Production of Fast Rare Ion Beams

1. Introduction to production of Fast Rare Ion Beams
2. Production Area
3. Separation
4. Identification
5. Production of new isotopes
6. LISE++: Utilities
7. Radioactive beam physicist task
2. Production

1. Choice of place for the experiment
   - Intensities
   - Primary beam lists

2. Planning of Fast RIB Experiment
   - Ion yields after target

3. Settings
   - Beam
   - Target
   - Fragment of interest
   - Charge state model
   - Energy loss model
   - Secondary reactions in target
   - Reaction mechanism

4. Reaction mechanisms
   - Evaporation cascade
     - Fission barrier
   - Projectile fragmentation
   - Fission fragment production model
   - Coulomb fission
   - Abrasion-Fission
   - Fusion-Fission
   - Fusion-Residual
   - Two body reactions
   - Others

5. Efficiency transmission at target

Some definitions will be used in the lectures

- for whom this information
- who is responsible

User
Advanced
Beam physicist

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Choice of place for the experiment with RIBs

- What is priority?
  - Energy & Intensity combination
  - Energy
  - Intensity
  - Purity

- Technical devices (Detector arrays, specific targets)
- Beam Inclination on target (LISE@GANIL, A1900@NSCL)
- Specific separation devices (Wien-filter, RF-kicker)
- Reliability of accelerator complex

- Out of discussion
  - Your proposal: how difficult to pass through a PAC
  - How expensive travelling and lodging
  - Visa troubles, local food, and so on

- Accelerator type is not criteria

Information:
- Primary beam list
- Technical devices availability
- Call for proposal
### Intensity: Factors for production of new isotopes

\[ Y = I \ \frac{\sigma}{\varepsilon_t \varepsilon_s \varepsilon_i} \]

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Separator</th>
<th>Energy, MeV/u</th>
<th>target thickness</th>
<th>atoms/cm²</th>
<th>Intensity, pnA</th>
<th>Experiment time</th>
<th>published measured cross section [barn]</th>
<th>dose, beam particles</th>
<th>reduced* CS, barn</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSI</td>
<td>FRS</td>
<td>500-1000</td>
<td>Be:1-10g</td>
<td>8.00E+22</td>
<td>3.00E-03</td>
<td>1 week</td>
<td>1E-10 M.Bernas et al., PL B 415 (1997) 111</td>
<td>1E+13</td>
<td>1E-12</td>
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<tr>
<td>GANIL</td>
<td>LISE</td>
<td>75</td>
<td>Ta:1g</td>
<td>3.60E+21</td>
<td>10-100</td>
<td>1 week</td>
<td>2E-13 O.Tarasov et al., PL B409 (1997) 64</td>
<td>2E+17</td>
<td>1E-15</td>
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<tr>
<td>RIKEN</td>
<td>RIPS</td>
<td>90</td>
<td>Ta:0.7g</td>
<td>2.30E+21</td>
<td>10-100</td>
<td>1 week</td>
<td>2E-14 H.Sakurai et al., PL B448 (1999) 180</td>
<td>2E+17</td>
<td>3E-15</td>
</tr>
<tr>
<td>GANIL</td>
<td>LISE</td>
<td>50</td>
<td>Ta:0.3g</td>
<td>8.80E+20</td>
<td>10-100</td>
<td>1 week</td>
<td>6E-14 S.Lukyanov et al., J Phys G 28 (2002) L41</td>
<td>4E+17</td>
<td>3E-15</td>
</tr>
<tr>
<td>RIKEN</td>
<td>BigRIPS</td>
<td>340</td>
<td>Be:1g</td>
<td>6.20E+22</td>
<td>0.1-10</td>
<td>1 week</td>
<td>1E-13 T.Ohnishi et al., JPSJ 79 (2010) 073201</td>
<td>9E+14</td>
<td>2E-14</td>
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<tr>
<td>Dubna</td>
<td>GFS</td>
<td>6-10</td>
<td>Bk: 3e-4 g</td>
<td>7.30E+17</td>
<td>1000</td>
<td>half year</td>
<td>1E-13 Yu.Oganessian et al., PRL 104 (2010) 142502</td>
<td>1E+20</td>
<td>1E-14</td>
</tr>
<tr>
<td>NSCL</td>
<td>A1900</td>
<td>140</td>
<td>W:1.9g</td>
<td>6.30E+21</td>
<td>8.00E+01</td>
<td>11 days</td>
<td>9.4E-15 T.Baumann et al., Nature 449 (2007) 1022</td>
<td>5E+17</td>
<td>3.3E-15</td>
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<tr>
<td>NSCL</td>
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<td>130</td>
<td>Be:0.7g</td>
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<td>2.50E+01</td>
<td>1 week</td>
<td>8E-15 O.Tarasov et al., PRL 102 (2009) 142501</td>
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<tr>
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<td>Be:0.8g</td>
<td>5.35E+22</td>
<td>3.50E+01</td>
<td>1 week</td>
<td>3E-15 O.T. et al., PR C 87 (2013) 054612</td>
<td>1E+17</td>
<td>1.4E-16</td>
</tr>
</tbody>
</table>

