Calculation of Isotope Yields for Radioactive Beam Production

Fatima Garcia

MSc Candidate
Supervisors: Dr. C. Andreoiu, Dr. P. Kunz
Simon Fraser University

fatimag@sfu.ca

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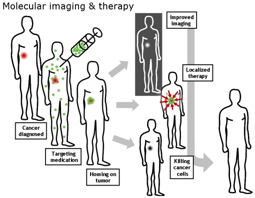
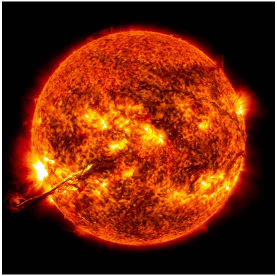
SFU TRIUMF

The Need for RIBs

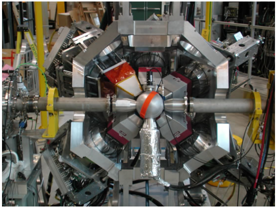
The same tools are used for diverse applications.



Nuclear medicine



Nuclear astrophysics



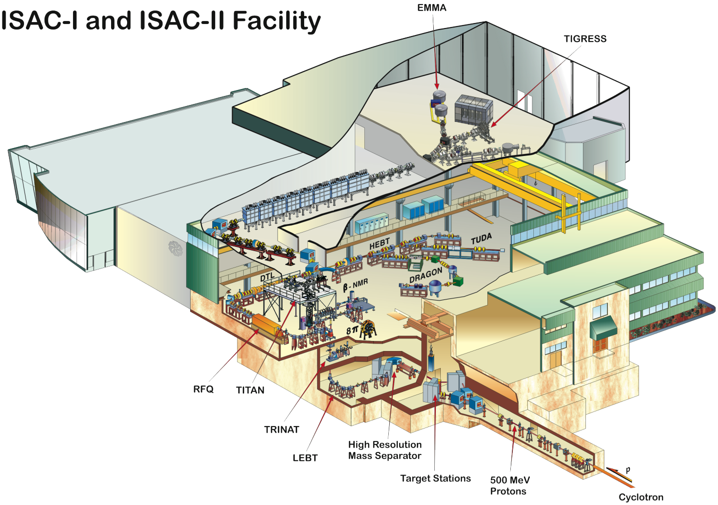
Fundamental Nuclear Science

Wikibooks contributors, 'Nanotechnology', *Wikibooks, The Free Textbook Project* (Dec 10, 2013)

NASA, Goddard Space Flight Center

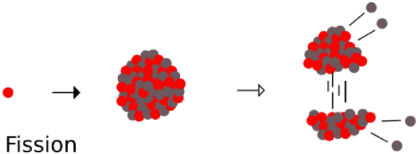
SFU Nuclear Science

TRIUMF

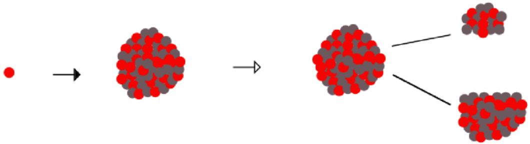


TRIUMF Website

ISOL Technique & Production Mechanisms

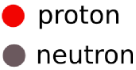


Fission
Single nucleons are kicked out, and the remnant splits into two or more parts

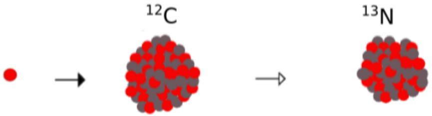


Fragmentation
A part of the nucleus is kicked out, this and the other piece remain bound

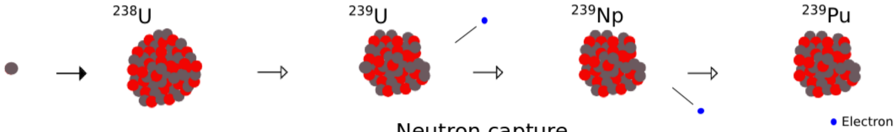
Spallation
Small groups and single nucleons are removed from the larger piece



