Understanding radioactive ion beam production at ISAC through yield measurements and simulations

KUNZ, Peter (TRIUMF), ANDREOIU, Corina (Simon Fraser University); GARCIA, Fatima H. (Simon Fraser University); LASSEN, Jens (TRIUMF); RADCHENKO, Valery (TRIUMF); YANG, Hua (TRIUMF)

ISAC (Isotope Separation and ACceleration) facility

The high-intensity proton beam of the TRIUMF H^- 500 MeV cyclotron offers unique opportunities to produce rare isotopes by irradiating a variety of targets. The facility provides the infrastructure to deliver customized rare ion beams to experiments in the fields of nuclear structure, astrophysics, medicine, and material science. ISAC target stations can host a wide range of targets, from graphite to uranium carbide. Each target material generates a unique set of isotopes through nuclear reactions induced by the proton beam.

Nuclear simulation codes such as Geant4 are important tools to calculate target performance and the range of isotope production.

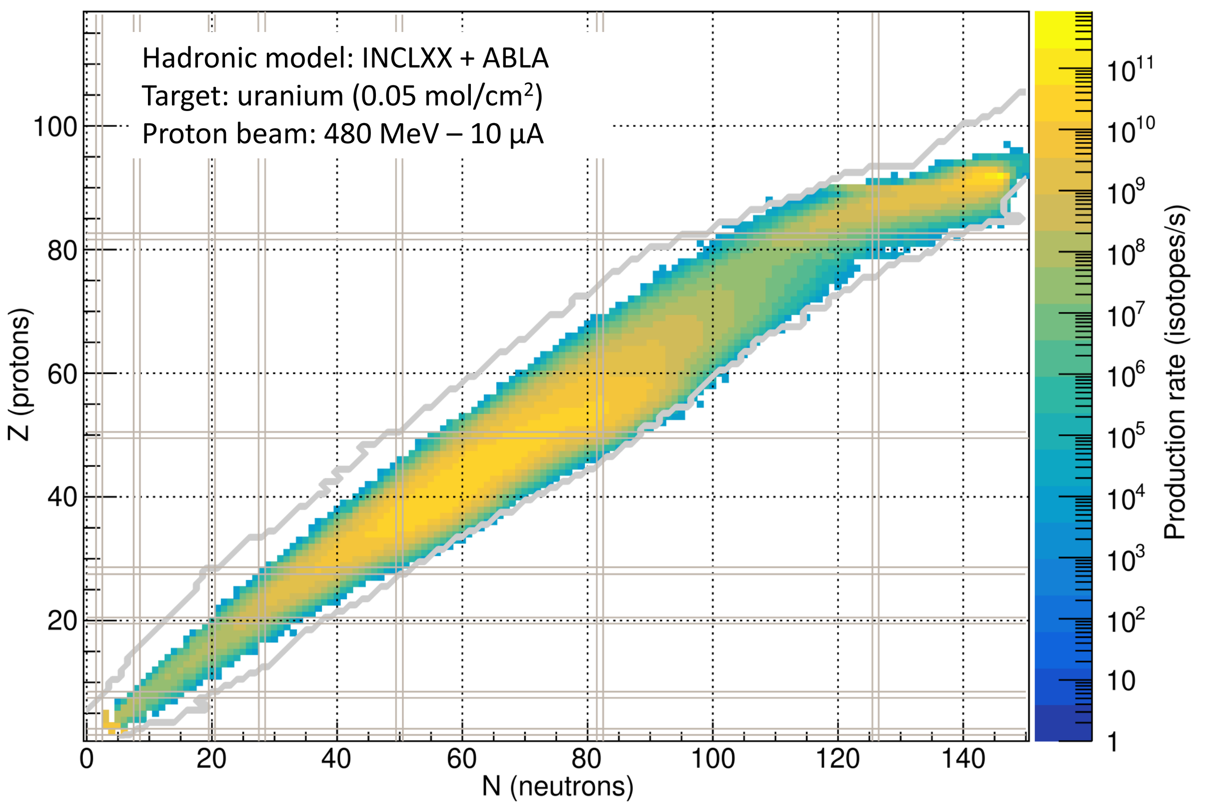

Fig. 1: Geant4 simulation of isotope production rates from a typical ISAC uranium carbide target.

