(4) \text{ W.u.}$ used to estimate the $T_{1/2}$ of 8$^+$ states in $^{216,218}$Po

*Lifetimes of 6$^+$, 4$^+$, 2$^+$ states can be accessed through fast-timing measurement.*
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$^{216}$Bi
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$^{218}$Bi
- beam intensity of 44(8) ions/μC [2] using UCx target + RILIS
- similar decay level scheme as $^{216}$Bi but no known lifetimes

Beam production

- Use the same proven method: UCx target + RILIS [1,2]
- Yields recently extracted during IS608 at MR-ToF in 2016

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Rate estimate (ions/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>$^{216}\text{Bi}$</td>
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</tr>
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<td>$2 \times 10^2$</td>
</tr>
</tbody>
</table>

(2 μA proton current)

Beam production

- Use the same proven method: **UCX target + RILIS** [1,2]
- Yields recently extracted during IS608 at MR-ToF in 2016.
- Short-lived contaminants such as Fr can be easily removed using the pulsed release technique and **HRS** (instead of GPS used in 2017 at IDS)

### Chart of nuclides for the isotopes north-east of $^{208}$Pb [1]

#### Isotope Rate estimate (ions/s)

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</table>

(2 μA proton current)

The pulsed release technique [1]: the different time scales for the $\alpha$ decay of the contaminants and the $\beta^-$ decay under investigation allow for a selective suppression.

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Fast-timing measurements at the ISOLDE Decay station

**Ranges:**
- Centroid shift method: - 10 ps - 100 ps
- Slope method: - 50 ps - 50 ns (or longer)

[H. Mach et al. NIM A 280, 49 (1989)]

**Key Points:**
- Well established technique at IDS since 2014 [1,2,3]
- Detection system comprising of:
  - 4 Clover HPGe - 7% abs. eff. at 500keV
  - 2 LaBr₃(Ce) - 3% abs. eff. at 500keV
  - 1 Plastic Scintillator - 20% abs. eff.

Example: lifetime measurement of $8^+$ state in $^{218}$Po

\[ \text{Rate} = 59\% \times 20\% \times 8\% \times 23\% \times 100 \text{ ions/s} \]
\[ = 0.2 \text{ counts/s} \]
\[ = 6.1 \times 10^3 \text{ counts/shift} \]

**Observation:** a conservative rate of 100 ions/s instead of 200 ions/s considering transmission to IDS (70-80\%) and beam downtime.
Example: lifetime measurement of $6^+$ state in $^{218}$Po

<table>
<thead>
<tr>
<th>Level</th>
<th>Start (eff)</th>
<th>Stop (eff)</th>
<th>Cleaning gate (eff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8^+$</td>
<td>$\beta$ (20%)</td>
<td>263.0 (2 x 4%)</td>
<td>385.7 or 425.5 or 509.7 (23%)</td>
</tr>
<tr>
<td>$6^+$ (2+,4+)</td>
<td>263.0 (4%)</td>
<td>385.7 (3%)</td>
<td>425.5 or 509.7 or $\beta$ (14%+20%)</td>
</tr>
</tbody>
</table>

Rate = 59% * (4% * 3% * 2) * (14%+20%) * 100 ions/s
= 0.05 counts/s
= 1.4 * $10^3$ counts/shift
### Rate estimates

<table>
<thead>
<tr>
<th>Nucleus/Yield</th>
<th>$J^π$</th>
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<td>244.1</td>
<td>13(1) ns [6]</td>
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<td>$^{216}$Po $10^3$ ions/s</td>
<td>$2^+_1$</td>
<td>549.7</td>
<td>$&gt; 15$ ps</td>
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<td>$4^+_1$</td>
<td>418.8</td>
<td>$&gt; 58$ ps</td>
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Rate estimates

- Half-lives for yrast states in $^{214,216,218}$Po estimated using:
  - $\text{B(E2)} < 10 \text{ W.u.}$ for $2,4,6^+$ states
  - $\text{B(E2)} \sim 0.5 \text{ W.u.}$ [1] for $8^+$ states

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Within the reach of the fast-timing setup available at IDS (> 10 ps)

Beamtime request: **7 shifts**

- **2 shifts** for $^{218}\text{Bi}$ (in order to reach a statistics > 1000 counts for the time distribution of the $2_1^+$ state)
- **1 shift** for $^{216}\text{Bi}$
- **1 shift** for $^{214}\text{Bi}$ (the incoming rate will be reduced in order to avoid pile-up effects)
- **1 shift** for online fast-timing calibrations using implantation sources (eg. $^{138}\text{Cs}$, $^{88}\text{Rb}$, $^{140}\text{Ba}$)
- **2 shifts** for laser tuning

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**Observation:**

If approved, this experiment can be scheduled together with the remaining 3 shifts of the IS608 experiment (HFS measurements of $^{216,218}\text{Bi}$) because of the following considerations:
- both measurements can be performed using the same fast-timing configuration of IDS
- the stable beam and RILIS tuning will be done only once
Collaboration

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Fig. 3. The decay scheme of $^{216}$Bi.