Secondary Reactions



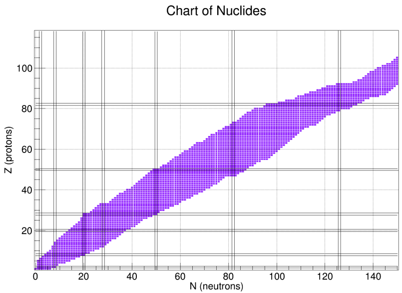
Proton Capture

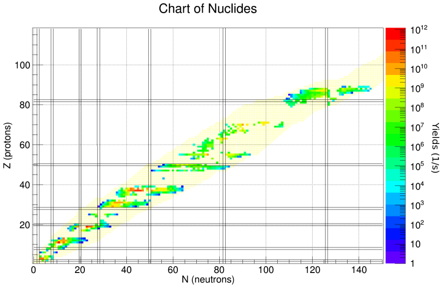


Neutron capture

A Theoretical Framework

We are working on a simulation of the targetry at TRIUMF, to be used as a predictive model for future target material studies.

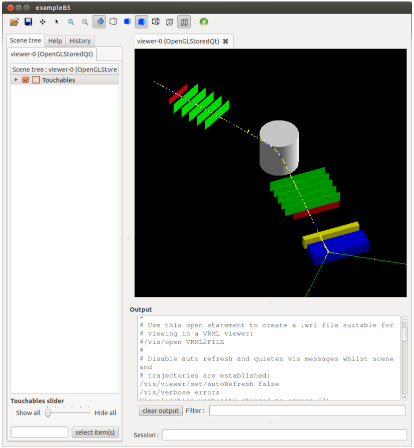




Kunz et al. TRIUMF ISAC Yield Database http://mis.triumf.ca/science/planning/yield/target

GEANT4: GEometry ANd Tracking

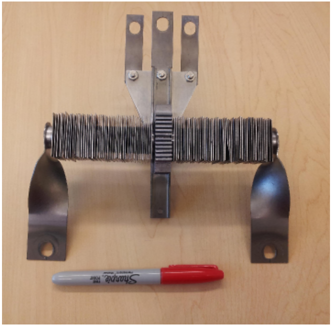
Monte Carlo based, C++ nuclear transport toolkit.



- Comprehensive geometry definition
- Well established physics models
- User specified physics

GEANT4 Collaboration

Targets

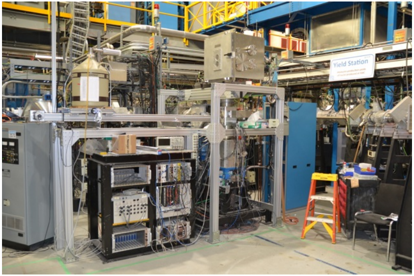


High temperature target container

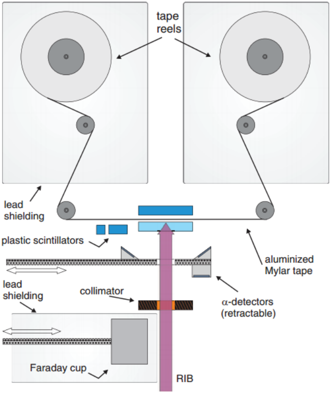
The target material is placed inside a tantalum target container and placed along the beamline.

Product isotopes are then extracted in the form of ion beams.

