Liquid targets for isotope production

Jerry Nolen
Physics Division, Argonne National Laboratory

NuFact'11 XIIIth Workshop on Neutrino Factories, Superbeams and Beta-beams
CERN and University of Geneva

August 3, 2011

This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.
### High-Q and Low-Q pairs

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$^6$He</th>
<th>$^{18}$Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/Z</td>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>decay</td>
<td>$\beta^-$</td>
<td>$\beta^+$</td>
</tr>
<tr>
<td>$\tau_{1/2}$ [s]</td>
<td>0.81</td>
<td>1.67</td>
</tr>
<tr>
<td>Q [MeV]</td>
<td>3.51</td>
<td>3.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$^8$Li</th>
<th>$^8$B</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/Z</td>
<td>2.7</td>
<td>1.6</td>
</tr>
<tr>
<td>decay</td>
<td>$\beta^-$</td>
<td>$\beta^+$</td>
</tr>
<tr>
<td>$\tau_{1/2}$ [s]</td>
<td>0.83</td>
<td>0.77</td>
</tr>
<tr>
<td>Q [MeV]</td>
<td>12.96</td>
<td>13.92</td>
</tr>
</tbody>
</table>

#### NuBase

- t$_{1/2}$ at rest (ground state)
- 6He and $^{18}$Ne
- 8Li and $^8$B

Higher Q-value gives higher $\nu$-energy, better x-sections but needs longer baseline.
CERN Beta Beams, Synoptic

Baseline

Decay Ring: $B_\rho \sim 500$ Tm, $B = \sim 6$ T, $C = \sim 6900$ m, $L_{ss} = \sim 2500$ m, $\gamma = 100$, all ions
The Production Ring (8B and 8Li)

“Inverse”: $^6$Li beam on $^3$He gas jet. “Direct”: $^3$He beam on $^6$Li target.

- High-Q 8B and 8Li will not be considered for the time being
- We will not explore the low-Q gamma 350 option

Supersonic gas jet target, stripper and absorber

Production of 8B and 8Li
C. Rubbia, EUROnu proposal

Gas Jet target proposed in FP7:
- too high density would be needed
- vacuum problems

Direct Production (D. Neuffer) with liquid film targets
- Collaboration ANL (Benedetto/Nolen)

Can liquid lithium targets be used at the necessary power levels?

- High-Q 8B and 8Li will not be considered for the time being

Aachen Univ., GSI, CERN
Direct vs. inverse kinematics

**INVERSE**

- 😊 ⁸Li/⁸B emitted at θ~10° similar energy as projectile
- 😞 Supersonic jet target
- 😊 Efficient cooling removal
- 😞 Low densities
- 😊 Collection + diff./effusion

**DIRECT**

- 😊 30° emission angle and smaller velocity
- 😞 Larger M.C. Scattering
- 😊 Larger emittance, less SC
- 😊 Solid/liquid target
- 😞 Cooling / jet instabilities
- 😊 High densities
- 😊 Collection? Spectrometer?

*See also D. Neuffer, NIM A 585 (2008) 109*
Production/cooler rings: direct or inverse kinematics