**FUTURE**

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Separator</th>
<th>Energy, MeV/u</th>
<th>target thickness</th>
<th>atoms/cm²</th>
<th>Intensity, pnA</th>
<th>Experiment time</th>
<th>published measured cross section [barn]</th>
<th>dose, beam particles</th>
<th>reduced* CS, barn</th>
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</thead>
<tbody>
<tr>
<td>GSI</td>
<td>SuperFRS</td>
<td>1.50E+03</td>
<td>Be:15g</td>
<td>1.00E+24</td>
<td>1.60E+02</td>
<td>1 week</td>
<td>6E+17</td>
<td>1E+17</td>
<td>1.7E-18</td>
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<tr>
<td>FRIB</td>
<td>A2400</td>
<td>200</td>
<td>Be:1g</td>
<td>6.20E+22</td>
<td>1.00E+04</td>
<td>1 week</td>
<td>4E+19</td>
<td>4.3E-19</td>
<td></td>
</tr>
</tbody>
</table>

* reduced, \( Y = 1 \), assuming \( \varepsilon_t \varepsilon_s \varepsilon_i \) equal to 100%, 100% time just for one production run

** RIKEN : \(^{48}\text{Ca} \ 345 \text{ MeV/u} \ 150 \text{ pnA}**
## Developed Primary Beams

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy (MeV/nucleon)</th>
<th>Intensity (pA)</th>
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<tbody>
<tr>
<td>$^{16}$O</td>
<td>150</td>
<td>175</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>$^{20}$Ne</td>
<td>170</td>
<td>80</td>
</tr>
<tr>
<td>$^{22}$Ne</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>$^{22}$Ne</td>
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<td>100</td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td>170</td>
<td>60</td>
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<tr>
<td>$^{36}$Ar</td>
<td>150</td>
<td>75</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>140</td>
<td>75</td>
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<tr>
<td>$^{40}$Ca</td>
<td>140</td>
<td>50</td>
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<tr>
<td>$^{48}$Ca</td>
<td>90</td>
<td>15</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>140</td>
<td>80</td>
</tr>
<tr>
<td>$^{58}$Ni</td>
<td>160</td>
<td>20</td>
</tr>
<tr>
<td>$^{64}$Ni</td>
<td>140</td>
<td>7</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>130</td>
<td>25</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>140</td>
<td>35</td>
</tr>
<tr>
<td>$^{78}$Kr</td>
<td>150</td>
<td>25</td>
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<tr>
<td>$^{80}$Kr</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>$^{86}$Kr</td>
<td>140</td>
<td>25</td>
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<tr>
<td>$^{96}$Zr</td>
<td>120</td>
<td>1.5</td>
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<tr>
<td>$^{112}$Sn</td>
<td>120</td>
<td>4</td>
</tr>
<tr>
<td>$^{118}$Sn</td>
<td>120</td>
<td>1.5</td>
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<tr>
<td>$^{124}$Sn</td>
<td>120</td>
<td>1.5</td>
</tr>
<tr>
<td>$^{124}$Xe</td>
<td>140</td>
<td>10</td>
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<tr>
<td>$^{136}$Xe</td>
<td>120</td>
<td>2</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>85</td>
<td>1.5</td>
</tr>
<tr>
<td>$^{209}$Bi</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>45</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>80</td>
<td>0.2</td>
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</tbody>
</table>

## Beam Current (pA)

<table>
<thead>
<tr>
<th>Beam particle</th>
<th>$E/A$(MeV)</th>
<th>Maximum (instantaneous) achieved so far</th>
<th>Expected (or exp. planning in your proposal)</th>
<th>Injector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>250</td>
<td>1000</td>
<td>200</td>
<td>AVF</td>
</tr>
<tr>
<td>$d$(pol.)</td>
<td>250</td>
<td>120</td>
<td>30</td>
<td>AVF</td>
</tr>
<tr>
<td>$^4$He</td>
<td>320</td>
<td>1000</td>
<td>1000</td>
<td>AVF</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>250</td>
<td>400</td>
<td>400</td>
<td>RILAC</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>345</td>
<td>1000</td>
<td>500</td>
<td>RILAC</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>345</td>
<td>415</td>
<td>150</td>
<td>RILAC</td>
</tr>
<tr>
<td>$^{76}$Zn</td>
<td>345</td>
<td>100</td>
<td>75</td>
<td>RILAC</td>
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<tr>
<td>$^{76}$Ge</td>
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<td>not tested</td>
<td>N/A</td>
<td>RILAC</td>
</tr>
<tr>
<td>$^{78}$Kr</td>
<td>345</td>
<td>under development</td>
<td>50</td>
<td>RILAC</td>
</tr>
<tr>
<td>$^{86}$Kr</td>
<td>345</td>
<td>30</td>
<td>50</td>
<td>RILAC</td>
</tr>
<tr>
<td>$^{130}$Xe</td>
<td>345</td>
<td>not tested</td>
<td>20</td>
<td>RILAC2</td>
</tr>
<tr>
<td>$^{125}$Xe</td>
<td>345</td>
<td>27</td>
<td>20</td>
<td>RILAC2</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>345</td>
<td>15.1</td>
<td>10</td>
<td>RILAC2</td>
</tr>
</tbody>
</table>

Note: Some intensities are limited by shielding requirements.