Yield station



ISAC Yield Station



ISAC Yield Station Schematic

Kunz, P. Andreoiu, C. et al. Rev. Sci. Instrum. 85 (2014)

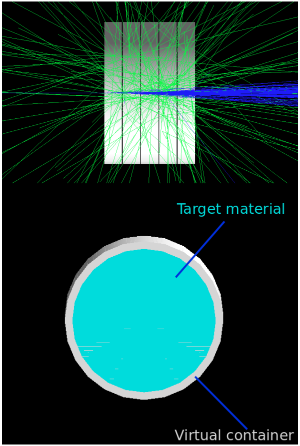
Standard Geometry

The simulated geometry consists of

- 5 disks
- Disk Thickness: 0.05 g/cm^2
- Radius: 9.5 mm
- Material: Depleted Uranium

The incident particle:

- Proton
- 500 MeV



Physics Lists

Different physics lists operate at different energies and with different specifications:

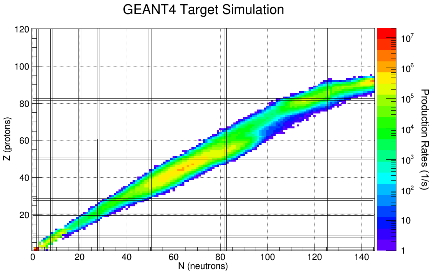
List	Energy Range	Treatment of Nucleus
Bertini	0 MeV - 10 GeV	Three concentric shells of different densities
Binary	1 MeV - 2 GeV	Isotropic density
Liege	1 MeV - 20 GeV	Fermi gas in static potential

Each with its own advantages and disadvantages.

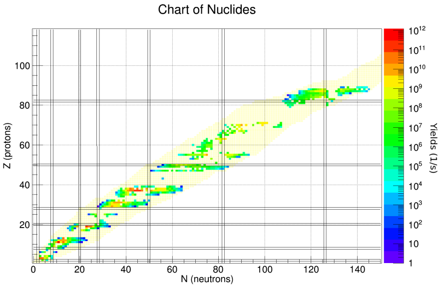
GEANT4 Collaboration. *GEANT4 Physics Reference Manual*. CERN (2014)

Simulation vs. Yield data

Differences arise from the challenges of doing a real experiment



Data output by the Liege Model



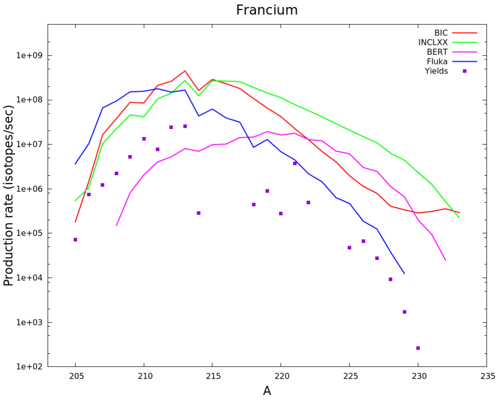
Isotopes generated at TRIUMF

Challenges

Yield rates are sensitive to:

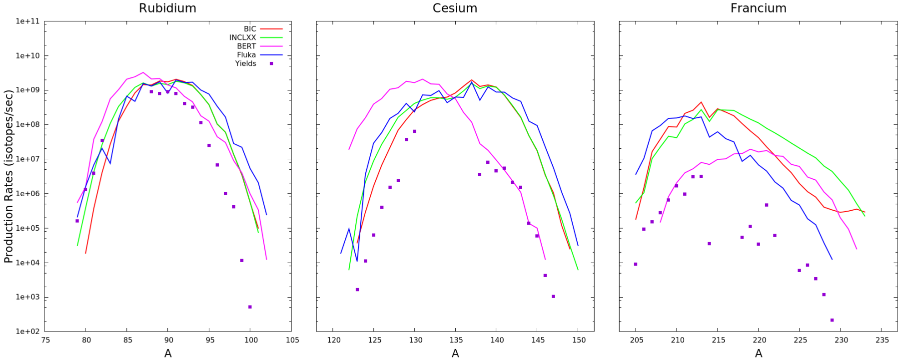
- Isotope half life
- Transport

Inclusion of these factors may help in determining the most accurate physics list.



Comparison Results

Alkalis are efficiently released, and thus are used as comparisons between data and simulation.

