Yields from extended p-driver capabilities
-
calculations and experimental results

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Lay out

1. Introduction
2. Critical characteristics of the ISOL method
3. General aspects of relevant nuclear reactions
4. View on some specific extensions of the driver
5. Summary

Introduction

Standard Option for EURISOL Driver

Protons, 1 GeV

200 μA beam current for direct-target option

3-4 mA beam current for converter-target option

Experience from ISOLDE with proton beam,
600 MeV, 1 to 1.4 GeV

Options for Extended Capabilities considered

- <u>Eurisol RTD report, Accelerator group</u>
  1. $A/q = 2$ at 43 A MeV and $A/q = 3$ at 28 A MeV
  2. $A/q = 2$ at 500 A MeV
  3. $A/q = 3$ at 100 A MeV and $A/q = 2$ at 150 A MeV
- <u>Eurisol RTD report, Target and Ion-Source group</u>

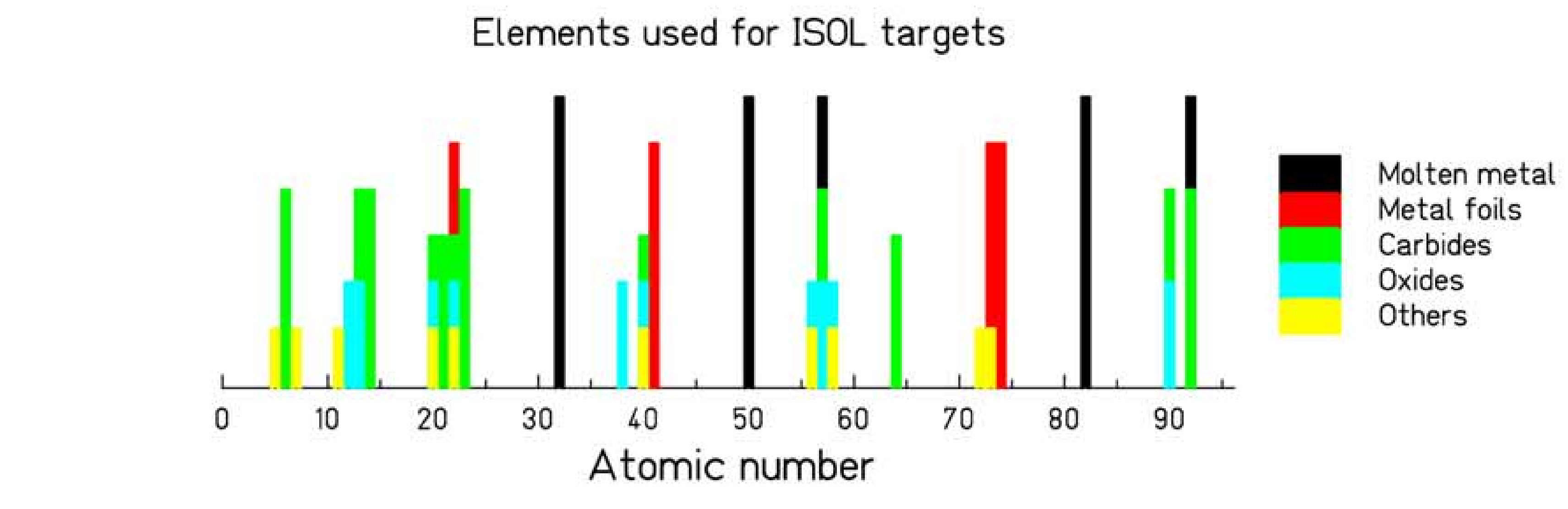
  $A/q = 6$ at 166.5 A MeV and $A/q = 3$ at 333 A MeV
- <u>Additional options</u>

  $^{3}He^{2+}$, $E = 2$ GeV

  Deuterons, $E \leq 250$ MeV, $I \approx 5$ mA

Critical characteristics of the ISOL method

Characteristics of the ISOL method
I. Target Materials



Extracted from
"ISOLDE target and ion source chemistry", U. Köster, Radiochim. Acta 89 (2001) 749

⟶ Typical gaps in Z_{target} of ≈ 10 or ≈ 20 elements.

Characteristics of the ISOL method
II. Extraction Efficiencies

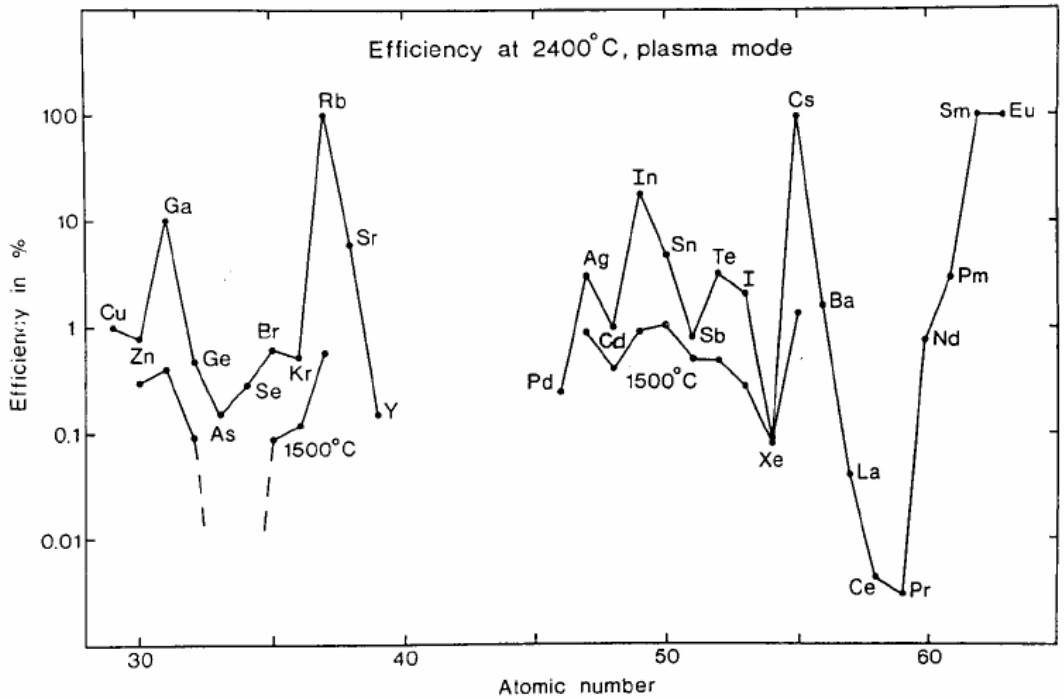
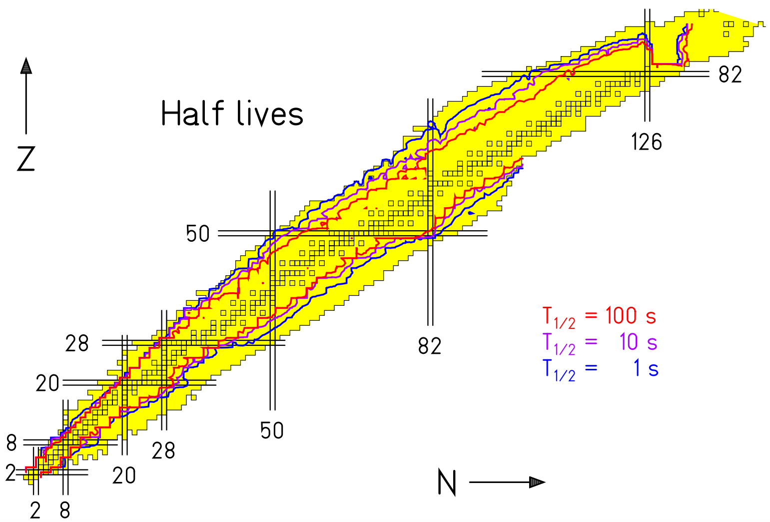