The intensity of a specific isotope beam extracted from a target (yield) depends on the production rate P as well as efficiencies for release ε_R, ionization ε_I and transport ε_T.

$$Yield = P\,\epsilon_R\,\epsilon_I\,\epsilon_T$$

The main tool for characterizing isotope beam intensities and composition is the ISAC Yield Station [1]. The results from all major targets are summarized in Fig. 2. Detailed information on measured yields and production rate simulations are available for TRIUMF users in the TRIUMF Isotope Database [2].

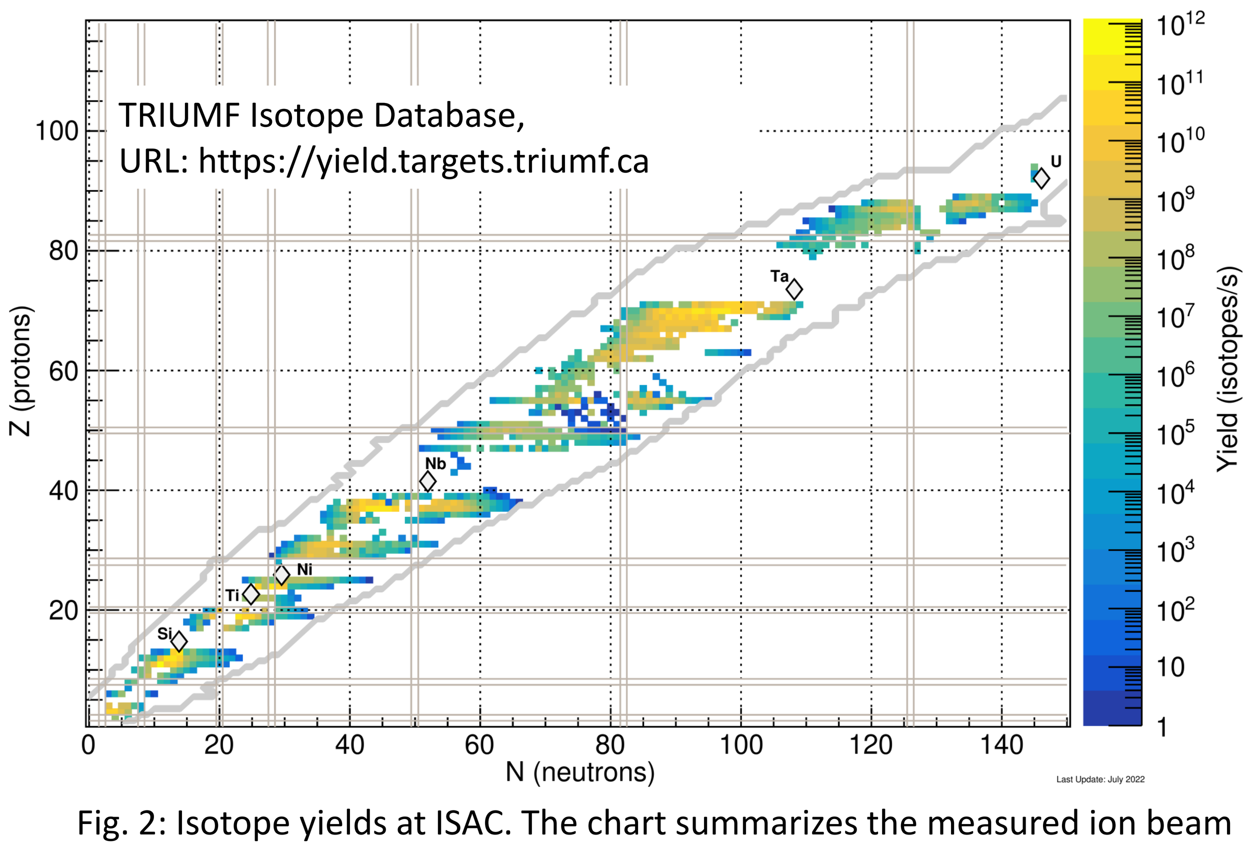

Fig. 2: Isotope yields at ISAC. The chart summarizes the measured ion beam intensities of close to 1000 radioactive isotopes. ◊ indicate the most common target elements.