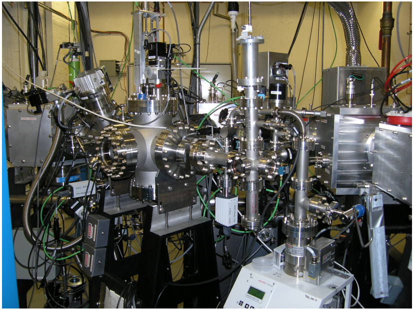


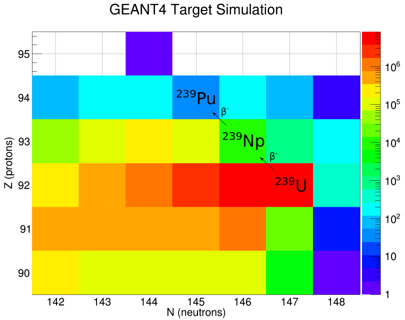
Results for runs with 10^9 primaries, and scaled to 1 μA

FLUKA Data: A. Laxdal, Private Communication 2015

^{239}Pu Yield Measurement

Via the ^{239}U neutron capture, TRIUMF has generated and implanted ^{239}Pu.



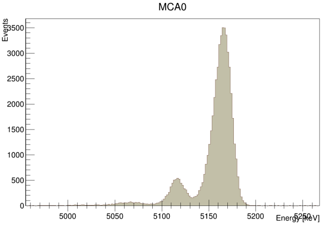


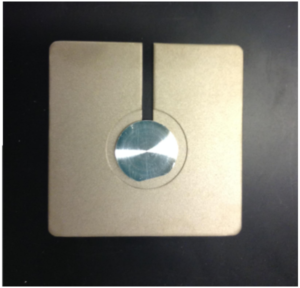
This will be used as a further check of the model validity.

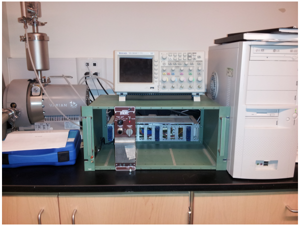
Alpha Spectrometry

Experiment specs

Half life	24110 years
Implantation time	12 hrs
Decay time	151 days
Measurement time	20 days
Activity	0.32 Bq







^{239}Pu Production Rates

Isobar	Bertini	Binary	Liege
^{239}U	3.12e9	3.25e10	3.23e10
^{239}Np	1.68e7	5.46e7	6.29e7
^{239}Pu	3.12e4	2.42e5	3.28e5

Production rates given in atoms/sec and scaled to 1 μA

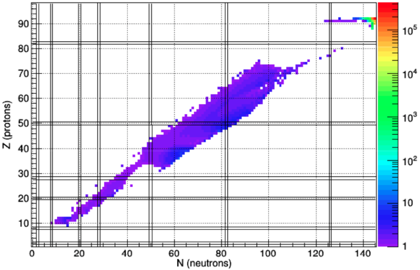
Source	^{239}Pu Production
Experiment	$\sim$ 1e7
Bertini	4.10e9
Binary	4.25e10
Liege	4.24e10

Rates given in nuclei/sec

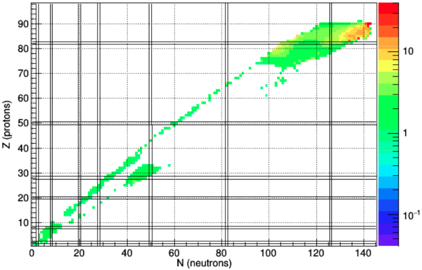
Isotopes for Nuclear Medicine

Actinium and Radium isotope rates are important quantities in nuclear medicine

Uranium/Thorium Rates



Thorium/Uranium Rates



Rates given in isotopes/sec

Current Status

So far I have:

- Compared available physics lists
- Predicted isotope output during online experiments
- Validated the model via ^{239}Pu production
- Extended the scope by predicting medical isotope output