## Stable beams


## SPIRAL beams

http://pro.ganil-spiral2.eu/users-guide/accelerators/spiral-beams/
Planning of Fast Rare Ion Beam Experiment

- Select correct configuration file
- Choose reaction for desired product
- Choose of primary beam and production target based on the reaction choice

Settings
- Set desired fragment
- Multi-step fragmentation in very thick targets?
- Set options (energy loss, charge state and so on) corresponding to these energies, reaction and so on
- Define momentum acceptance
- Set wedge slits

Define detector system in beam-line

Optimize target thickness
- Compromise between target yield and energy loss
- Use optimum target calculator

Choose wedge thickness
- Compromise between intensity and purity
- Also depends on the type of experiment
- Can use target-wedge optimizer, but slow…

Forecast of yields and purity

Define detector system in the focal plane

Test of experiment feasibility
Select correct configuration file

LPP = LCN + LOPT + Experiment settings + Calculation results + User Cross sections

Table 1. File extensions used by LISE++.

<table>
<thead>
<tr>
<th>Type of file</th>
<th>LISE++</th>
<th>Default directory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>lpp</td>
<td>/files</td>
</tr>
<tr>
<td>Configuration (set-up)</td>
<td>lcn</td>
<td>/config</td>
</tr>
<tr>
<td>Option</td>
<td>lopt</td>
<td>/options</td>
</tr>
<tr>
<td>Degrader</td>
<td>degra</td>
<td>/degrader</td>
</tr>
<tr>
<td>Calibration</td>
<td>cal</td>
<td>/calibrations</td>
</tr>
<tr>
<td>Matrix</td>
<td>mat</td>
<td>/files</td>
</tr>
<tr>
<td>Cross section</td>
<td>cs</td>
<td>/CrossSections</td>
</tr>
</tbody>
</table>

After installation of the LISE++ package

Default configuration: A1900_2013.lcn
Default option file: A1900_2013.lopt
which are set for projectile fragmentation (~80-200 MeV/u)
Question:
What reaction and beam for production of neutron rich calcium isotopes?

Answer:
Projectile fragmentation of $^{82}\text{Se}$
Ion yields after target

\[ Y = I \ t \ N_t \ \sigma \ \varepsilon_t \ \varepsilon_s \ \varepsilon_i \]

**Y**  \( Y \) number of registered events

**σ**  production cross section

**Nₜ**  \( N_t \) number of target atoms

\( N_t = d_t \ M_t / N_A \)

where

\( d_t \)  target thickness

\( N_A \)  Avogadro number

\( M_t \)  atomic mass number

**I**  \( I \) beam intensity

**t**  \( t \) duration of measurement

**εₜ**  \( \varepsilon_t \) efficiency transmission at target

**εₛ**  \( \varepsilon_s \) efficiency transmission through separator

**εᵢ**  \( \varepsilon_i \) identification efficiency

**εₜ εₛ εᵢ**

---

**Reaction**

- lost of primary beam and fragments of interest due to reaction in target and stripper
- Charge state factor after target (stripper)
- Gain due to secondary reactions

**Target**

**Beam**

**Settings, Options**

**εₜ**

**εₛ**

**εᵢ**

---

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for all icons in the toolbar and in the production panel there are corresponding commands in the menu.
Projectile fragmentation

- Heavy target: larger cross sections

- Light targets have more nuclei per electron, hence larger nuclear interaction probability at fixed electronic slowing down than heavy target

- Overall case for projectile fragmentation: \((\sigma N_t)_\text{light} > (\sigma N_t)_\text{heavy}\)

- Chemical and physical properties of material as melting point, thermal conductivity etc,
  
  so lifetime of Be target >> lifetime of equivalent Ta target

- Charge state distribution after target:
  
  light targets provide higher average \(q\) of ions
  * using strippers after heavy targets

- Dissipation process larger with heavy targets
  
  so \(^{40}\text{Mg}\) and \(^{44}\text{Si}\) been have observed in \(^{48}\text{Ca+W}\)

This favors light targets (NSCL uses Be)
Use “Charge state” for
• Low energy
• Heavy fragments

For example in the reaction $^{82}\text{Se}(140\text{MeV/u}) + \text{Be}$ no charge states expected.

It is recommended to turn off charge states to provide fast calculation.

Alternative:
LISE++ can find the optimum charge state combination
Charge state fraction

Should pay attention for charge state distribution after target and each time passing material.