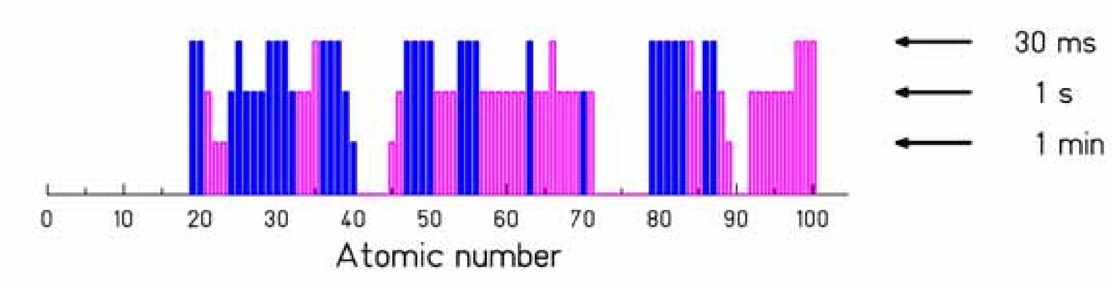
Fig. 13. The overall efficiency of the OSIRIS target and ion source as a function of atomic number of fission-product nuclei. The upper curve is measured at a target temperature of 2400°C. For comparison the lower curve shows the efficiencies of the previously used system at 1500°C.

Taken from "*Comparison of radioactive ion-beam intensities produced by means of thick targets bombarded with neutrons, protons and heavy ions*" H. L. Ravn et al., Nucl. Instr. Meth. B 88 (1994) 441

—► Efficiencies depend on Z (figure only for qualitative illustration).

Characteristics of the ISOL method
III. Extraction Losses



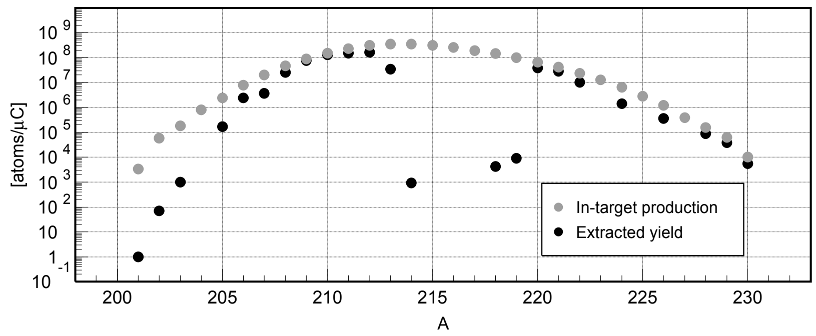


1% overall efficiency for indicated half-life.

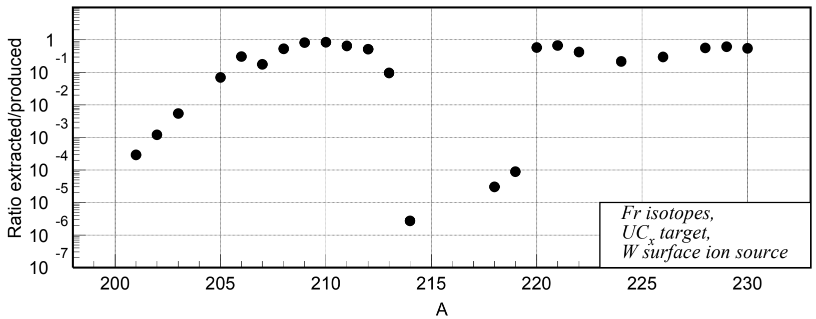
R. Kirchner, GSI (2001)

→ Losses due to radioactive decay before extraction.