The following examples demonstrate how information on yields and production rates help with planning and scheduling experiments but also provide insights into unusual production pathways like the creation of trans-uranium isotopes.

Example: ^{155}Tb for life science research

The ISAC facility provides the opportunity to collect exotic isotopes for nuclear medicine applications [3]. Neutron-deficient lanthanide isotopes such as ^{155}Tb are produced at high rates in tantalum metal foil targets.

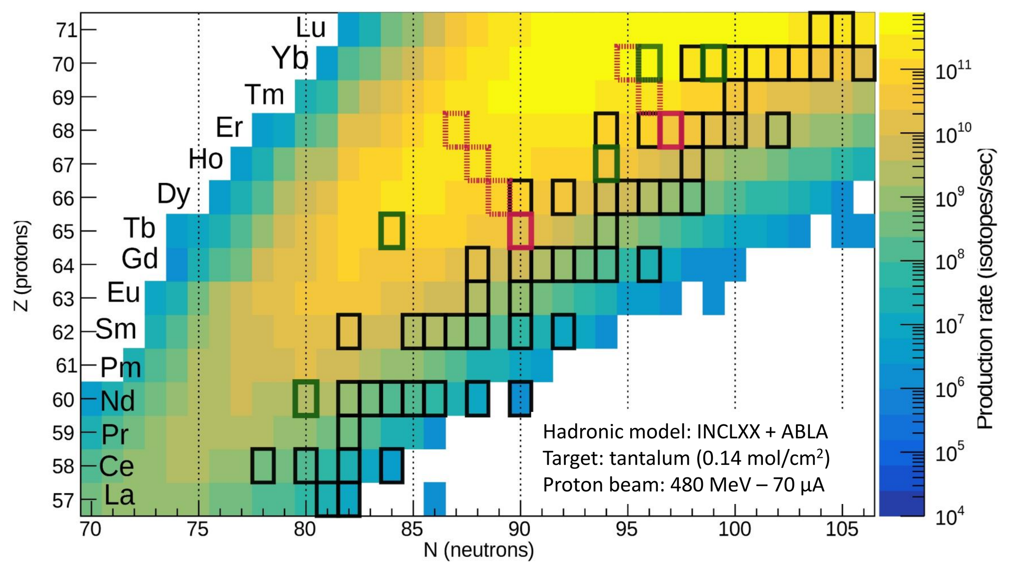

Fig. 3: Geant4 simulation of lanthanide production rates. [] stable isotopes. [] relevant to the collection of medical isotopes ^{155}Tb and ^{165}Er [5].

Radioactive ion beam (RIB) of a specific mass is collected at the ISAC Implantation Station (Fig. 4). The most efficient way to produce high activities of ^{155}Tb ($T_{1/2}$ = 5.32 d) is to collect isobaric RIB components Er, Ho and Dy which are produced at higher rates and eventually decay into ^{155}Tb.

$$^{155}\mathrm{Er} \xrightarrow[5.3m]{\beta^+/ec} {}^{155}\mathrm{Ho} \xrightarrow[48m]{\beta^+/ec} {}^{155}\mathrm{Dy} \xrightarrow[9.9h]{\beta^+/ec} {}^{155}\mathrm{Tb}$$