**Then more materials**
(at low energies or with heavy elements experiment),
then less setting ion transmission

**Depends on:**

- Primary beam atomic number
- Primary beam energy
- Target atomic number
- Initial ionic charge before passing material (for non-equilibrium process)

**Complicates particle identification of radioactive beam**

- Isotopes of different masses and charges become mixed up during Bp selection
Setting the Charge state option

New Alternative way

Bp distribution of $^{238}\text{U}(80\text{MeV/u})$ after Au(10 mg/cm$^2$)
• The model used in Global allows to calculate non-equilibrium charge states distributions

• The programs Global and Charge [13] have been incorporated into the LISE++ package

• These programs developed in GSI are intended to calculate atomic charge-changing cross-sections, charge state evolution

<table>
<thead>
<tr>
<th>Model</th>
<th>Ref.</th>
<th>Region (AMeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>J. Winger</td>
<td>[10] &gt;15</td>
</tr>
<tr>
<td>3</td>
<td>K. Shima</td>
<td>[12] &lt;5</td>
</tr>
<tr>
<td>5</td>
<td>G. Schiwietz</td>
<td>[14] &lt;15</td>
</tr>
</tbody>
</table>

Plot of Charge state distributions

$^{238}\text{U}$ equilibrium charge distribution after Target (Be)

$^{238}\text{U}$ (60.0 MeV/u) + Be (443.61 mg/cm$^2$)

Calculations for $^{238}\text{U}$; Material Be

Charge Distribution Method is 1; Coefficient Width=1.00

Menu
“1D-plot” ⇒
“Charge distributions”
Non-equilibrium charge state calculations

Charge state evolution* of the fragment $^{118}$Sn after a C-stripper as a function of its thickness for equilibrium and non-equilibrium cases in the reaction $^{124}$Xe (90 MeV/u)+Pb(20 mg/cm²)+C(x mg/cm²).

* C.Scheidenberger et al, NIM B142 (1998) 441-462; web-docs.gsi.de/~weick/charge_states/

The following energy loss calculation methods are available in LISE++:

1. He-parameterization [1]; the starting point at 2.5 AMeV is given by range tables [2]
4. ATIMA 1.2: without LS-corrections

References:
Secondary (multi-step) reactions in target

Applied for thick targets

- In this process, the projectile undergoes a series of successive reactions until the fragment of interest is produced.

- For the second and next reactions \( \text{LISE}^{++} \) always assumes a projectile fragmentation and uses the EPAX parameterizations to speed up calculations.

Parent nuclei: multistep production probability

\[ ^{82}\text{Se} (140.0 \text{ MeV/u}) + \text{Be} (443.61 \text{ mg/cm}^2) \rightarrow ^{64}\text{Ti} \]
Sketch of main production mechanisms for RIB

Yield in target can be simulated in inverse kinematics

Yield in target can be simulated in inverse kinematics

\[ E_R = \frac{m_p}{m_p + m_t} E_P \]

few (≤ 20)
## Reactions and production models implemented in LISE++

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Production cross-section model</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile fragmentation</td>
<td>EPAX 2.15, 3.1</td>
<td>[17]</td>
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<tr>
<td></td>
<td>LISE++ abrasion–ablation</td>
<td>[27]</td>
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<tr>
<td>Fusion-residues</td>
<td>LisFus model</td>
<td>[27]</td>
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<td></td>
<td>PACE4 (manually)</td>
<td>[28]</td>
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<td>Fusion–fission</td>
<td>LISE++ package</td>
<td>[29]</td>
</tr>
<tr>
<td>Coulomb fission</td>
<td>LISE++ package</td>
<td>[30]</td>
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<td>Abrasion–fission</td>
<td>LISE++ 3EER model</td>
<td>[31]</td>
</tr>
<tr>
<td>Two body kinematics</td>
<td>EPAX 2.15 (temporary)</td>
<td></td>
</tr>
</tbody>
</table>

## References:

Reaction mechanism: Evaporation Cascade

- The evaporation cascade is used in Abrasion-Ablation (Projectile Fragmentation), All fission reactions, Fusion-Residue

- It is treated in a macroscopic way on the basis of a master equation which leads to a diffusion equations
  

- The LISE++ evaporation model works with probability distributions as a function of excitation energy, taking into account possible parent and daughter channels (n, 2n, p, 2p, d, t, 3He,a), as well as fission and breakup de-excitation channels

- The influence of dissipation on the fission process is taken into account
  

- The analytical solution of the evaporation cascade is performed using the transport integral
  
  D. Bazin, B. Sherrill, Phys. Rev. E 50 (1994) 4017

- The main advantage is speed. Only such a type of fast calculations is suitable for calculating the production of nuclei with very low cross-sections

- Disadvantages are …

- Monte Carlo version will be done soon
Evaporation Example: $^{216}\text{Fr}$, $E^*=50\text{ MeV}$, $\sigma=1\text{ barn}$

Couple seconds and... Fission $= 18.6\text{ mb}$, Residues $981\text{ mb}$

Final Evaporation Residue cross-sections (LisFus)

Evaporation calculator will be discussed on Friday
Example: $^{216}$Fr, $E^*=50$ MeV, $\sigma=1$ barn $\Rightarrow ^{206}$Bi

$^{206}$Bi excitation distributions

EVAPORATION - Compound nucleus $^{216}$Fr

Excit. Energy: 50.0-51.0 MeV; Fus. CS: 1000.0 mb; Fus. Barrier: 10.82 fm; $h_\omega$ omega = 5.0 MeV

NP=64; SE: "DB0+Cal1" Density: "auto" GeomCor: "On" Tung: "auto" $^{206}$Bar=41 $^{206}$Bar=2=1.00 Modes=1010 1011 110

Input parent distr.