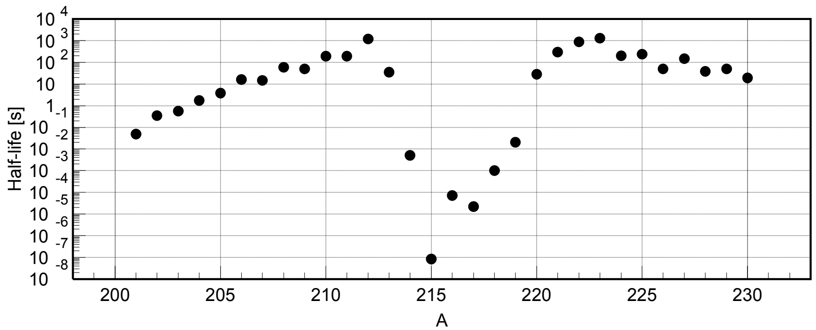
Determination of the release function



Fr isotopes
Calculated in target yields compared with measured ISOLDE yields



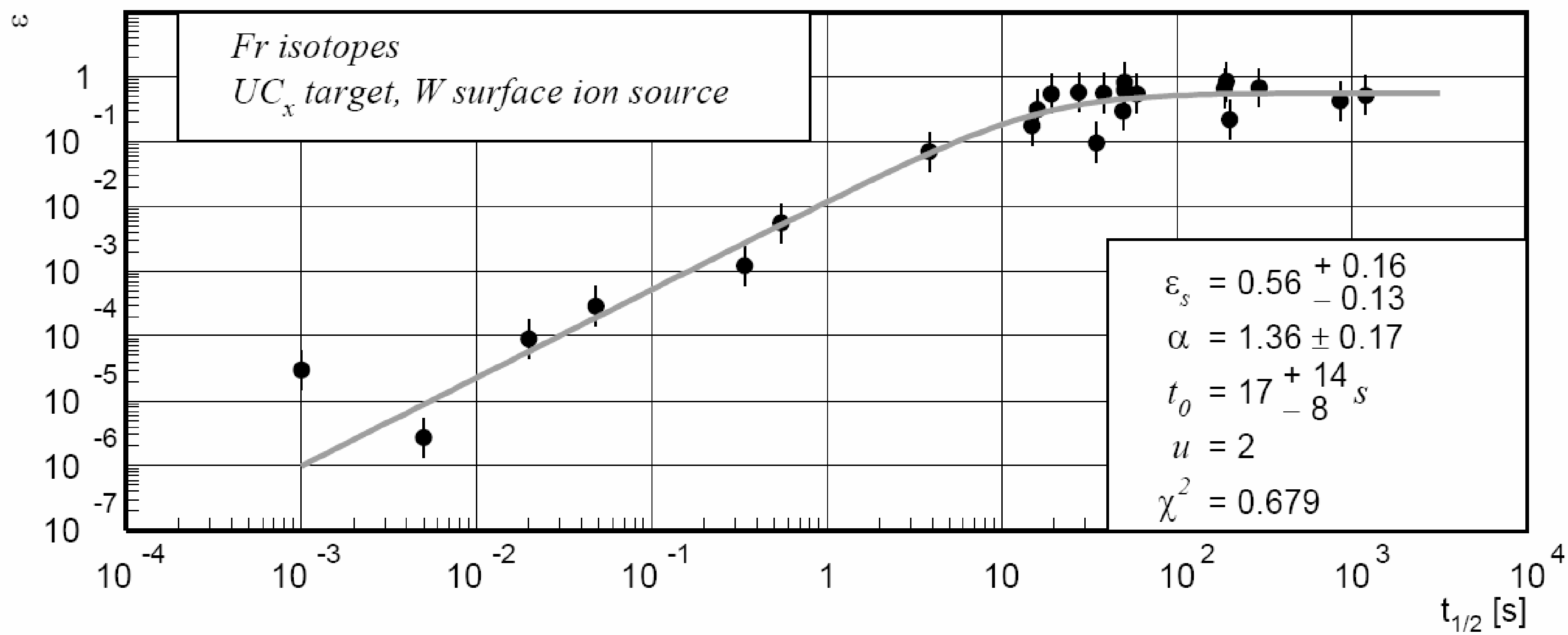
Extraction efficiencies



Half lives

S. Lukic et al., NIM A 565 (2006) 784

Release function



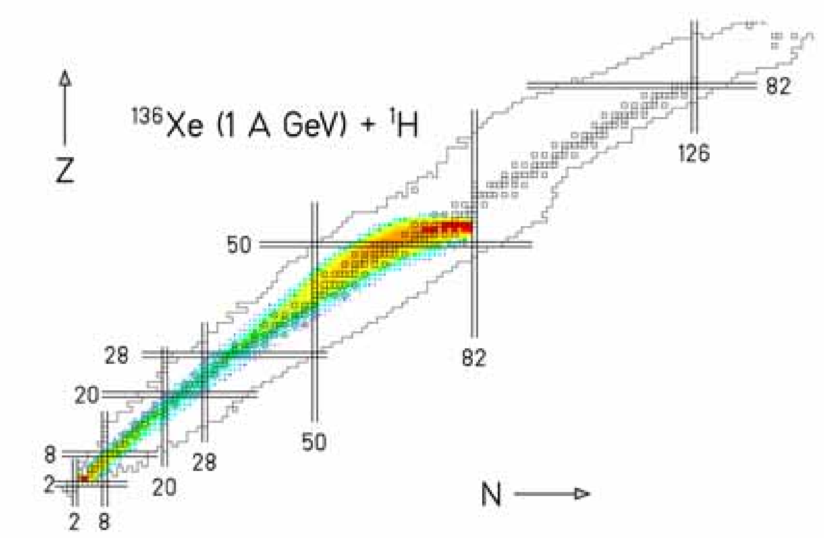
$$\varepsilon\left(t_{1/2}\right) = \frac{\varepsilon_s}{1 + \left(\dfrac{t_{1/2}}{t_0}\right)^{-\alpha}}$$

Empirical parameterisation by Lukic et al., NIM A 565 (2006) 784

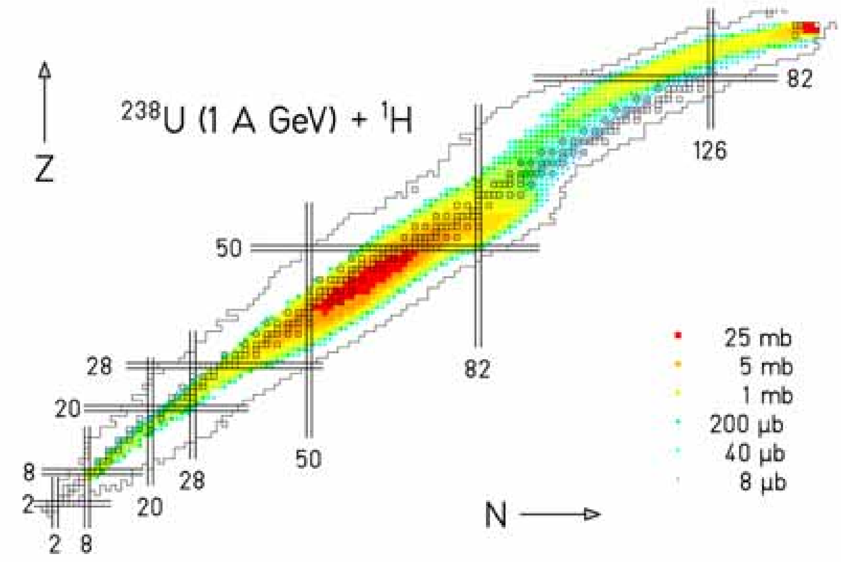
General aspects of relevant nuclear-reactions

