Predictions of Isotope Production Yields

by Oleg B. Tarasov (NSCL/MSU)

- Introduction to LISE++ code
- FRIB rates
- “Direct” production: $^{44}$Ti example
- Commensal operation: Helium-Jet Ion-Guide System

LISE++: Exotic Beam Production with Fragment Separators
The LISE++ program is designed

- to predict intensities and purities for the planning of future experiments with in-flight separators
- is also essential for radioactive beam tuning where its results can be quickly compared to on-line data.

**In-Flight isotope production: Basic principle of operation**

1. Production
2. Separation
3. Registration, Identification
### Table

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<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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<td>LISE++ package</td>
<td>[29]</td>
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<td>LISE++ 3EER model</td>
<td>[30]</td>
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<td>EPAX 2.15 (temporary)</td>
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### References:

**Electromagnetic separation devices in LISE++**

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<th>Selection by</th>
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<tr>
<td>Magnetic dipole</td>
<td>Magnetic (B[T])</td>
<td>$\vec{F}_B = q\vec{v} \times \vec{B}$</td>
<td>Magnetic rigidity $B\rho = \frac{mv}{q} [\text{T-m}]$</td>
</tr>
<tr>
<td>Gas-filled separator</td>
<td>Magnetic (B[T])</td>
<td>$\vec{F}_B$</td>
<td>Magnetic rigidity</td>
</tr>
<tr>
<td>Solenoid</td>
<td>Magnetic (B[T])</td>
<td>$\vec{F}_B$</td>
<td>Focusing (combination $A, q, v$)</td>
</tr>
<tr>
<td>Electrostatic dipole</td>
<td>Electric (E [kV/m])</td>
<td>$\vec{F}_E = q\vec{E}$</td>
<td>Electric rigidity $E\rho = \frac{mv^2}{q} [\text{J/C}]$</td>
</tr>
<tr>
<td>RF kicker</td>
<td>Electric (E [kV/m])</td>
<td>$\vec{F}_E$</td>
<td>Time</td>
</tr>
<tr>
<td>RF buncher</td>
<td>Electric (E [kV/m])</td>
<td>$\vec{F}_E$</td>
<td>Bunching</td>
</tr>
<tr>
<td>Wien-filter E-cross-B filter</td>
<td>Magnetic (B[T])</td>
<td>$\vec{F} = \vec{F}_B + \vec{F}_E$</td>
<td>Velocity</td>
</tr>
</tbody>
</table>

- “Wedge” selection
- Decay time selection
Fragment Separator Construction

- with different sections called "blocks" (magnetic and electric multipoles, solenoid, velocity filter, RF deflector and buncher, material in beam, drift, rotation element, and others).

- a user-friendly interface that helps to seamlessly construct a fragment separator from the different blocks.

Fig. 1. Updated view of the “Spectrometer Design” dialog window.

Configuration: A1900_S800BL (2nd order) 164 blocks
Application

Includes **extended** configurations of separators at NSCL/MSU, RIKEN, GANIL, GSI, FLNR/JINR, TAMU, TRIUMF, ANL and others.

- SECAR, MSU
- DRAGON, Canada
- PRISMA, Italy
- SHEL, Russia
- S$^3$, France
- BigRIPS+ZeroDegree, Japan
- MARS, TAMU
- SuperFRS_HEB, Germany
LISE++ package

- The code is distributed free with the LISE++ user license
- Official site: lise.nscl.msu.edu
- Current version 9.10.343, 15-Aug-2016

Version 10 will be released soon
- Current operating system: MS Windows
- Currently porting to new framework: cross platform & parallel computing

**Built-in powerful tools:**

- Monte Carlo simulation of fragment transmission,
- Monte Carlo simulation of fission fragment kinematics,
- Ion Optics calculation and Optimization (new),
- LISE for Excel (MS Windows, Mac OS - download)

**LISE++ calculators:**

- «Physical Calculator»,
- «Relativistic Kinematics Calculator»,
- «Evaporation Calculator»,
- «Radiation Residue Calculator» (new),
- «Ion Mass calculator" (new),
- «Matrix calculator"

**Implemented codes:**

- «PACE4» (fusion-evaporation code),
- «MOTER» (raytracing-type program for magnetic optics),
- «ETACHA4» (charge-state distribution code) (new),
- «Global» (charge-state distribution code),
- «Charge» (charge-state distribution code),
- «Spectroscopic Calculator" (of J.Kantele)