Output daughter distr.

Channels in exc.nucleus

Emitted particle energies
Fission barriers are necessary to calculate fission de-excitation channels and estimate
- total cross-sections of fission reactions
- evaporation residue cross-sections
- decay widths in the post-scission nucleon emission process

\[ B_{f}^{\text{final}} = B_{f}^{\text{init}} \cdot b + \epsilon_{\text{shell}} + \epsilon_{\text{odd-even}} \]

default value of \( b = 1 \)
In SHE region first three models significantly underpredict.
For estimation it is possible to take experimental data (if they exist) or calculations from Prof. V. I. Zagrebaev in order to normalize Fusion-Residue cross sections playing with the Barfac value.

### Abrasion reactions: LISE++ de-excitation channels

<table>
<thead>
<tr>
<th>De-excitation channel</th>
<th>Collisions</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasion – Evaporation</td>
<td>peripheral</td>
<td>Projectile fragmentation</td>
</tr>
<tr>
<td>Abrasion – Ablation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abrasion – Fission</td>
<td>peripheral</td>
<td>In-flight fission</td>
</tr>
<tr>
<td>Abrasion – Breakup</td>
<td>central</td>
<td>Multi-fragmentation</td>
</tr>
</tbody>
</table>

**Diagram: Abrasion reactions**

- **Abrasion – Evaporation**
- **Abrasion – Fission**
- **Abrasion – Breakup**

**Graph:**

- Final Abrasion-Evaporation Residues
- Break-up deexcitation channel
- Fission deexcitation channel

**Nuclear charge yields for different de-excitation channels after $^{238}$U(1AGeV) abrasion on a Be-target.**

---

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Cross sections for projectile fragmentation

- EPAX parametrizations [1] based on fragmentation data
- LISE++ Abrasion-Ablation model (analytical) [2]
- Possibility to input cross sections manually via file

ABRABLA : Abrasion-Ablation Monte Carlo [3]

COFRA : a simplified, analytical version of ABRABLA, which only considers neutron evaporation from the pre-fragments formed in the abrasion stage [4].

Intra-nuclear Cascade Models, e.g. ISABEL [5]

References:

## Projectile Fragmentation Cross Section Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Plus</th>
<th>Minus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EPAX</strong> 1-step calculation</td>
<td>fast</td>
<td>no primary beam energy dependence</td>
</tr>
<tr>
<td></td>
<td>wide distributed</td>
<td>does not take nuclide masses: predicts yield for unbound isotopes, no shell and even-even effects</td>
</tr>
<tr>
<td></td>
<td>reference line</td>
<td></td>
</tr>
<tr>
<td></td>
<td>no parameters to modify</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EPAX modifications are very rare</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LISE</strong> Ablation</td>
<td>Takes nuclide masses for evaporation cascade</td>
<td>no beam energy dependence (yet)</td>
</tr>
<tr>
<td>(analytical)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Using experimental results, it can be applied to deduce excitation energy parameters in order to predict an yield of more exotic nucleus</td>
<td>difficult choice of excitation energy initial parameters</td>
</tr>
<tr>
<td></td>
<td>User-friendly results analysis and visualization</td>
<td>large set of parameters to play</td>
</tr>
<tr>
<td><strong>HIPSE</strong> D.Lacroix et al., PRC69, 054604 (2004)</td>
<td>More physics involved</td>
<td>developed for multifragmentation and multi-nucleon transfers: significant overprediction for stripping of several nucleons</td>
</tr>
<tr>
<td></td>
<td>Building partition Reaggregation phase evaporation stage</td>
<td>slow, difficulties to predict exotic yield (Monte Carlo)</td>
</tr>
<tr>
<td></td>
<td>Excitation energy of prefragment and fragment kinetic energy can be extracted</td>
<td>Fixed parameters just for 25,50,80 MeV/u</td>
</tr>
</tbody>
</table>

AMD, Isabel and so on..

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$^{82}\text{Se} (139 \text{ MeV/u}) + \text{Be, W} : \text{exp. cross sections vs. EPAX3}$
$^{82}\text{Se (139 MeV/u)} + \text{Be, W : exp. cross sections vs. AA}$
More probable prefragments are Ti-isotopes ($dZ=2$)
$^{48}\text{Ca}(140\text{MeV/u}) + \text{W,Be}$

A simple systematic framework was found to describe the production cross sections based on thermal evaporation from excited prefragments that allows extrapolation to other weak reaction products.


Figure. The variation of the cross sections for the production of neutron rich nuclei as a function of the two-body $Q$ values [$Q_{gg}$, left panels (a), (b)] and as a function of the one-body $Q$ value [$Q_g$, right panels (c), (d)]. Upper panels (a), (c) show data for W (Ta), lower panels (b), (d) for Be targets.

$$Q_g = ME(Z = 20, A = 48) - ME(Z, A)$$
Production cross sections from $^{82}\text{Se}$ fragmentation as indications of shell effects in neutron-rich isotopes close to the drip-line
Production cross sections as indications of shell effects in neutron-rich isotopes close to the drip-line

Figure. Two-neutron separation energy (\(S_{2n}\)) versus neutron number (\(N\)), and connected by lines of constant \(N-Z\). Values are calculated using results from the GXPF1B5\(^*\) model.