General features of spallation reactions

(direct-target option, protons 1 GeV)



D. Henzlova

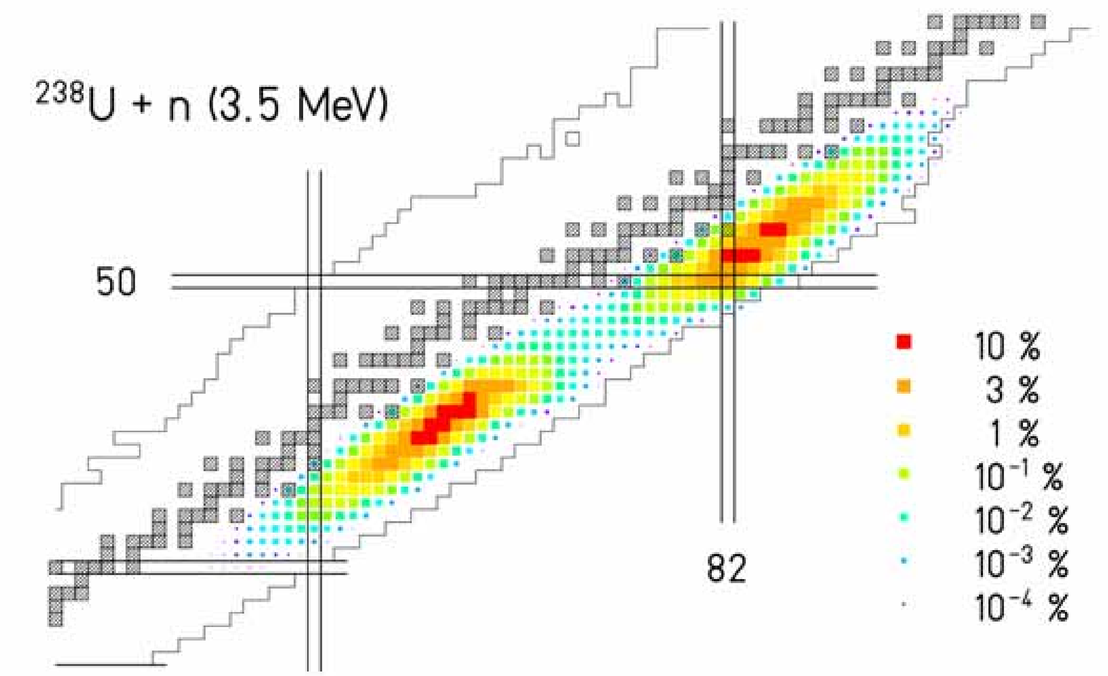


M. Bernas, M.-V. Ricciardi, J. Taïeb

- Spallation-evaporation produces nuclides reaching from the projectile to about 10 to 15 elements below. (A few neutron-rich, most neutron-deficient)
- Spallation-fission (from Th, U) produces neutron-rich nuclides up to Z = 65.

Experiments performed at GSI

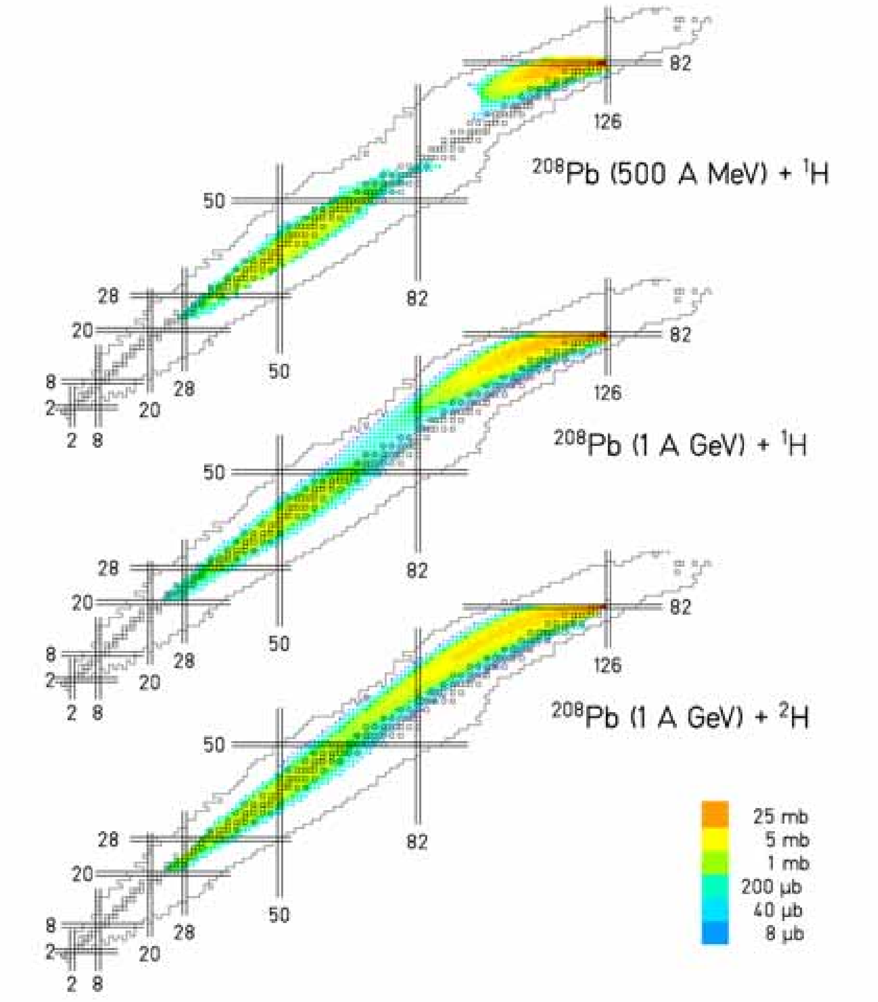
General features of low-energy fission
(converter-target option)



- Nuclide production on two limited neutron-rich regions of the chart of the nuclides.