**LISE++ Utilities:**

- Stripper Foll Lifetime Utility,
- Brho Analyzer,
- Twinsol (solenoid) utility,
- Units Converter,
- ISOL Catcher,
- Decay Analysis (includes Proton, Alpha, Cluster, Sp.Fission half-lives calculation),
- Reaction Utilities (Characteristics, Converters, Plots),
- «BI» the automatized search of two-dimensional peaks in spectra

**Databases:**

- Nuclide and Isomeric State databases with utilities,
- Large Set of Calculated Mass Tables (includes FRIB mass tables),
- Ionization Energy database (used with the Ion Mass calculator),
- Decay Branching Ratio database (used with the Radiation Residue calculator),

permit to work well below this energy limit, and this makes the program very attractive for all users dealing with physics of heavy ions from 10 keV up to some GeV per nucleon.
New utility from 08/01/16
“Radiation Residue Calculator”
is important tool regarding to isotope harvesting

http://lise.nscl.msu.edu/9_10/RadiationResidue.pdf
FRIB: Beams and Rates

**Site:** [https://groups.nscl.msu.edu/frib/rates/fribrates.html](https://groups.nscl.msu.edu/frib/rates/fribrates.html)

<table>
<thead>
<tr>
<th>Enter values for A and Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
</tr>
<tr>
<td>Z</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>T$_{1/2}$</td>
</tr>
</tbody>
</table>

**Beam**

<table>
<thead>
<tr>
<th>AZ</th>
<th>68Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>275.3 MeV/u</td>
</tr>
</tbody>
</table>

**Fragment**

<table>
<thead>
<tr>
<th>Energy</th>
<th>223.9 MeV/u</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_p (Q=Z)$</td>
<td>4.560 Tm</td>
</tr>
<tr>
<td>Fast beam rate</td>
<td>1.46e+10 pps</td>
</tr>
</tbody>
</table>

| Stopped beam rate | 1.17e+8 pps |
| Reaccelerated beam rate | 3.28e+7 pps |

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A). The LISE**++ code** (v.9.2.68) has been used for transmission calculations.
B). The rates are estimated based on the EPAX 2.15[1] cross section parameterization for fragmentation and the LISE++ 3EER model[2,3] for in-flight fission.
C). Reaccelerated and stopped beam rates above 1E+9 are very uncertain. The use of solid catchers may yield higher rates in some cases.
D). Estimated rates may change as the various assumptions are tested and refined.


For further information regarding these calculations, please refer to the [readme file](https://groups.nscl.msu.edu/frib/rates/fribrates.html) (PDF - 420 kB).

Applet created by Dennis Wey.

Please contact Oleg Tarasov with any questions or comments concerning to yields or this site.
FRIB: Beams and Rates

LISE++

FRIB rates (v.1.07)
The rates are estimated based on the EPAX 3.1 cross section parameterization for fragmentation and the LISE++ 3EER model for in-flight fission. Primary beam intensities and energies based on 400 kW and 200 MeV/u for FRIB.

FRIB beams

OT@IHW.msu.edu  08/18/16
“Direct” production: $^{44}$Ti example

Table 1. Priority isotopes for harvesting at FRIB. These isotopes were identified at a Working Group meeting in Santa Fe, NM September 30 – October 1, 2010.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{32}$Si</td>
<td>160 y</td>
<td>Tracer; geology and botany</td>
</tr>
<tr>
<td>$^{44}$Ti</td>
<td>60 y</td>
<td>Medicine, astrophysics, nuclear structure</td>
</tr>
<tr>
<td>$^{48}$V</td>
<td>16 d</td>
<td>Stockpile Stewardship</td>
</tr>
<tr>
<td>$^{67}$Cu</td>
<td>2.6 d</td>
<td>Medicine</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>10.0 d</td>
<td>Astrophysics, stockpile stewardship</td>
</tr>
<tr>
<td>Eu*</td>
<td></td>
<td>Stockpile Stewardship</td>
</tr>
<tr>
<td>$^{211}$Rn</td>
<td>14.6 h</td>
<td>Medicine</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>14.9d</td>
<td>Medicine, Electric Dipole Moment</td>
</tr>
<tr>
<td>$^{225}$Ac</td>
<td>10.0 d</td>
<td>Medicine</td>
</tr>
</tbody>
</table>

settings

Use the wedge for purity

http://lise.nscl.msu.edu/9_10/radiation/RadiationResidue_44Ti.pdf
$^{44}\text{Ti}$’s case: Residues