- Models [1-3]: Gaussian distributions
- Model [4]: Convolution
- Proton rich side: low-exponential energy tails create difficulties with purity of RIBs
82\text{Se} (139 \text{ MeV/u}) + \text{Be} : \text{Momentum Distributions}

O.T. et al., will be submitted to NIMA
The fission fragment production model is at the basis of all fission reactions implemented in LISE++. The fissile nucleus (A,Z), fission channel cross section ($\sigma_{fis}$), and excitation energy ($E^*$) are the input parameters. The kinetic energy of the fissile nucleus is used for kinematics calculations in order to estimate the transmission through the separator.

1-st step: Calculation of an initial fission cross-section matrix of excited fragments using the semi-empirical model of Benlliure. This model has some similarities with previously published approaches with the added advantage of describing fission properties of a large number of fissile nuclei over a wide range of excitation energies.

2-nd step: Post-scission nucleon emission. The code calculates the number of post-scission nucleons with LISE evaporation cascade, which enables the user to make rapid and qualitative calculations.

Less than 5 seconds for low-energy fission!

References
1. The program assumes that the reaction takes place in middle of the target. Therefore the first step is the calculation of the primary beam energy in the middle of the target.

2. Total fission cross-section and average excitation energy:
   a. Calculation of differential electromagnetic cross-section.
   b. Deexcitation fission function $d\sigma^f/d(E^*)$.
   c. Calculation of statistical parameters of the deexcitation fission function: mean value $<E^*>$, and area $\sigma^f$.

3. Calculation of an initial fission cross-section matrix

4. Post-scission nucleon emission
Electromagnetic excitation

A well-known review of the processes generated by the electromagnetic interaction in relativistic nuclear, and atomic collisions, by C. Bertulani and G. Baur [Physics Report 163 (1988) 299-408] has been used to obtain the excitation energy function for fission.

The differential cross-section for electromagnetic excitation is given by:

\[
\frac{d\sigma_{em}}{dE_\gamma} = \frac{n_{E1}}{E_\gamma} \cdot \sigma_{E1} + \frac{n_{E2}}{E_\gamma} \cdot \left(\sigma_{E2,1} + \sigma_{E2,2}\right)
\]

with \(n_{E1}\), \(n_{E2}\) being the number of equivalent photons for electric dipole and quadrupole excitations respectively. \(\sigma_{E1}, \sigma_{E2}\) are the photon absorption cross-sections for giant E1 and E2 excitations, where for E2 excitations \(i=1\) denotes isoscalar and \(i=2\) denotes isovector giant quadrupole resonances. Multiple excitations of the quadrupole resonances are neglected.

Differential cross-sections of GDR (red solid curve), GQR(IS) (blue dashed curve), and GQR(IV) (black dot curve) excitations in \(^{238}\text{U}\) as calculated from the equivalent photon spectrum representing a \(^{208}\text{Pb}\) projectile nucleus at 600 MeV/u.
Deexcitation channels for $^{238}$U nuclei at 600 MeV/u excited by a lead target. The solid red curve represents fission decay. The blue dashed line represents 1n-decay channel, black dotted and green dot-dashed curves respectively 2n- and 3n-decay channels.
Comparison of different calculation methods

**LISE++ Distribution Method**

**LISE++ MC method**

**MOCADI**

\[ ^{238}\text{U}(920\text{AMeV})+\text{Pb}(5\text{g/cm}^2)\rightarrow ^{100}\text{Zr} \]
2D-plots $A_x$ (horizontal component of the angle in the laboratory frame) versus Energy per nucleon of $^{132}\text{Sn}$ final fragment after $^{238}\text{U}(600\text{MeV/u}, \text{Ex}=50\text{MeV})$ fission. Angular acceptances $H=60\text{mrad}$ and $V=20\text{mrad}$. The left plot has been produced with very thin target, the right picture represents the case of thick target (Pb 4mm).
- **ABRABLA**: Abrasion-Ablation Monte Carlo
  

- **PROFI**: semi-empirical fission Monte-Carlo code
  

- **LISE++ 3EER Abrasion-Fission model (analytical)**
  
  O.T., Tech. Rep. MSUCL1300, NSCL, Michigan State University, 2005
  [http://lise.nscl.msu.edu/7_5/lise++_7_5.pdf](http://lise.nscl.msu.edu/7_5/lise++_7_5.pdf)
Summary of High Energy Production Mechanisms

A. Kelić, S. Lukić, M. V. Ricciardi, K.-H. Schmidt

http/www.gsi.de/charms

Experiment (FRS)  ABRABLA07

E = 1 GeV

238U + 1H
208Pb + 1H
136Xe + 1H
56Fe + 1H

25 mb
5 mb
1 mb
200 µb
40 µb
8 µb
Contribution of different reaction mechanisms:
$^{208}\text{Pb} \ (86 \text{ MeV/u}) + \text{Be} \ \text{data vs. LISE++}$

Good qualitative agreement between experimental data & LISE++ AA & AF

How do we calculate?