Calculation performed with ABRABLA

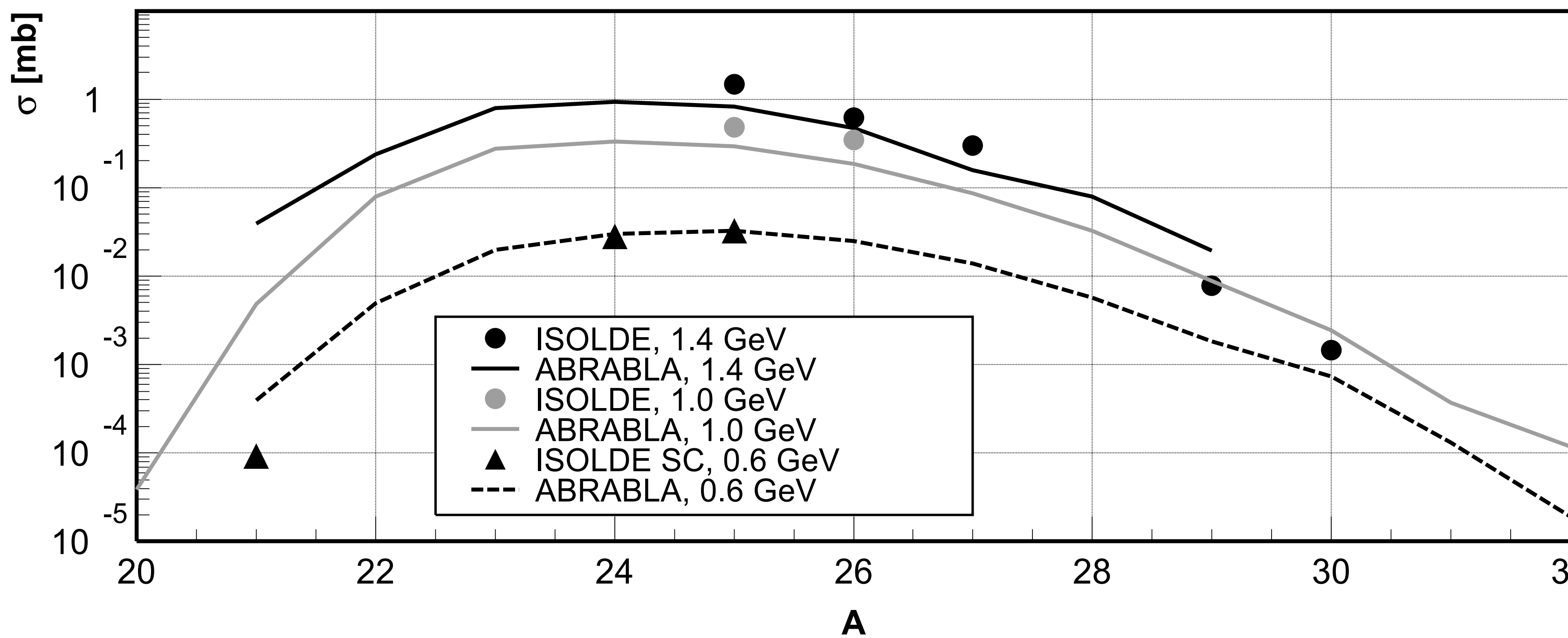
Spallation – energy dependence



Region of spallation-evaporation on the chart of the nuclides extends to lower masses with increasing energy available in the system.

Experiments performed at GSI

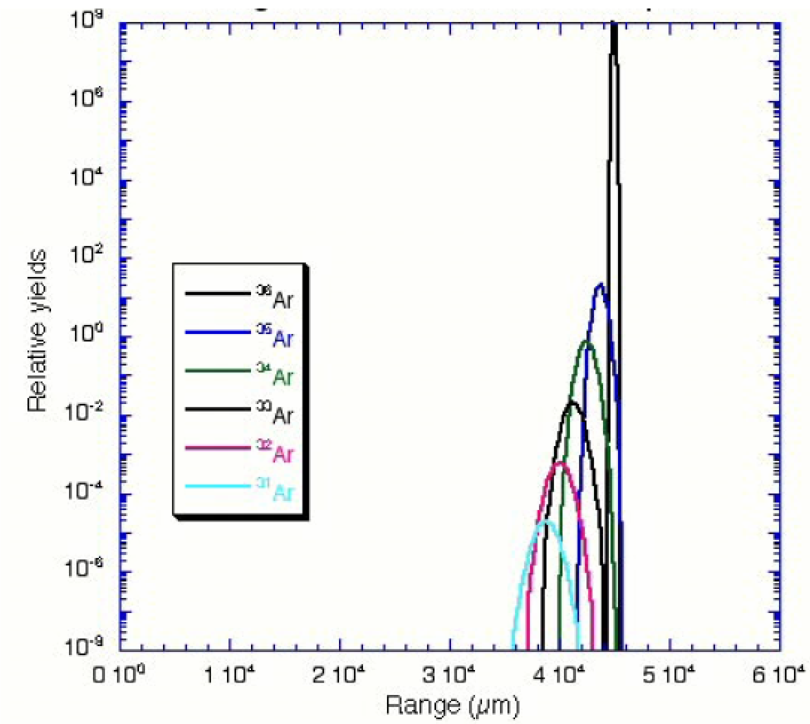
Production of sodium in $^{238}U + p$ – dependence on beam energy



