INCL4.5-Abla07: What's new for the assessment of spallation target activation?

Jean-Christophe David

(CEA-Saclay/Irfu/SPhN - France)
### INCL4.5 and Abla07

<table>
<thead>
<tr>
<th>INCL4</th>
<th>Abla</th>
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<td><strong>Intra-Nuclear Cascade Liège</strong> (CEA and U-Liège)</td>
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**Emitted particles**

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**INCL4.5 and Abla07**

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<td>n, p, d, t, $^3$He, α and $A \leq 8$</td>
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<td>n, p, d, t, $^3$He, α and IMF</td>
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INCL4.5 and Abla07

**INCL4**  
Abla  
Intra-Nuclear Cascade Liège (CEA and U-Liège)  
Deexcitation (GSI)  
Break-up; evaporation; fission

**Emitted particles**

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MegaPie

- Demonstrator for liquid Pb-Bi target
- Within SINQ (PSI)
- Operated in 2006
- Proton beam
- 575 MeV and 1.4 mA (~0.8 MW)
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Main differences:
- Tritium contribution
- CEM03 higher
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- Tritium contribution
- CEM03 higher

Main contributors

Incl4.5-Abla07
Bert-Dres
Cem03
**Activity LBE**

Possible explanation ➔ Elementary data

**Main contributors**

**Activity in LBE**

- **Possible explanation**
- **Elementary data**

---

**INCL4.5-Abla07: What’s new for the assessment of spallation target activation?**

J.-C. David
Possible explanation

Ex. $^{203}\text{Pb}$ contribution

$p^{+}^{208}\text{Pb} @500\text{MeV}$

$\text{INCL4.5-Abla07} \approx \text{CEM03}$

But…

@~500MeV

$^{203}\text{Pb} = 80\% \ 203\text{Pb}$

$20\% \ 203\text{Bi}$

@~70MeV

$203\text{Pb} = 50\% \ 203\text{Pb}$

$50\% \ 203\text{Bi}$

… same story with $^{202}\text{Pb}$

INCL4.5-Abla07: What's new for the assessment of spallation target activation?
Main differences:
- Tritium contribution
- CEM03 higher

INCL4.5-Abla07 better than the other codes in the MegaPie energy range
Delayed Neutrons in LBE

Neutrons:
- prompt (reaction)
- delayed (decay of precursors)

Liquid metal target → Precursors can move →

Measurement of DN @ MegaPie in 2006

Attempt to calculate DN with INCL4.5-Abla07

D. Ridikas et al., Proc. of PHYSOR2006, Vancouver, Canada
Delayed Neutrons in LBE

DN flux ($a$) and contributors ($a_i$)

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

- $\tau_a$: activation time
- $T$: (total) circulation time
- $\tau_d$: transit (decay) time
- $i^{th}$ precursor #i

Fit of DN measurement with 3 precursors

<table>
<thead>
<tr>
<th>Group</th>
<th>Precursor</th>
<th>Half-life (s)</th>
<th>$a_i$, %</th>
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<tbody>
<tr>
<td>1</td>
<td>$^{87}$Br</td>
<td>55.6</td>
<td>4.3</td>
</tr>
<tr>
<td>2</td>
<td>$^{88}$Br</td>
<td>16.3</td>
<td>3.3</td>
</tr>
<tr>
<td>3</td>
<td>$^{17}$N</td>
<td>4.16</td>
<td>92.4</td>
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...$^{17}$N is produced now in INCL4.5-Abla07...
Delayed Neutrons in LBE

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

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@ 1 GeV

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\(^{17}\text{N}, ^{87}\text{Br}, ^{88}\text{Br}\): difficult to estimate

- \(^{87}\text{Br}, ^{88}\text{Br}\): very rich neutron Br isotopes
- \(^{17}\text{N}\): 2 mechanisms
Delayed Neutrons in LBE

\[
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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INCL4.5-Abla07 has to improved N/Br ratios…
But able to calculate them!