Experiment #05120 @ NSCL

Preprint MSUCL1409, NSCL/MSU 2009
Abrasion-Fission: ocean of fissile nuclei

\[
\text{Stopping processes: } Z_{\text{U}} \rightarrow Z_{\text{Z}} \rightarrow Z_{\text{A}} \rightarrow Z_{\text{A'}}
\]

\[A_{3} + A_{4} < 238\]

Fission channel cross-sections

\[\text{ABRASION-ABLATION - } ^{238}\text{U} + H\]
Abrasion-Fission: ocean of **hot** fissile nuclei

\[
^{238}\text{U} + \text{Pb} 
\xrightarrow{\text{\textbullet}} 
^{A_2}_{Z_2}\text{^*} 
\xrightarrow{\text{\textbullet}} 
^{A_3}_{Z_3}\text{^*} 
\xrightarrow{\text{\textbullet}} 
^{A_4}_{Z_4}\text{^*} 
\xrightarrow{\text{\textbullet}} 
^{A_4'}_{Z_4'} \text{^*} 
\xrightarrow{\text{\textbullet}} 
^{A_3'}_{Z_3'} \text{^*} 
\xrightarrow{\text{\textbullet}} 
^{A_3'}_{Z_3'} + ^{A_4'}_{Z_4'} < 238
\]

Abrasifission

**Average fission excitation energy**

\[\text{ABRASION-ABLATION} - ^{238}\text{U} + H\]
Abrasion-Fission : 3 EER model

Fission channel cross-sections

ABRASION-ABLATION - $^{238}$U + Pb
Excit. Energy Method: $< 2 >$; $< E^* >$: 13.3 MeV

- 238U, 1337 mb
- 231Th, 474 mb
- 216Po, 817 mb

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Three-excitation-energy-region model

LISE++ package:

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Fission excitation functions

\[ ^{238}\text{U}(1000.0\text{MeV/u}) + \text{Pb} \]

**LISE++ hint for the fissile nucleus from excitation energy**

<table>
<thead>
<tr>
<th></th>
<th>LOW</th>
<th>MIDDLE</th>
<th>HIGH</th>
<th>EM fission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope</td>
<td>236U</td>
<td>231Th</td>
<td>217At</td>
<td>238U</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>28.8</td>
<td>92.6</td>
<td>263.9</td>
<td>15.9</td>
</tr>
<tr>
<td>Cross section (mb)</td>
<td>509.5</td>
<td>510</td>
<td>679.4</td>
<td>1942.4</td>
</tr>
</tbody>
</table>

**Excitation energy (MeV)**

0 100 200 300 400 500

**Different cross-section (mb/MeV)**

1e+0 2 3 4 5 6

1e-1 1e+0 2 3 4 5 6

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Three-excitation-energy-region model

Partial and total mass distributions of Strontium fission fragments in the reaction $^{238}$U(80MeV/u)+Be.

Cross-section $mb$

$^{238}$U(80MeV/u)+Be $\rightarrow$ AF $\rightarrow$ Z=38

 boundaries 60 & 250
$^{238}\text{U}(1\text{AGeV}) + \text{Pb}$

Cross section [mb]

Proton number

$^{238}\text{U}(1\text{AGeV}) + \text{Pb} \rightarrow \text{fission}$

NIZ

$^{230}\text{U}(1\text{AGeV}) + \text{Pb} \rightarrow \text{fission}$

$^{238}\text{U}(1\text{AGeV}) + \text{Pb} \rightarrow \text{fission} \rightarrow Z=35$

$^{238}\text{U}(1\text{AGeV}) + \text{Pb} \rightarrow \text{fission} \rightarrow Z=50$

Mass number

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Experiment [Enq99] LISE AF

Experiment [Enq99] LISE AF
In-flight fission of $^{238}\text{U}$ with Be and Pb targets

**Abrasion fission**

$^{238}\text{U} + \text{Be (7mm)}$ at 345 MeV/u

- \( B_\rho = 7.249 \text{Tm} \)
- \( \Delta P/P = \pm 1\% \)

**Coulomb fission**

$^{238}\text{U} + \text{Pb (1.5 mm)}$ at 345 MeV/u

- \( B_\rho = 6.992 \text{Tm} \)
- \( \Delta P/P = \pm 0.1\% \)

Courtesy of T. Kubo (BigRIPS, RIKEN)
Production rates by $^{238}$U + Be(7mm) at $B\rho = 7.249$ Tm

1 setting, no energy degraders used

**LISE++ Abrasion-Fission**  Fairly good reproduction

$B\rho = 7.2$ Tm ± 1%

By LISE++

Even Z

- $Z = 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50$
- $^{70}$Ni
- $^{76}$Ni

Odd Z

- $Z = 21, 23, 25, 27, 29, 31, 33, 35, 37, 39, 41, 43, 45, 47, 49$

Production yield (pps/pnA)

Mass number

FWHM = 21%

+16%

+9.8%

+4.0%

Courtesy of T.Kubo (BigRIPS, RIKEN)
Q_g - systematics for Abrasion-Fission products ($^{238}$U+Be)