Isotopes selected by the Fragment-Separator are implanted in FP_SCI detector

http://lise.nscl.msu.edu/9_10/radiation/44Ti%20from%2058Ni.lpp

10 hours of irradiation, 10 hours of decay: $^{44}\text{Ti}$’s number of atoms is highest!

Radioactive decay residues

Implantation detector: "FP_SCI" (36 different isotopes)
Irradiation Time (IT) = 3.60e+04 sec; Decay Time (DT) = 3.60e+04 sec; Plot only Radioactive
N_Implant=1000, N_Resid=1000, Abs.Error=1.0e-09, Rel.Error=1.0e-03, Threshold=1.0e-08, Model="Ol"
Evolution of Radiation Residue Yield

Implantation detector: "FP_SCI" (36 different isotopes)

Irradiation Time (IT) = 3.60e+04 sec; Decay Time (DT) = 3.60e+04 sec; Plot only Radioactive

N_Implant=1000, N_Resid=1000, Abs_Error=1.0e-09, Rel_Error=1.0e-03, Threshold=1.0e-08, Model=

Number of atoms

Time [sec]

Activity [disintegration per sec]

Time [sec]
Commensal operation:

- Rare isotopes produced off-axis of the fragment separator are caught in a high-pressure cell filled with a helium-aerosol mixture.
- Harvested isotopes are transported to the helium-jet ion source.
- Rare isotopes are accelerated, purified and delivered to experimental stations.
Assume the production $^{58}\text{Ca}$ from using the $^{82}\text{Se}$ beam with the A1900 fragment separator, and the He-jet block located at 40-160 mm (I2 position)

http://lise.nscl.msu.edu/9_10/radiation/82Se_58Ca.lpp
“He-jet” case calculation

Steps to create the “He-jet” configuration from previous case:

1. Set Width of I2 slits equal to the He-jet block width (+/- 60 mm)
2. Behind the I2 slits insert a thick material enough to stop all products
3. After this material set the Faraday cup
4. Insert the shift block dX=100 mm in front of the I2 slits, assuming the central axis is passing through the center of He-jet block

http://lise.nscl.msu.edu/9_10/radiation/82Se_58Ca_He-jet.lpp
"He-jet" case calculation

82Se_58Ca.lpp

Protons (Z)

Rate 0.02 pps

82Se_58Ca_He-jet.lpp

Protons (Z)

Rate 1.6e5 pps
“He-jet” case calculation

1. Calculate all products with new 82Se_58Ca_He-jet.lpp file
2. Call the Radiation Residue Calculator
3. Set the Irradiation and Detector (Transportation) times (for example* 1 & 10 hours)
4. Chose “He-jet block” as detector
5. Click the “Calculation” button

Maximum number of iterations (50000) has been reached for N_implantation=100 for two last implantation steps

* It is a JUST EXAMPLE!
“He-jet” case calculation: Activity

Activity

Implantation detector: "He-jet block" (161 different isotopes)
Irradiation Time (IT) = 3.60e+03 sec; Decay Time (DT) = 3.60e+04 sec; Plot All isotopes
N_Implant=500, N_Resid=500, Abs.Error=1.0e-11, Rel.Error=1.0e-03, Threshold=1.0e-10, Model="ODE"

Activity

Implantation detector: "He-jet block" (161 different isotopes)
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N_Implant=500, N_Resid=500, Abs.Error=1.0e-11, Rel.Error=1.0e-03, Threshold=1.0e-10, Model="ODE"
"He-jet" case calculation: Final residue products

Only radioactive residues

Radioactive decay residues

Implantation detector: "He-jet block" (161 different isotopes)
Irradiation Time (IT) = 3.60e+03 sec; Decay Time (DT) = 3.60e+04 sec; Plot only Radioactive
N_Implant=500, N_Resid=500, Abs_Error=1.0e-11, Rel_Error=1.0e-03, Threshold=1.0e-10, Model="ODE"
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