Measurements of DN Yields and Time Spectra from p(1 GeV) + natPb & p(1 GeV) + 209Bi

D. Ridikas¹, A. Barzakh³, V. Blideanu¹, J.C. David¹, D. Doré¹, D. Fedorov³, X. Ledoux², F. Moroz³, V. Panteleev³, A. Plukis⁴, R. Plukiene⁴, A. Prévost¹, O. Shcherbakov³, A. Vorobyev³

¹CEA Saclay, DSM/DAPNIA, 91191 Gif-sur-Yvette, France
²CEA/DIF, DAM/DPTA, 91680 Bruyères-le-Châtel, France
³Petersburg Nuclear Physics Institute, 188350 Gatchina, Leningrad district, Russia
⁴Institute of Physics, Savanoriu pr. 231, 02300 Vilnius, Lithuania

Collaboration:
• PNPI, Russia
• IoP, Lithuania
• PSI, Switzerland

Financial support:
• CEA
• FR Ministry of Foreign Affairs
• GEDEPEON
Introduction

- high-energy high-power accelerators →
  use of liquid metal targets (Hg, Pb, Pb-Bi, …)

- long flowing metal loop →
  activated metal close to electronics, in hot cells,
  heat exchanger, pumps, …

- short transit time →
  “moving” beta, photon and delayed neutron (DN) radioactivity

Goal:
Characterization of DNs from high-energy spallation-fission reactions
Examples (A)

J-PARC/JAEA - thanks to H. Nakashima

- **Delayed neutrons**
- **Prompt neutrons**

**short Hg transit time → delayed neutron (DN) activity**
MegaPie/PSI - thanks to F. Groeschel

Beam on the target from 14 August to 23 December!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_p )</td>
<td>570 MeV</td>
</tr>
<tr>
<td>( I_p )</td>
<td>1.2 mA (1.8)</td>
</tr>
<tr>
<td>W</td>
<td>0.7MW (1.0)</td>
</tr>
<tr>
<td>( V_{PbBi} )</td>
<td>~ 82 liters</td>
</tr>
<tr>
<td>Main pump</td>
<td>~4.00 l/s</td>
</tr>
<tr>
<td>( T_{transit} )</td>
<td>~20 s</td>
</tr>
</tbody>
</table>

DN and PN estimates using MCNPX+CINDER’90

\[
\Phi_n (DN) \approx 10^6 \text{ n/(s cm}^2) \\
\Phi_n (PN) \approx 10^6 \text{ n/(s cm}^2)
\]

Important: DN yields are very sensitive to the choice of physics models!

D. Ridikas et al., Proc. of PHYSOR2006, Vancouver, Canada

Contact: ridikas@cea.fr
## Model-dependence of DN yields

<table>
<thead>
<tr>
<th>Group</th>
<th>$T_{1/2}$, s</th>
<th>$a_p$ n/p times 10^6</th>
<th>INCL4 +ABLA model</th>
<th>CEM2k model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$T_{1/2}$, s</td>
<td>$a_p$ n/p times 10^6</td>
</tr>
<tr>
<td>1</td>
<td>55.49</td>
<td>0.87</td>
<td>55.60</td>
<td>6.78</td>
</tr>
<tr>
<td>2</td>
<td>16.29</td>
<td>0.89</td>
<td>16.35</td>
<td>15.25</td>
</tr>
<tr>
<td>3</td>
<td>4.99</td>
<td>0.44</td>
<td>4.66</td>
<td>23.58</td>
</tr>
<tr>
<td>4</td>
<td>1.90</td>
<td>1.19</td>
<td>1.63</td>
<td>174.24</td>
</tr>
<tr>
<td>5</td>
<td>0.52</td>
<td>0.21</td>
<td>0.45</td>
<td>129.95</td>
</tr>
<tr>
<td>6</td>
<td>0.20</td>
<td>0.00</td>
<td>0.11</td>
<td>233.52</td>
</tr>
<tr>
<td>Total/average</td>
<td>18.70</td>
<td>3.59</td>
<td>1.90</td>
<td>583.35</td>
</tr>
</tbody>
</table>

**Difference by 2 orders of magnitude!**

*D. Ridikas et al., Proc. of Fission2005, CEA Cadarache, France*
Model-dependence of $Y_{in}(A,Z)$ yields

- INCL4-ABLA gives “reasonable” predictions
- other models overestimate significantly the neutron-rich side

1. Fission yields on the very neutron-rich side are difficult to reach
2. **No available data** on DN yields from high energy fission-spallation
DN measurements from p (1GeV)+Pb at PNPI Gatchina (Russia)