**Excitation energy of one fission fragment (LISE++ for all EERs)**

--- just ONE fragment --- $^{238}$U (750.0 MeV/u) + Be (1.01 g/cm$^2$) -> sum Z = 1-200

"Average weighted" mode; TXEmethod: 1 (f=0.0045); Shells: N1={83,-2.65,0.70}, N2={90,-3.80,0.15}

Fission => Odd-Even corrections: Yes; Post-scission evaporation: Yes

Just to show, how high is excitation energy for a fission fragment with Z>60

Remind: $Q_g$ is a simple systematic framework was found to describe the production cross sections based on thermal evaporation from excited prefragments.
Q_g - systematics for in-flight fission products

M. Bernas et al., NPA A765 (2006) 197

238U + p at 1A GeV


238U + Be at 1A GeV

J. Kurcewicz et al., Published in PLB
Fusion-Fission is a new reaction mechanism to produce exotic radioactive beams

O.T. and A. C. C. Villari, NIM B 266 (2008) 4670

2010: E547 @ LISE3.GANIL

Figure. Charge Schematic layout of the experimental setup shows the equipment that has been used for the production, separation and detection of fragments produced in reactions with the $^{238}$U beam.
Fusion-Fission: experiment E547

- Handle with charge states
- Identify fragments $(A,Z,q)$

Non-equilibrium

Non-equilibrium

equilibrium

O. Dealune’s thesis
O. Delaune, F. Farget, O. T. et al, will be submitted to PRC
Pay attention for the Fission Barrier model!

- Fusion – Evaporation code PACE 4 in the LISE++ package
- Partner site: NRV
Two-body reactions

Differential Cross Section

http://lise.nscl.msu.edu/9_6/DifCS/9_6_44_DifCS.pdf
Fig. 6. Energy spectra calculated by the “Distribution” method of $^{38}$Ar fragments produced by different reaction mechanisms, using an $^{40}$Ar beam at 20 MeV/u on a $^{4}$He target (1 mg/cm$^2$) and gated by a rectangular angular acceptance $X' = \pm 100$ mrad, $Y' = \pm 60$ mrad. The Monte-Carlo calculation of the energy spectrum of $^{38}$Ar fragment produced in two body reaction is also shown. The default LISE++ production cross-sections EPAX 2.15 and LisFus model were used to estimate the rates.
• LISE++ Simulation for $^{124}$Xe and $^{208}$Pb fragmentation

Relatively ‘easy’ to collect due to small phase space

$^{100}$Sn

$^{200}$W

- Angles $\leq \pm 20$ mrad
- Momentum $\pm 3 - 8%$

M. Hausmann, T. Nettleton

Courtesy of B. Sherrill
In-Flight Fission at 400 MeV/u

- LISE++ Fission model for $^{238}$U

$^{132}$Sn

$^{76}$Ni

- Angles ± 40 - 60 mrad
- Rigidity ± 6 - 10 %
- Plus correlations due to fission kinematics

M. Hausmann, T. Nettleton

Courtesy of B. Sherrill
Efficiency transmission at target

- Lost of primary beam and fragments of interest due to reaction in target and stripper
- Charge state factor after target (stripper)
- Gain due to secondary reactions

Let's consider the following case:

${}^{136}\text{Xe} \ (345 \text{ MeV/u}) + \text{Be} \ (2\text{g/cm}^2) \rightarrow {}^{125}\text{Ag}^{47+}$

Clicking the right button of mouse on the $^{125}\text{Ag}$ cell in the table of nuclides

<table>
<thead>
<tr>
<th>$^{125}\text{Ag}$</th>
<th>Beta- decay (Z=47, N=78)</th>
<th>Silver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1 (Dipole 1)</td>
<td>47</td>
<td>45</td>
</tr>
<tr>
<td>Q2 (Dipole 2)</td>
<td>47</td>
<td>45</td>
</tr>
<tr>
<td>Q3 (Wien)</td>
<td>47</td>
<td>45</td>
</tr>
<tr>
<td>Q4 (D6)</td>
<td>47</td>
<td>45</td>
</tr>
</tbody>
</table>

- Production Rate (pps) 7.73e+0 6.71e-1 1.4e-2
- Sum of charge states (pps) 8.41e+0 8.41e+0 8.41e+0
- Reaction
  - Fragmentation
  - Fragmentation
  - Fragmentation
- Sum of all reactions (pps) 8.41e+0 8.41e+0 8.41e+0
- CS in the target (mb) 1.35e-5 1.35e-5 1.35e-5
- Total transmission (%) 68.521 5.954 0.124

Target (%): 68.52 5.95 0.124
Unreacted in mater. (%) 71.17 71.17 71.17
Q (Charge) ratio (%) 91.85 7.98 0.166
Unstopped in mater. (%) 100 100 100
Secondary Reactions (coef) 1.05 1.05 1.05

Total transmission includes blocks from Target up to Faraday Cup 1
End of Lecture 2

Questions?
Haben Sie Fragen?
Вопросы?
有問題嗎？
¿Preguntas?
Demando?
質問？
Pytania?
Domande?
Sorular?