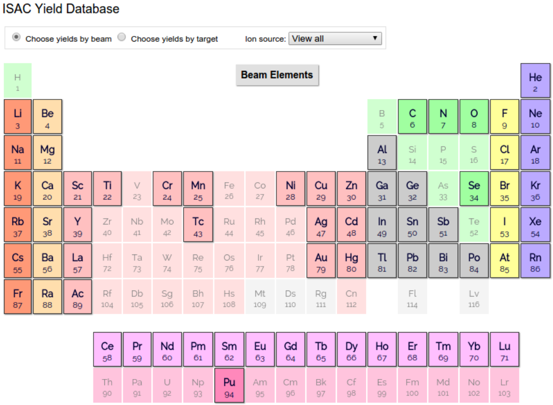
The next steps include:

- Continue optimization
- Implement different target materials

Different Targets for Different Isotopes

Data is available for:

- Silicon
- Titanium
- Nickel
- Zirconium
- Niobium
- Tantalum
- Thorium

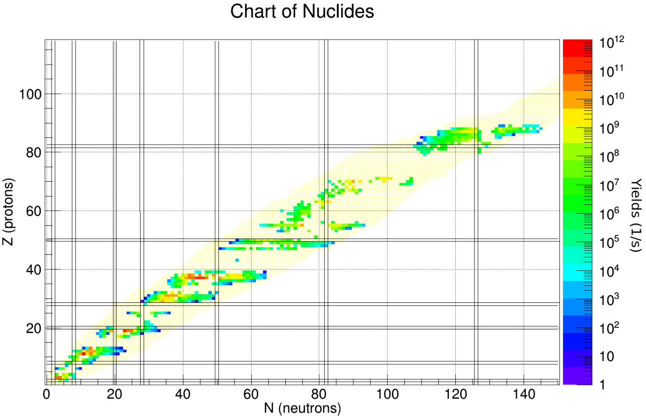


Isotope beams available at TRIUMF

Kunz et al. TRIUMF ISAC Yield Database. http://mis.triumf.ca/science/planning/yield/beam

New Tool for Future Experiments

The purpose of this predictive model is to provide a tool to guide future target materials studies and upcoming experiments.

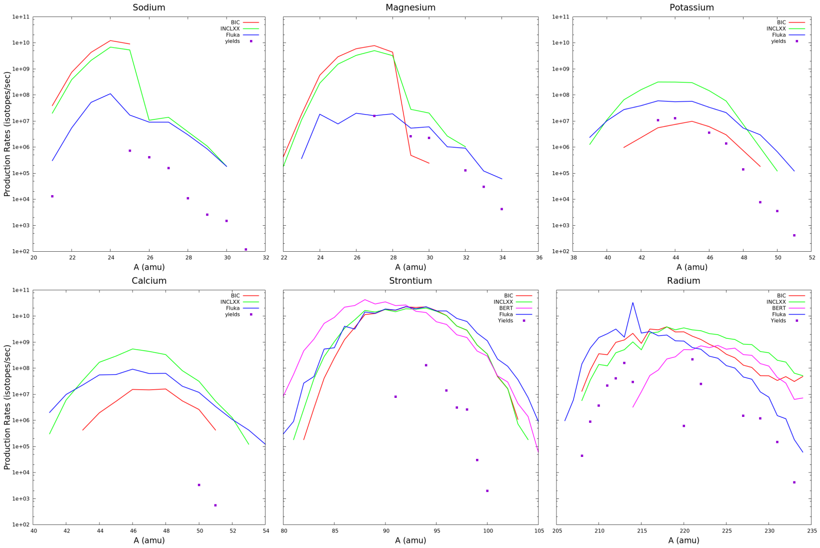


Acknowledgements

- Dr. C. Andreoiu
- Dr. P. Kunz
- A. Laxdal
- SFU Chemistry
- TRIUMF
- SFU Graduate Studies
- NSERC