PNPI synchrocyclotron

Location of the experiment

Pb target
1 GeV protons ~20 nA

³He counter
He-3 counter calibration:
\(^{252}\text{Cf}\) neutron source + Monte Carlo

Proton beam monitoring:
\(^{27}\text{Al}\) foils and gamma spectroscopy from \(^{22}\text{Na},^{24}\text{Na}\) and \(^{7}\text{Be}\)

Measurement strategy:
- a) No target at all – long irradiations
- b) Concrete block – long irradiation
- c) Iron thick target – long irradiations
- d) Lead target of variable thickness;
  short (350 \(\mu\)s), intermediate (20 s) and long (300 s) irradiations
Proton beam monitoring

**Beam size/profile:** by photo-films at exit and entrance positions

**Beam intensity:** by $^{27}$Al foils and gamma spectroscopy from $^{22}$Na, $^{24}$Na and $^{7}$Be

- $^{27}$Al($p,x$)$^{7}$Be monitor reaction cross section $7.5 \pm 0.3$ mb was taken as a reference
- Ratios of $^{24}$Na & $^{22}$Na with respect to $^{7}$Be were equal to $1.73 \pm 0.15$ & $1.99 \pm 0.07$

→ Uncertainty in proton beam monitoring from 8 % to 12 %
Accumulated raw data

6-9 May 2007, SCK*CEN Mol, Belgium
DN decay curve: \( p + \text{natPb} \) (55 cm)

\[
DN(t) = \sum_i a_i \exp(-\lambda_i t)(1 - \exp(-\lambda_i T_{irrad}))+C
\]

<table>
<thead>
<tr>
<th>Group</th>
<th>Half-life, s</th>
<th>Precursor</th>
<th>( P_n (\beta-n) ), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55.60</td>
<td>(^{87}\text{Br})</td>
<td>2.52</td>
</tr>
<tr>
<td>2</td>
<td>16.29</td>
<td>(^{88}\text{Br})</td>
<td>6.58</td>
</tr>
<tr>
<td>3</td>
<td>4.173</td>
<td>(^{17}\text{N})</td>
<td>95.10</td>
</tr>
<tr>
<td>4</td>
<td>0.178</td>
<td>(^{9}\text{Li})</td>
<td>50.80</td>
</tr>
</tbody>
</table>

“Understandable” from x-sections

- \( p(1\text{GeV}) + \text{Pb} \rightarrow \(^{9}\text{Li}\) \sim 1000 \mu b \\
- \( p(1\text{GeV}) + \text{Pb} \rightarrow \(^{17}\text{N}\) \sim 600 \mu b \\
- \( p(1\text{GeV}) + \text{Pb} \rightarrow \(^{87}\text{Br}\) \sim 30 \mu b \\

Contact: ridikas@cea.fr
DN decay curves: $p + \text{natPb}$

- Reproduced with 4 major contributions: $^9\text{Li}$, $^{17}\text{N}$, $^{88}\text{Br}$, and $^{87}\text{Br}$
DN decay curves: $p + ^{209}$Bi

- The same 4 major contributions: $^9$Li, $^{17}$N, $^{88}$Br, and $^{87}$Br
Experimental precursor yields (atoms/proton)

- Saturation is observed for targets thicker than 20 cm
- Similar shapes and absolute values both for Pb and Bi

\[ DN(t) = \sum_i a_i \exp(-\lambda_i t)(1-\exp(-\lambda_i T_{irrad})) + C \]

\[ DN(t = 0) = \sum_i a_i + C \]

\[ P^i Y^i = a_i / (\varepsilon_{He-3} I_p \Delta t_{ch} N_{cycles}) \]

D. Ridikas et al., EPJ A (2007); in print
Precursor yields: data versus PHITS simulations


- INC (JAM) + EVAP(GEM)
  JAM: Jet AA Microscopic Transport Model
  GEM: Generalized Evaporation Model

→ Predictions within a factor of 2!
Extraction of x-sections: $^{17}$N & $^{87,88}$Br

Using thin targets

$\Rightarrow$ Good agreement with old data and/or systematics!
Conclusions and outlook

• importance of DNs in liquid metal targets for radioprotection issues
• importance of the measurements to test model calculations

• DN yields and time spectra measured for the 1st time for p(1GeV) on thick natPb and Bi targets

• Estimates of errors on DN decay curves : below 20 %

• Major contributors are: $^{87}$Br, $^{88}$Br and $^{17}$N → extraction of x-sections

• PHITS code “recommended” for such studies

• Consequences and “in-situ” experiment…
Absolute DN production yields: consequences