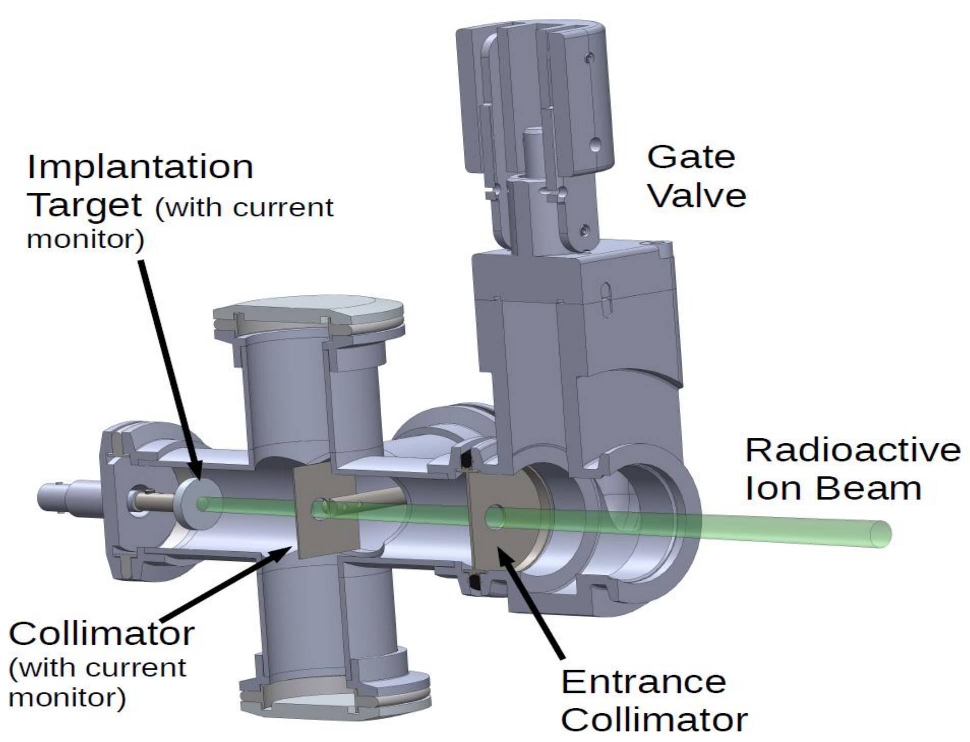

Fig. 4: Ion beam implantation vessel for collection of medical isotopes. During isotope collection it is attached to the ISAC Implantation Station beamline. When the implantation process is complete, the vessel is detached and the accumulated activity is transferred under vacuum to its destination.

The ^{155}Tb collection process consists of two stages. During the implantation period all isobaric RIB components at A=155 are implanted in the collection vessel (Fig. 4), including the most intense beams of Er, Ho and Dy. The implantation time is calculated on the basis of the desired ^{155}Tb activity and individual beam intensities of each isotope which are determined at the ISAC Yield Station.

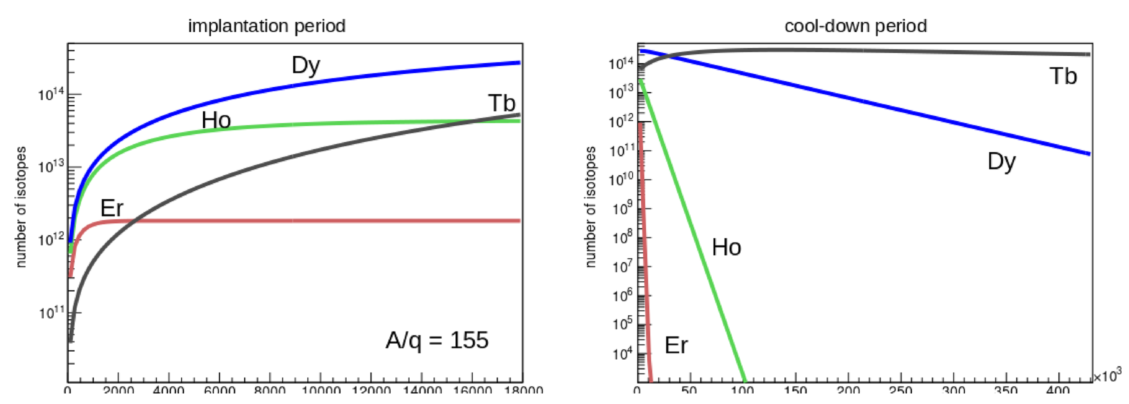

Fig. 5: Implantation (left) and cool-down (right) periods of a typical ^{155}Tb collection. The implantation plot shows the accumulation of isotopes over several hours at constant beam intensities. The cool-down plot shows the decay of short-lived isotopes and the build-up of ^{155}Tb activity over several days.

A typical ^{155}Tb activity is ~370 MBq, requiring implantation periods of several hours. At the and of the implantation total activities of up to 10 GBq can be reached. Several days of cool-down (Fig. 5, right) are required to reduce the sample activity to a manageable level and for ^{155}Tb activity to build up.