Table 1
Low-energy ion cooling examples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Reverse dynamics</th>
<th>Direct scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td></td>
<td>$^6$Li</td>
<td>$^3$He</td>
</tr>
<tr>
<td>Absorber</td>
<td></td>
<td>$^3$He</td>
<td>$^6$Li</td>
</tr>
<tr>
<td>Momentum (MeV/c)</td>
<td>$P$</td>
<td>530</td>
<td>265</td>
</tr>
<tr>
<td>Kinetic energy (MeV)</td>
<td>$T_0$</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>Speed</td>
<td>$\beta = v/c$</td>
<td>0.094</td>
<td>0.094</td>
</tr>
<tr>
<td>Absorber density (reference)</td>
<td>$\rho_{\text{ref}}$ (liquid or solid)</td>
<td>0.09375</td>
<td>0.46</td>
</tr>
<tr>
<td>Energy loss (MeV/cm)</td>
<td>$dE/ds$</td>
<td>110.6</td>
<td>170.4</td>
</tr>
<tr>
<td>Radiation length (cm)</td>
<td>$L_R$</td>
<td>756</td>
<td>155</td>
</tr>
<tr>
<td>Betatron functions at absorber (m)</td>
<td>$\beta_{\perp, \parallel}$</td>
<td>0.3, 0.3</td>
<td>0.3, 0.3</td>
</tr>
<tr>
<td>Rms angle (°)</td>
<td>$\delta \theta_{\text{rms}} (\beta_l = 0.3 \text{ m})$</td>
<td>2.25$K_s$</td>
<td>3.8$K_s$</td>
</tr>
<tr>
<td>Rms beam size (cm)</td>
<td>$\sigma_l$ (at $\beta_l = 1 \text{ m}$)</td>
<td>2.15$K_s$</td>
<td>3.6$K_s$</td>
</tr>
<tr>
<td>Absorber thickness (3000 turn lifetime) (cm)</td>
<td>$\lambda_{\text{abs}}$</td>
<td>0.018</td>
<td>0.00725</td>
</tr>
<tr>
<td>Characteristic cooling length (cm)</td>
<td>$(dP/(ds/P))^{-1}$</td>
<td>0.45</td>
<td>0.147</td>
</tr>
<tr>
<td>Multiple scattering (cm$^{-1}$)</td>
<td>$d(\theta^2)/ds$</td>
<td>$8.84 \times 10^{-4}K_s^2$</td>
<td>$0.0078K_s^2$</td>
</tr>
<tr>
<td>Straggling (MeV$^2$/cm)</td>
<td>$d(\delta E^2)/ds$</td>
<td>0.0868</td>
<td>0.143</td>
</tr>
<tr>
<td>Sum of partition numbers</td>
<td>$\sum J_l$</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Eq. transverse emittance (m)</td>
<td>$\theta_{t,N,\text{rms}}$</td>
<td>$4.35 \times 10^{-5}K_s^2$</td>
<td>$0.000123K_s^2$</td>
</tr>
<tr>
<td>Equilibrium $\delta P/P (J_z = 0.13)$</td>
<td>$\delta_{\text{rms}}$</td>
<td>0.0078</td>
<td>0.0115</td>
</tr>
<tr>
<td>Production energy (MeV)</td>
<td>$E_{\text{B-s}}$</td>
<td>8.3, 21.5</td>
<td>0.93, 8.3</td>
</tr>
<tr>
<td>Production speed</td>
<td>$\beta_{\text{B-s}}$</td>
<td>0.047–0.078</td>
<td>0.016–0.047</td>
</tr>
<tr>
<td>Maximum production angle (°)</td>
<td>$\theta_{\text{max}}$</td>
<td>14</td>
<td>30</td>
</tr>
</tbody>
</table>
Recent presentation by the Argonne liquid lithium group

Thin liquid lithium targets for high power density applications: heavy ion beam strippers and beta beam production

Presented at
4th High Power Targetry Workshop

May 2nd to May 6th 2011
Hilton Malmö City

Claude Reed, Jerry Nolen, Yoichi Momozaki, Jim Specht, Dave Chojnowski,
Ron Lanham, Boni Size, and Richard McDaniel

Nuclear Engineering Division and Physics Division
Thick target and thin target development

REVIEWS OF SCIENTIFIC INSTRUMENTS 76, 073501 (2005)

Behavior of liquid lithium jet irradiated by 1 MeV electron beams up to 20 kW

J. A. Nolen
Physics Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

C. B. Reed and V. J. Novick
Nuclear Engineering Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

J. R. Specht and J. M. Bogaty
Physics Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

P. Plotkin
Energy Technology Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

Y. Momozaki
Nuclear Engineering Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

Development of a liquid lithium thin film for use as a heavy ion beam stripper JINST 4:P04005 (2009)

Yoichi Momozaki\textsuperscript{a}, Jerry Nolen\textsuperscript{b}, Claude Reed\textsuperscript{a}, Vincent Novick\textsuperscript{a} and James Specht\textsuperscript{b}

\textsuperscript{a} Argonne National Laboratory, Nuclear Engineering Division, 9700 South Cass Avenue, Argonne, Illinois 60439, U.S.A.
\textsuperscript{b} Argonne National Laboratory, Physics Division, 9700 South Cass Avenue, Argonne, Illinois 60439, U.S.A.
E-mail: momo@anl.gov

Liquid targets for isotope production
High Power Test of a Liquid-Lithium Fragmentation Target

A 20 kW electron beam produces the same thermal load as a 200 kW U beam on the windowless liquid Li target.

Li jet is confirmed stable in vacuum with a U beam equivalent thermal load.