Assumption: \( p(1\text{GeV}) + \text{Pb} \) (55 cm thick; 10 cm \( \varnothing \)) at 1 mA (1 MW)

\[ \sim 5 \cdot 10^{10} \text{ n/s} \]

Important data for:
- SNS based on liquid metal targets
- ToF facilities (DNs \( \rightarrow \) background neutrons)

\( T_{\text{irrad}} = 300 \text{s} \)

\( \sim 20 \text{ s after} \)
CEA/ DSM/ DAPNI A’s contribution for MegaPie

6-9 May 2007, SCK*CEN Mol, Belgium

Contact: ridikas@cea.fr
MegaPie: geometrical model

Cross section S, cm²

Contact: ridikas@cea.fr
Use of parameters extracted from PNPI/Gatchina experiments

Estimates:
\( \tau_a \sim 0.5 \text{ s irradiation} \)
\( T \sim 20 \text{ s relaxation} \)
\( \tau_d \sim 10 \text{ s heat exchanger} \)

\[
a(x) = \sum_{i=1}^{n} a_i(x) = \sum_{i=1}^{n} a_i \frac{1 - \exp(-\lambda_i \tau_a)}{1 - \exp(-\lambda_i T)} \exp(-\lambda_i \tau_d(x))
\]

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DN decay curves: Fe and “brick”

\[ p(1\text{GeV}) + ^{\text{nat}}\text{Fe} \rightarrow ^{9}\text{Li}, ^{17}\text{N}, \ldots \]

\[ p(1\text{GeV}) + \text{“brick”} \rightarrow ^{9}\text{Li}, ^{17}\text{N}, \ldots \]

\[ T_{1/2} = 4.19 \pm 0.02 \text{ s} \]
\[ T_{1/2} = 0.188 \pm 0.004 \text{ s} \]

Contact: ridikas@cea.fr
1. $^{252}$Cf neutron source at $y = 170\text{cm}$ and different $x$ 
   $\rightarrow$ modeling with MCNPX: agreement within 5-6% 

2. Use of Monte Carlo with 
   $\rightarrow$ exact experimental conditions 
   $\rightarrow$ variable target thickness 
   $\rightarrow$ variable DN energy 
   $\rightarrow$ estimated uncertainty below 10%
He-3 neutron counter
$^3$He (8 atm.) + Ar(2 atm.)
Example (A)

- SNS, J-PARC, EURISOL → liquid Hg
- MegaPie, ADS → liquid PbBi

SNS/ORNL - thanks to F. Gallmeier
Physics: ratios of relative yields relative to $^{87}$Br

<table>
<thead>
<tr>
<th>Target thickness, cm</th>
<th>$a_2(^{88}\text{Br})/a_1(^{87}\text{Br})$</th>
<th>$a_3(^{17}\text{N})/a_1(^{87}\text{Br})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.7</td>
<td>354</td>
</tr>
<tr>
<td>10</td>
<td>1.4</td>
<td>235</td>
</tr>
<tr>
<td>20</td>
<td>1.3</td>
<td>118</td>
</tr>
<tr>
<td>40</td>
<td>1.3</td>
<td>102</td>
</tr>
<tr>
<td>55</td>
<td>1.4</td>
<td>90</td>
</tr>
</tbody>
</table>

stable decreasing

$\rightarrow$ Produced by different reaction mechanisms

<table>
<thead>
<tr>
<th>Target thickness, cm</th>
<th>$a_2(^{88}\text{Br})/a_1(^{87}\text{Br})$</th>
<th>$a_3(^{17}\text{N})/a_1(^{87}\text{Br})$</th>
<th>$a_4(^{6}\text{Li})/a_1(^{87}\text{Br})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.96</td>
<td>104</td>
<td>235</td>
</tr>
<tr>
<td>10</td>
<td>0.95</td>
<td>89</td>
<td>200</td>
</tr>
<tr>
<td>20</td>
<td>0.89</td>
<td>86</td>
<td>159</td>
</tr>
<tr>
<td>40</td>
<td>0.86</td>
<td>64</td>
<td>125</td>
</tr>
<tr>
<td>55</td>
<td>0.97</td>
<td>62</td>
<td>121</td>
</tr>
</tbody>
</table>

Confirmed by PHITS predictions

6-9 May 2007, SCK*CEN Mol, Belgium
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Thanks to P. Romain et al. CEA/DIF/DPTA

What is beyond 20 MeV?
Why only 4 exponentials are sufficient?

Production of Br isotopes

U fission ↔ Pb fission; low energy ↔ high energy