→ Steep increase of IMF production with increasing beam energy

Measurements at ISOLDE
Calculations with ABRABLA

Tailoring the range distribution by heavy-ion fragmentation



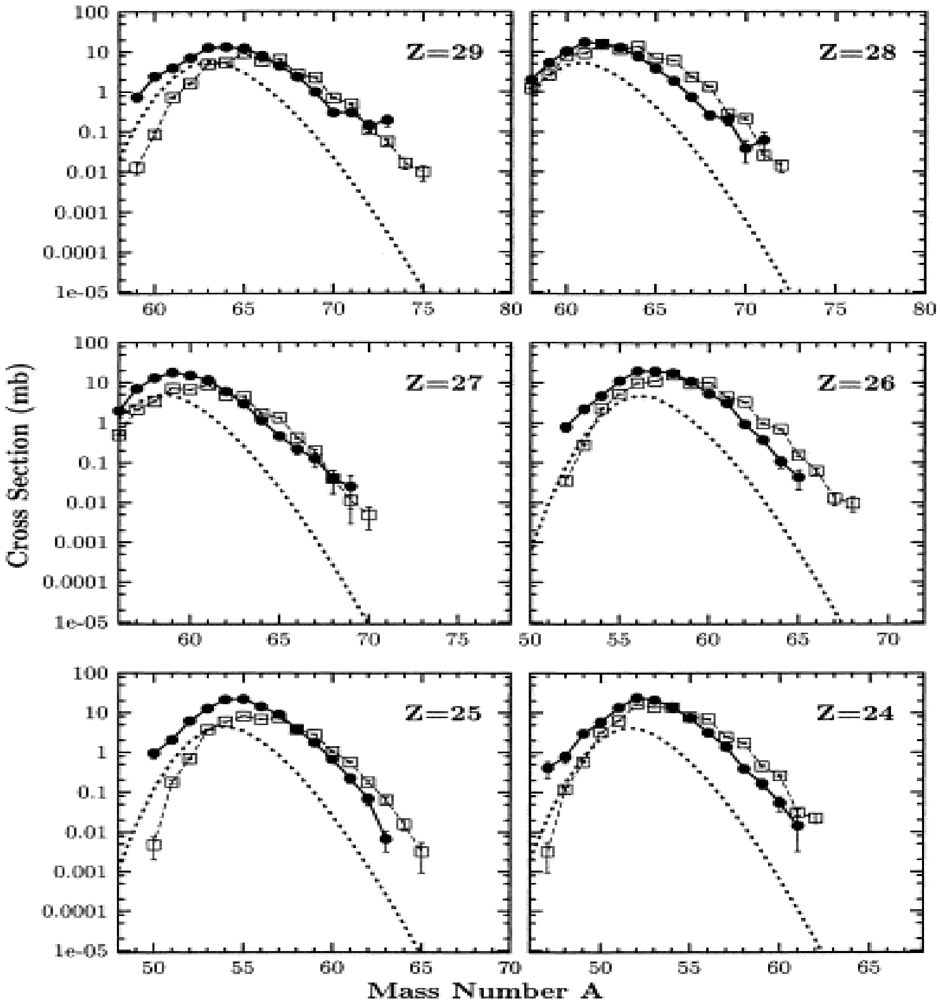
Fragmentation of ^{40}Ar to produce ^{31}Ar

75% of beam power
in the converter

Converter and catcher separated using HI beams.

Calculations by Villari and Mittig

Peculiarities of HI reactions at Fermi energies



^{124}Sn + ^{124}Sn at 20 *A* MeV

Full points: data

Open points: DIT+Gemini

Dashed lines: EPAX

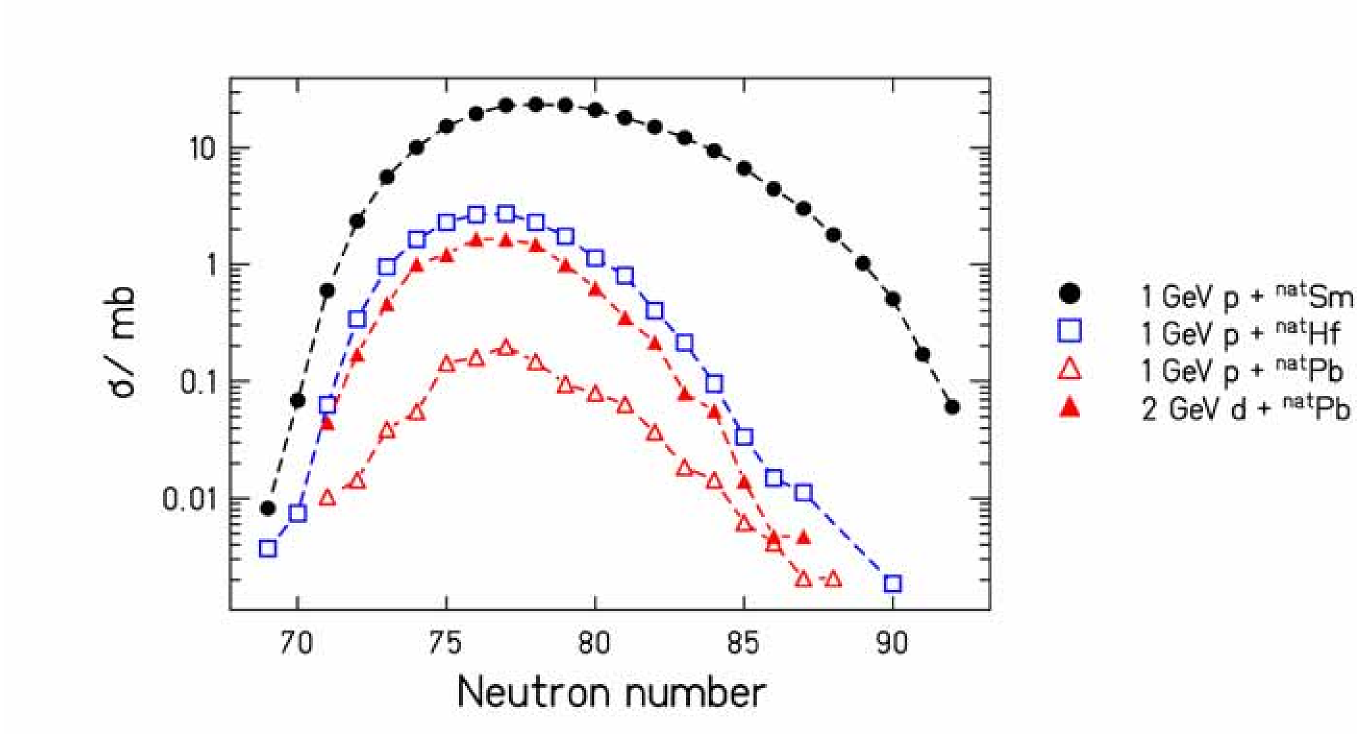
Deep-inelastic transfer produces neutron-rich nuclei of lighter elements (similar to fission).

Enhancement compared to fragmentation (EPAX).

Data by Souliotis et al.