Thank you

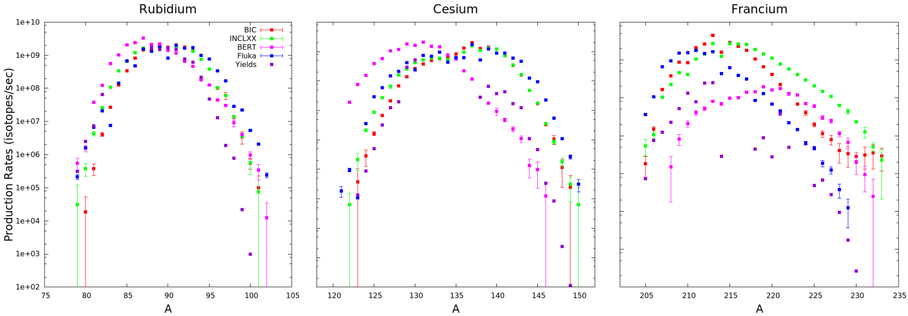
Comparison Results (cont.)



A. Laxdal, Private Communication 2015

Errors

Each point that comprises the curve has its own error associated with it.



Calculated using the average and standard deviation from eight runs, each with 10^8 primaries.

Nuclear Codes

Many different nuclear codes are available:

Code	Strengths	Weaknesses
FLUKA	Commercial maintenance User friendly	Proprietary Fixed physics models
Silberberg-Tsao	Fragmentation code Comprehensive	Theoretical formalism Antiquated
GEANT4	Open source software Worldwide collaboration	Extensive code Not user friendly

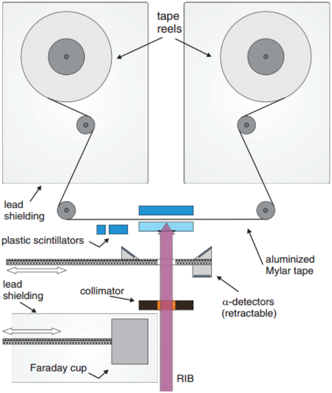
For its capabilities and uses, GEANT4 will be the toolkit used.

Böhlen, T. et al. Nucl. Data Sheets 120 (2014); Shinn, J. et al. NASA Technical Paper 3350 (1993)
Agostinelli, S. et al. Nuc. Instrum. Meth. 506 (2003)

Physics List Choices

- Binary cascade: time dependent hadron-nuclear collision
- Leige INCL++: time dependent with ordered interactions
- Pre-compound: handles isomers
- De-excitation: resolves excess energy near equilibrium

Yield Station



Yield station schematic

The yield station is capable of:

- α, β, γ decay measurements
- Lifetime measurements
- Beam characterization

Target Materials

The actinides are used for these experiments as they are:

- Highly refractory
- Very large and massive; U(IV) $r_{ionic} = 0.89$ Å, Th(IV) $r_{ionic} = 0.94$ Å

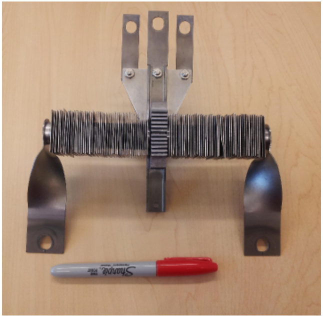
Hayes,C., Leznoff, D.B., Coord. Chem. Rev. 266-267 (2014)
Rough, F.A., Chubb, W. eds. doi:10.2172/4176185 (1960)

Benchmark Products

For comparison the alkalis will be used.

- Very little chemistry at operating temperature ($\sim 2000\ ^{\circ}$C)
- Surface ionization is efficient and well understood
- Not retained as molecules

Target Materials and Specs



- Tantalum
- 90 55 x 55 mm fins to dissipate heat
- Maintained at $\sim$2000 °C

Bricault, P., et al. Nuc. Instrum. Meth. B, 204 (2003)
Schmor, P.W., Nuc. Phys. A, 701 (2002)