Production of $^{99}$Mo Using High-Current Alpha Beams

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Introduction

• $^{99}$Mo from $^{96}$Zr by alpha bombardment
• $^{96}$Zr($\alpha$,n)$^{99}$Mo
• High specific activity (> 100 kCi/g)
• >14,000 6-day Ci/year/device
• No uranium involved
• Virtually no nuclear waste generated
• Simplified Chemical processing
• Compatible with current generators
The diagram illustrates the nuclear reactions and decay processes involving isotopes of Mo, Nb, and Zr.

- **Mo** from $^{98}$Mo decays to $^{98}$Nb via $(\alpha,2n)$, followed by $51m \beta^-$ to $^{99}$Mo, then $(\alpha,n)$ to $^{100}$Mo, followed by $(\alpha,\gamma)$ to $^{100}$Mo.
- **Zr** from $^{96}$Zr decays to $^{98}$Zr via $(\alpha,2p)$, followed by $30.7s \beta^-$ to $^{98}$Nb, then $(\alpha,pn)$ to $^{98}$Nb, followed by $2.6m \beta^-$ to $^{99}$Nb, then $(\alpha,p)$ to $^{99}$Nb, followed by $2.6m IT$ to $^{99}$Mo, followed by $(\alpha,\gamma)$ to $^{100}$Mo.
- **Zr** from $^{96}$Zr also decays to $^{98}$Zr via $20$ MeV alpha.

The arrows indicate the direction of the decay or reaction processes.
Molybdenum Production Cross Sections

- \( ^{96}\text{Zr}(\alpha,2n)^{98}\text{Mo} \)
- \( ^{96}\text{Zr}(\alpha,n)^{99}\text{Mo} \)
- \( ^{96}\text{Zr}(\alpha,\gamma)^{100}\text{Mo} \)

\( \alpha \) particle energy [MeV] vs. cross section [mb]
99Mo Yield vs. Specific Activity

At 20 MeV:
- 99Mo yield is beginning to taper off
- Specific activity is above 100 kCi/g
- Pure 99Mo is about 480 kCi/g
- Other reactions start to occur for higher beam energy
$^{99}$Mo Yield vs. Specific Activity
$^{99}$Mo Yield for 100 mA$_e$ Beam

- 54.2 6-day Ci/day
- High flexibility
  - Distributed production over several accelerators
  - Each on a different production cycle
- Inexpensive chemical processing
99Mo Yield for 100 mA_e Beam

- **Weekly yield:**
  - 380 6-day Ci/week, 7 batches/week
  - 202 6-day Ci/week, 1 batch/week
  - ~280 6-day Ci/week, 3 batches/week

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<th>Duty Cycle</th>
<th>Annual Yield (6-day Ci)</th>
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<td>7 batches/week</td>
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<td>3 batches/week</td>
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Target Material

- $^{96}\text{Zr}$ is 2.80% of natural zirconium
- Enriched $^{96}\text{Zr}$ is readily available at greater than 99.99%
- 99.99% enriched targets not necessary
- Slightly lower enrichment lowers target cost and allow additional enrichment methods
  - Little change in specific activity
  - Small decrease in yield
  - Still no significant waste material
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</table>
Zirconium Target Purity

- $^{93}\text{Mo}$ – Long-lived radioisotope
  - Suppress by removing $^{90}\text{Zr}$ and $^{91}\text{Zr}$

- $^{95}\text{Nb}$, $^{94}\text{Nb}$, $^{92}\text{Nb}$ – Long-lived radioisotopes
  - Waste disposal issue
  - Suppress by removing $^{90}\text{Zr}$, $^{91}\text{Zr}$, and $^{92}\text{Zr}$

- $^{93}\text{Zr}$ – Very long-lived radioisotope
  - Waste disposal issue
  - Potentially limit recycling of targets
  - Suppress by removing $^{91}\text{Zr}$
Alpha Particle Source

• Proprietary patented high-current source
• Required high current $^4\text{He}^{++}$ source
  • High current $^4\text{He}^+$ is easy to make
  • High current $^4\text{He}^{++}$ is not so easy
• Current source 32 mA$_e$ beam cw or pulsed
• 85% $^4\text{He}^{++}$ (by current)
• 6 mm beam aperture
• 0.1 (-0.05 +0.15) $\pi\cdot\text{mm}\cdot\text{mrad}$ normalize emittance
• X-ray free ECR source
• Operated for 23,000 hours without failure
• Proton, deuterium, tritium, helion, alpha, etc.
Alpha Particle Source
Alpha Source Expansion

- Current source expansion:
  - 96% $^4\text{He}^{++}$
  - 50 mA$_e$
  - Internal or external X-ray shielding

- Future source:
  - 96% $^4\text{He}^{++}$
  - 120 mA$_e$
  - External X-ray shielding
Accelerator

- Required high current $^4\text{He}^{++}$ source
  - 160 keV
- Magnetic LEBT
- Room temperature RFQ
  - 8 MeV
- Advanced beam structure – 20 MeV
  - Superconducting cavities
  - H-mode structure with PMQ focusing
  - Hybrid cooling (proprietary technology)
- 8-10 m total length
Targets

- 1 MW power dissipated in target
- Conventional approach:
  - Multiple targets
  - Spread beam over large area
  - Octupole expansion
  - \(~1-2 \text{ kW/cm}^2\)
- Proprietary high-power target
  - Single target can dissipate 500 kW-1 MW
  - Under development
Cost Analysis

- NEA Full Cost Recovery model
  - [https://www.oecd-nea.org/med-radio/guidance/docs/FCR-workbook.xlsx](https://www.oecd-nea.org/med-radio/guidance/docs/FCR-workbook.xlsx)

- 10 systems

<table>
<thead>
<tr>
<th>Duty Cycle</th>
<th>Weekly Yield (6-day Ci)</th>
<th>Full Cost Recovery</th>
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<tr>
<td>7 batches/week</td>
<td>3,800</td>
<td>$178</td>
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<td>3 batches/week</td>
<td>~2,800</td>
<td>~$185</td>
</tr>
<tr>
<td>1 batch/week</td>
<td>2,020</td>
<td>$217</td>
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</table>

* - corresponds to roughly same administrative overhead and other non-editable assumptions in the model. Actual Alpha Source solution is scalable without significant change in FRC/6-day Ci.
Post-Irradiation Processing

- Relatively simple chemical processing

- Several methods of target processing have already been developed and verified, including effectiveness of the $^{96}$Zr recycling
  - Ion-exchange chromatography
  - Fluorination
  - Solubility

- Additional methods are also being developed
Deployment

• Approximately 18 100 mA$_e$ systems could supply the US demand for $^{99}$Mo

• Seven 100 mA$_e$ systems could replace the gap created when NRU shuts down in 2016
Conclusions

• High-current alpha beams can be an efficient source for $^{99}$Mo
• No significant nuclear waste
• No uranium used
• Minimal proliferation concerns
• High specific activity
• Distributed, robust production
• Conformable to market demand