Quantitative view on some specific extensions of the driver

Filling gaps in mass by 2 GeV ^{3}He beam



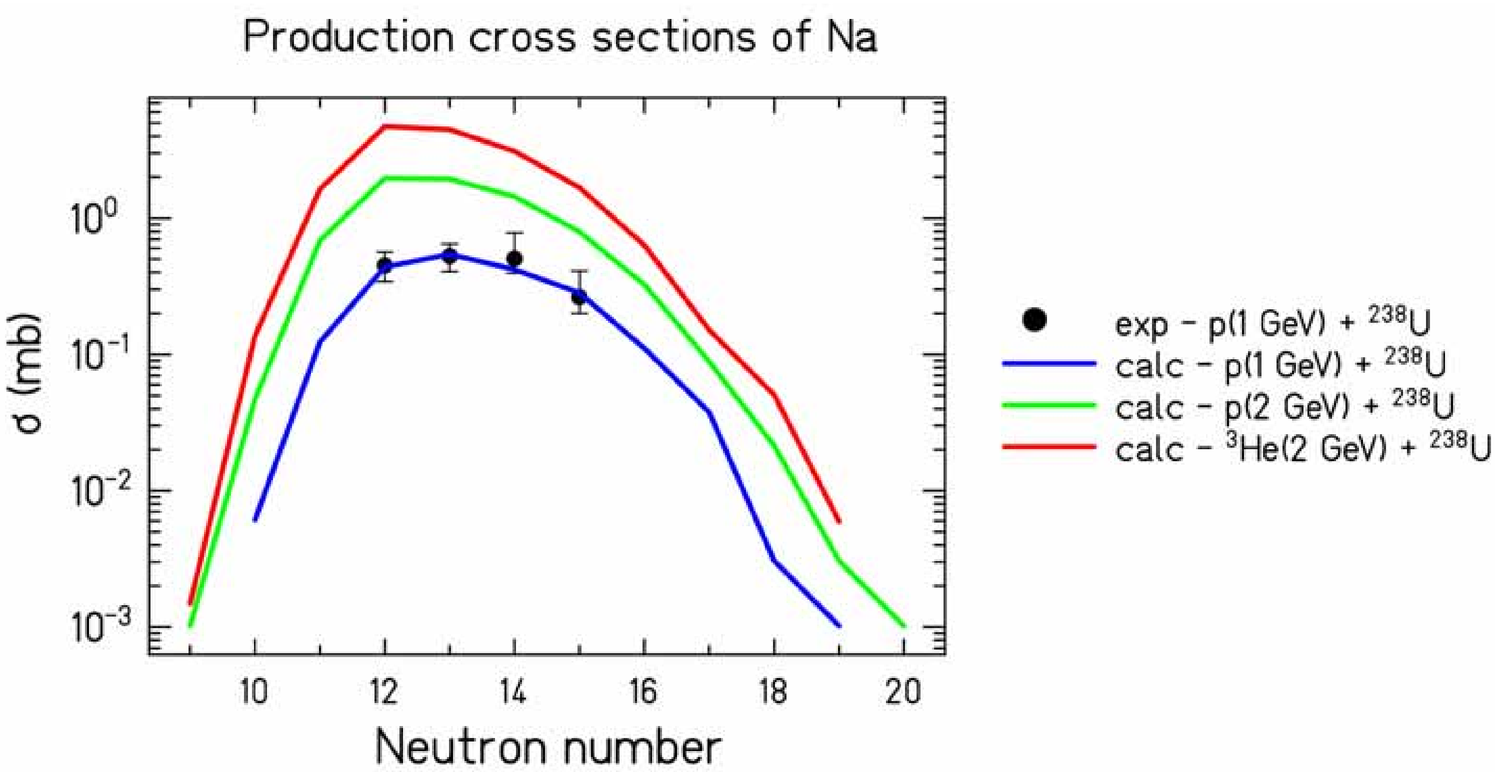
Production of Nd (Z = 60) isotopes with ΔZ = 2 (Sm-), 12 (Hf-), 22 (Pb-target)

Hypothetical calculation with ABRABLA (based on experimental data with ^{208}Pb)

Production at 1 GeV with ΔZ = 12 is comparable to 2 GeV with ΔZ = 22.

(Beam-power limitation reduces benefit of 2-GeV beam.)

Enhanced IMF production by 2 GeV ^{3}He beam

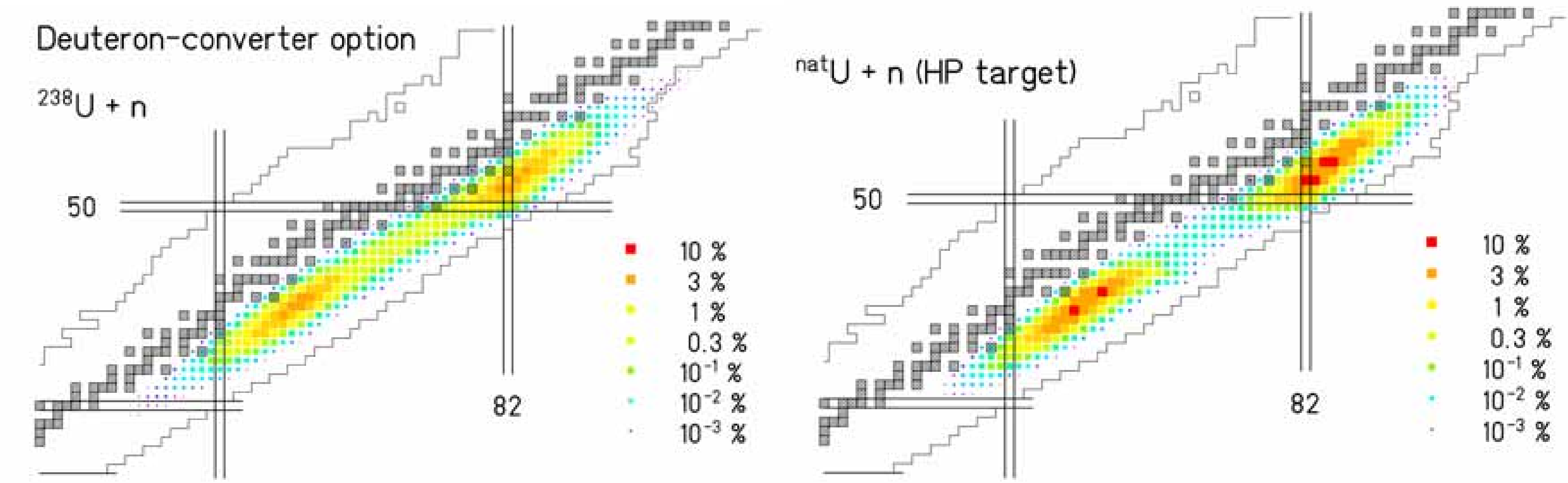


Calculations with INCL/ABLA

Production of neutron-rich IMF from ^{238}U enhanced by higher beam energy.