\(^{17}\text{N}, \(^{87}\text{Br}, \(^{88}\text{Br}: difficult to estimate

- \(^{87}\text{Br}, \(^{88}\text{Br}: very rich neutron Br isotopes
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Activity Window

- ~no difference…
- except Tritium!?
Tritium in Window

Tritium is directly produced and with the right rate

575 MeV

Tritium production

Tritium production cross-section (mb)

Incident energy (MeV)

Bogatin
Mekhodiev
Currie
Fremnan
Ayvat
HINDAS
Herbach
Berlin-Dresden
OSM03
INCL4.5-ABLA07
Cascade coalescence
Evaporation

INCL4.5-Abla07: What's new for the assessment of spallation target activation?

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Tritium in Window

BUT comes also from low energy neutrons:
- $^3\text{He}$ 29.7%
- $^6\text{Li}$ 1.6%

Tritium is directly produced and with the right rate.

Tritium production

575 MeV
Tritium in Window

Tritium is directly produced and with the right rate

production rate = #Target * σ * Flux_projectile

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By hand:
- $^3$He 20.5%
- $^6$Li 0.4%

BUT comes also from low energy neutrons:
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575 MeV
Tritium in Window

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BUT comes also from low energy neutrons:
- \(^3\text{He}\) 29.7%
- \(^6\text{Li}\) 1.6%

In a significant low energy neutron flux, take care of \(^3\text{He}\) production for tritium estimate!!!

By hand:
- \(^3\text{He}\) 20.5%
- \(^6\text{Li}\) 0.4%
He also produced and with the right rate. Production rate = \#Target * \sigma * Flux_{projectile}

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Release of volatiles in Pb/Bi has been studied at ISOLDE (Ep = 1.4 GeV) … and \(^{210}\text{At} \) were measured (Y. Tall et al., ND2007)

\(^{210}\text{At} \) is produced with low rates, but:

- \(^{210}\text{At} \) decays to Po (\(\alpha\) emitter)
- \(^{210}\text{At} \) more volatile than Po

\(\rightarrow\) \(^{210}\text{At} \) can become a safety issue

No model was able to reproduce \(^{210}\text{At} \) production
INCL4.5-Abla07 seems not really better (shape!)… ???  Why?

- Model?
- Data? ……→ data=measurement / calculation=in-target !!!
Two production channels:

- Bi ($p,\pi^-$) for light isotopes
- secondary reactions induced by He for heavy isotopes
- wrong shape of calculation!
Two production channels:
- Bi (p,π⁻) for light isotopes
- secondary reactions induced by He for heavy isotopes
→ wrong shape of calculation!

Only pion channel

$\text{p (480 MeV)} + \text{Bi}$

factor 2 (not 50!)

- $\pi$ spectra: OK!
- At production ($\pi$ channel only) not so bad
Two production channels:
- Bi \((p,\pi^-)\) for light isotopes
- secondary reactions induced by He for heavy isotopes

- wrong shape of calculation!

- production of He OK
- wrong production of At

- Exact reaction Q-values not taken into account
- Coulomb deviation not done in He induced reactions
Astatine @ ISOLDE

Improvement?

\[ ^{209}\text{Bi}(\alpha,n)^{212}\text{At} \text{ (independent)} \]

\[ ^{212}\text{At} \]

\text{INCL4.5}

\text{YES}

\[ ^{212}\text{At} \]

\text{INCL4.6}

\text{YES}
Astatine @ ISOLDE

Improvement!

$^{209}\text{At}$

INCL4.6

$^{210}\text{At}$

INCL4.6

$^{211}\text{At}$

INCL4.6

INCL4.5-Abla07: What's new for the assessment of spallation target activation?

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Next steps

- Improvements into MCNP(X) → new ISOLDE calculation
- Status on the data: $^{211}$At
Conclusion

We have seen that:

• Need of **Elementary Data** to understand *macroscopic results* **AND** taking into account all mechanisms
  - $^{203}\text{Bi}$ production for $^{203}\text{Pb}$ production (and at lower energies)
  - $^{3}\text{He}$(${^6}\text{Li}$) production for Tritium production

• **Delayed Neutrons** tricky to estimates due to
  - Combination of several mechanisms (evaporation/fission/break up)
  - Low probability channels

• “**Extented low energy**” spallation needed
  - Astatine (potential safety issue) from Helium $\sim 40\text{MeV} (<< 150 \text{ MeV})$

**INCL4.5 and Abla07** (try to) become comprehensive codes with very encouraging results
INCL4.5-Abla07:
What's new for the assessment of spallation target activation?

Authors

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