Power density is 8 MW/cm³ @ 400 kW beam power at 200 MeV/u.
Thermal Design Analysis for Liquid Metal Windowless Targets

Y. Momozaki, J. A. Nolen, C. B. Reed, J. Bailey, and P. Strons

The Third High-Power Targetry Workshop by Paul Scherrer Institut

September 10 to 14, 2007
Bad Zurzach, Switzerland
**Background**

**20 kW E-beam-on-Target Test at ANL**

- MCNPX:
  - for RIA, 200-kW uranium beam on Li
  - 1MeV, 20 mA, 1mm φ e-beam on Li

  \[ \text{peak energy deposition} = 2 \text{ MW/cm}^3 \]
  \[ \text{deposited in the first 4 mm} \]

- Test Objectives:
  - Using this equivalence, demonstrate that power densities equivalent to a 200 kW RIA uranium beam:
    - *Do not disrupt the Li jet flow*
    - *Li ΔT (across beam spot) is modest (~ 180º C)*
    - *Li vapor pressure remains low*

- Overall Objective:
  - To show that 2 MW/cm³, deposited in the first 4 mm of the flowing lithium jet, can be handled by the windowless target
What Experiment Indicates: power density for 1-MeV, 20-kW e-beam

- Thermal analysis
  - 3D Results (using Star CD)

- Estimated maximum temperature in the Li target is 872 K.
Thermal Design Analysis for a liquid tin beam dump for uranium beams

- Sn beam-dump for AEBL, ANL, USA

- Estimated maximum temperature in the Li target is $912 \, K$ ($P_{\text{sat}} \sim 1.8 \times 10^{-7} \, \text{Pa}$ for Sn).
Power density expectations give limitations for internal thin liquid lithium target size and speed

- Our prediction is for a peak temperature of 941K in a 13 micron thick film flowing at 58 m/s and 624 W deposited by a uranium beam with a 3σ beam width of 1 mm
  - Because of the high speed linear flow only the beam width is relevant
  - A 13 micron film is 0.65 mg/cm², so a 1 mg/cm² thickness can take 960 W/(mg/cm²) per mm of width
  - From David Neuffer’s paper the internal target can be 3.6 mg/cm² in thickness, and hence can take 3.5 kW per mm of width
  - He also predicts a power deposit from the $^3$He beam of 500 kW, so the width of the beam spot must be 143 mm at 58 m/s to keep the same temperature rise
  - If we can increase the speed to 200 m/s then the width can be 41 mm

- Issues:
  - The beam spot can be 41mm wide by 1mm tall, so is this size beam on target compatible with the ring optics? (the slit-shaped beam is probably good for the recoil collection geometry)
  - Can we scale the speed to 200 m/s or more? (requires ~500 psia pressure – probably OK)
  - Can we make a film 41 mm wide and 72 microns thick? (I think so)
Other potential uses of liquid metal technology at neutrino factories

- Alternative for production of $^8$B via fragmentation of $^{10}$B
  - ~1 MW $^{10}$B beam at ~200 MeV/u can produce in-flight $1E13$ $^8$B per second using a liquid lithium cooled target
  - The $^8$B is formed at high energy and already fully stripped
  - Studies of transverse and longitudinal cooling are necessary to compare overall rates with “ISOL” methods

- The 2-step $^6$He production target can probably benefit from liquid lithium cooling of the tungsten neutron converter

- The “pebble-bed” pion production target concept can probably benefit from liquid lithium cooling of the pebbles
Concept for a liquid-lithium cooled tungsten neutron converter for radioactive beams of fission fragments

This concept is applied to production of $^6\text{He}$ by replacing the uranium with BeO.

Liquid lithium cooling enables a more compact geometry.
Packed Bed Target Concept for Euronu (or other high power beams)

Packed bed cannister in parallel flow configuration

Packed bed target front end

Titanium alloy cannister containing packed bed of titanium or beryllium spheres
Cannister perforated with elliptical holes graded in size along length

Model Parameters
- Proton Beam Energy = 4.5GeV
- Beam sigma = 4mm
- Packed Bed radius = 12mm
- Packed Bed Length = 780mm
- Packed Bed sphere diameter = 3mm
- Packed Bed sphere material: Beryllium or Titanium
- Coolant = Helium at 10 bar pressure

Cold flow in
Hot flow out
Summary

- Initial estimates indicate that $^8\text{B}$ production via $^3\text{He}$ stored beam on a thin $^6\text{Li}$ target is not far from feasible ($^2\text{H}$ beam on $^7\text{Li}$ target is less demanding)

- Beam-on-target tests of the thin lithium film is the next priority for the FRIB stripper development

- An update of the ring parameters required for necessary production rates should be done

- Ring and cooling/heating dynamics with a slit-shaped beam spot on target must be investigated

- Liquid lithium technology is possibly applicable in other aspects of neutrino factory targetry