Example: ^{239}Pu production in ISAC targets

The majority of isotopes from ISAC targets is produced through proton-induced spallation and fragmentation reactions as well as fission for uranium and thorium targets. A smaller number is generated through nuclear reactions with secondary particles (e.g. neutrons, ^{2,3}H, ^{3,4}He). Evidence for such a process was obtained through the characterization of a ^{239}Pu beam extracted from a uranium carbide target [6]. A beam intensity of $1.89(6)\cdot 10^7$ ions/sec was detected and identified as ^{239}Pu through resonant laser ionization and alpha spectroscopy (Fig. 6).

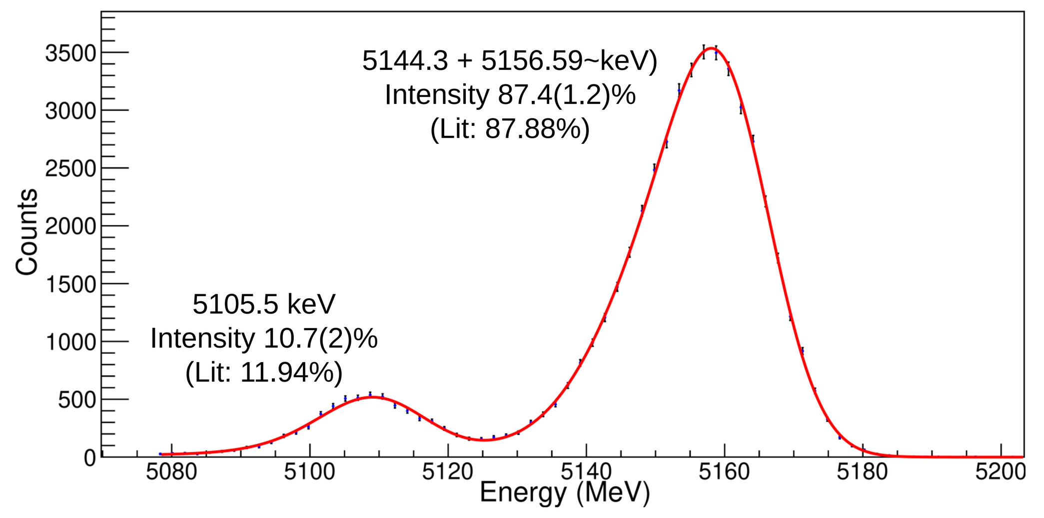

Fig. 6: Characteristic alpha decay lines of ^{239}Pu, collected from an ISAC uranium carbide target.

A Geant4 simulation (Fig. 7) provides information on production cross sections as well as direct and indirect production channels. Direct channels are ^{238}U(^{3}He,2n)^{239}Pu and ^{238}U(^{4}He,3n)^{239}Pu. An indirect path leads through neutron capture and the decay of ^{239}U.

$$^{239}\mathrm{U} \xrightarrow[23.45m]{\beta^-} {}^{239}\mathrm{Np} \xrightarrow[2.356d]{\beta^-} {}^{239}\mathrm{Pu}$$

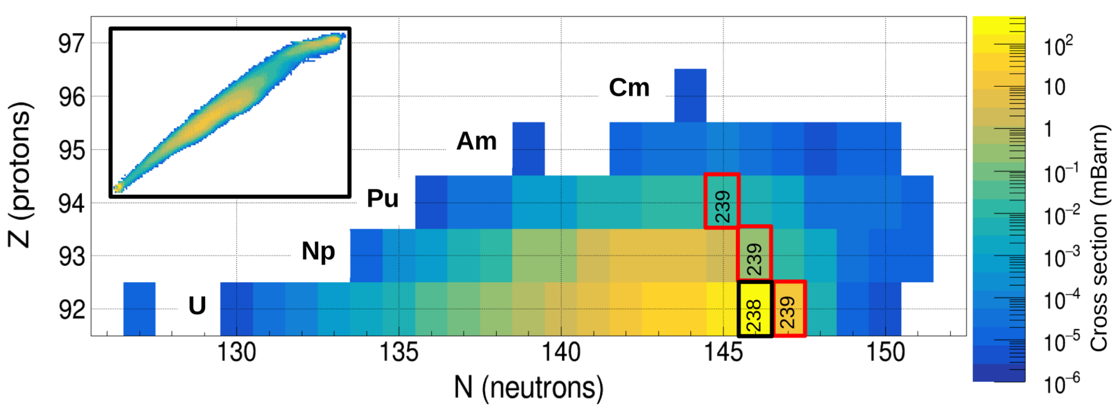

Fig. 7: Geant4 simulation results of total production cross sections of uranium and trans-uranium isotopes. The main target isotope ^{238}U, ^{239}Pu and isotopes contributing to the indirect production channel are highlighted.

The simulation results include information on the total production and kinetic energies of secondary particles as well as the fraction involved in ^{239}Pu production (Fig. 8). The conclusion (Tab. 1) is that most ^{239}Pu is produced through the neutron capture channel which requires that the intermediate isotope ^{239}Np is not efficiently released from the target.

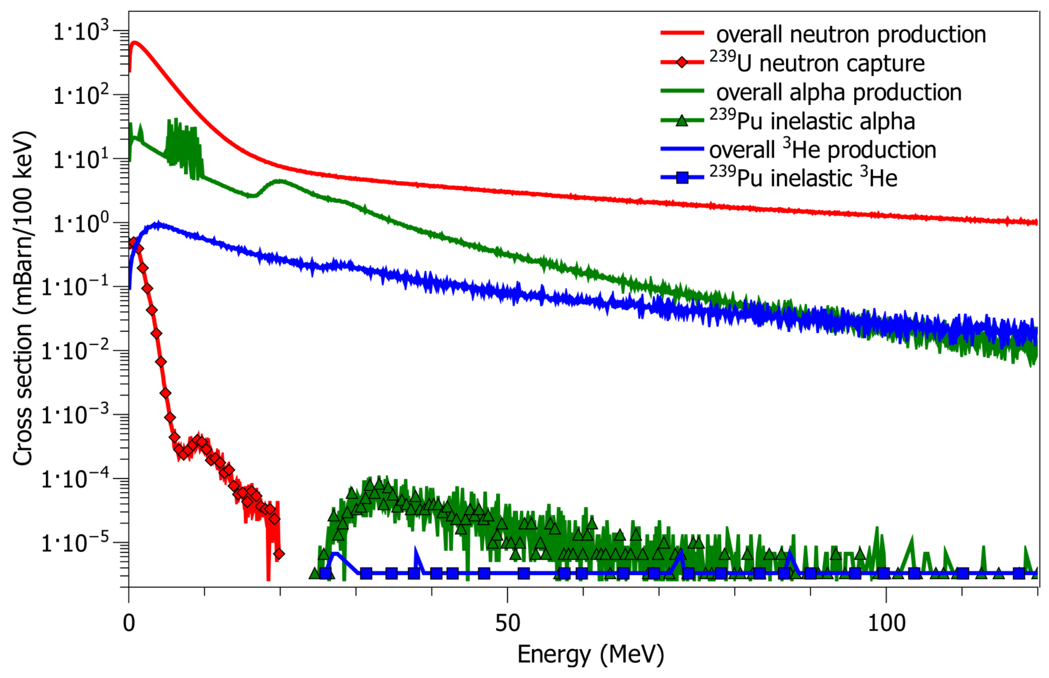

Fig. 7: Energy dependent total production cross sections of neutrons, ^{3}He and ^{4}He (alpha). The plots including symbols depict the fraction responsible for ^{239}Pu production through inelastic reactions.

Tab. 1: Total production cross-section for neutrons, ^{3}He, ^{4}He (alpha) and related ^{239}Pu production.

σ (mBarn)	overall	^{239}Pu
neutron	$3.13\cdot 10^4$	$9.04\cdot 10^0$
alpha	$2.38\cdot 10^3$	$1.13\cdot 10^{-2}$
^{3}He	$1.92\cdot 10^2$	$6.18\cdot 10^{-4}$

[1] Kunz, P., et. al., Rev. Sci. Inst. 85, 053305 (2014)
[2] TRIUMF Isotope Database, URL: https://yield.targets.triumf.ca
[3] Kunz, P.,et.al. EPJ Web of Conferences 229 06003. (2020).
[5] D. E. Fiaccabrino, et. al., Nuclear Medicine and Biology 94-95 (2021) 81-91.
[6] Kunz, P. et. al., submitted to NIM B

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