(Again: Beam-power limitation reduces benefit of 2-GeV ^{3}He beam.)

Deuteron-converter option



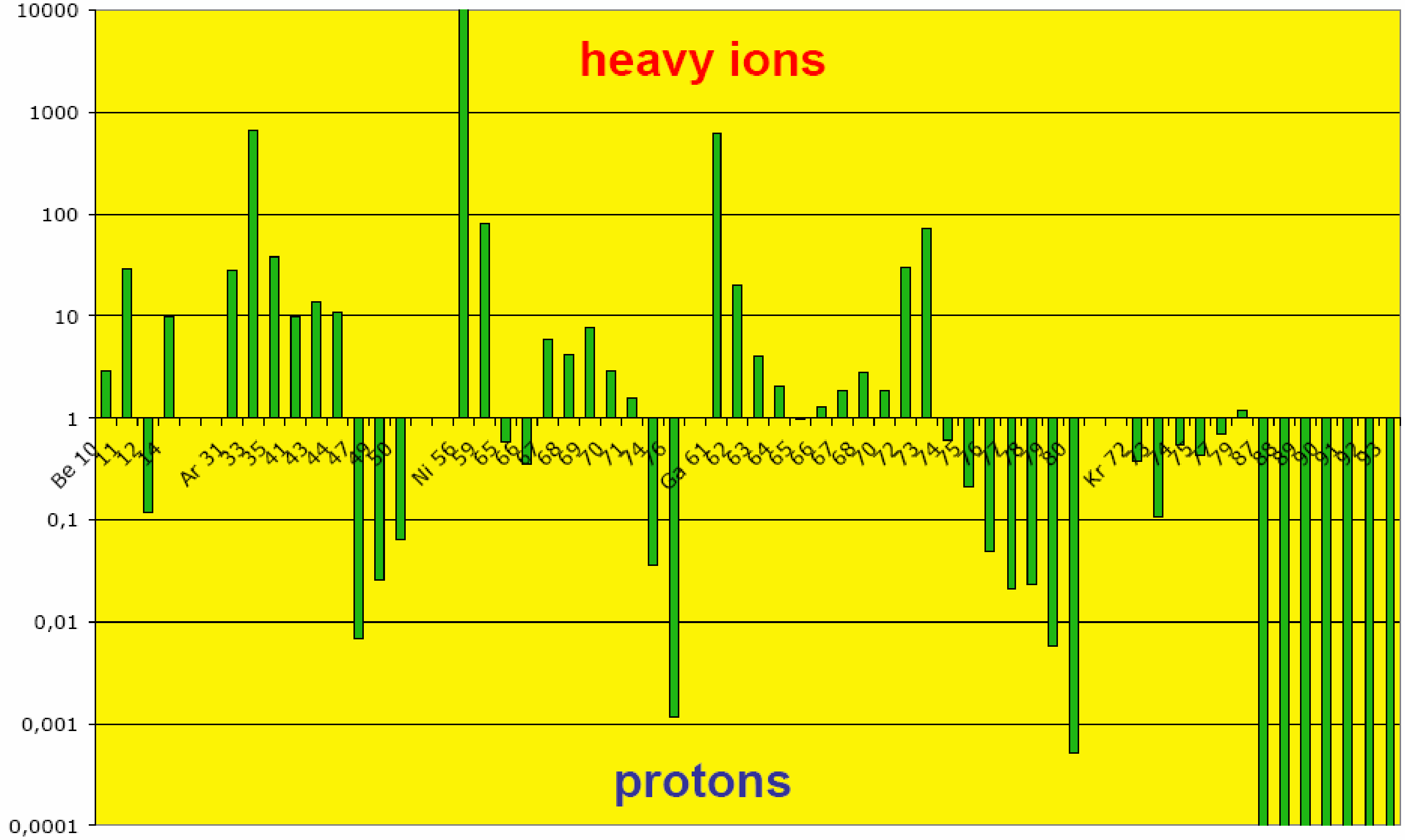
Calculations with ABRABLA

Deuteron option provides enhanced production for symmetric and extremely asymmetric fission.

Deuteron-converter option (example)
50 MeV deuterons
5 mA ($3 \cdot 10^{16}$ / s)
heat in converter target: 200 kW
fission rate: ≈ 10^{14} / s
heat in production target: 3 kW

High-power target (EURISOL)
1 GeV protons
3-4 mA ($2 \cdot 10^{16}$ / s)
heat in converter target : 3-4 MW
fission rate: ≈ 10^{16} / s
heat in production target: 4 x 70 kW

Converter-catcher - ISOL scenario using heavy ions



Calculations by Mittig, Villari for HI option in target and ion-source group.

Benefit for neutron-deficient isotopes of light elements.

Converter-catcher - ISOL scenario using heavy ions

Projectile	*E/A [MeV]*	*I [mA]*	*R [%]*						
			28 A MeV	43 A MeV	100 A MeV	150 A MeV	166.5 A MeV	333 A MeV	500 A MeV
B, C, O	333	1	~ 1	~ 2	8 – 13	16 – 24	20 – 28	**50 – 65**	73 – 86
Ar	333	0.5	~0.5	~ 1	~ 7	~ 13	~ 15	**~ 40**	~ 63
Ca	166.5	0.5	~ 0.5	~ 1	~ 5	~ 11	**~ 13**	~ 35	~ 55
Ni	166.5	0.4	~ 0.5	~ 1	~ 5	~ 10	**~ 12**	~ 32	~ 53
Zn, Ge, Se, Kr, Ag	166.5	0.3	~ 0.5	~ 1	~ 5	9 – 10	**11**	~ 30	~ 50
Sn, Te, Xe, Ce	166.5	0.2	~ 0.5	~ 1	~ 4	~ 8	**~ 10**	~ 27	~ 45

R: Range of the projectile -> scaling of usable target thickness!

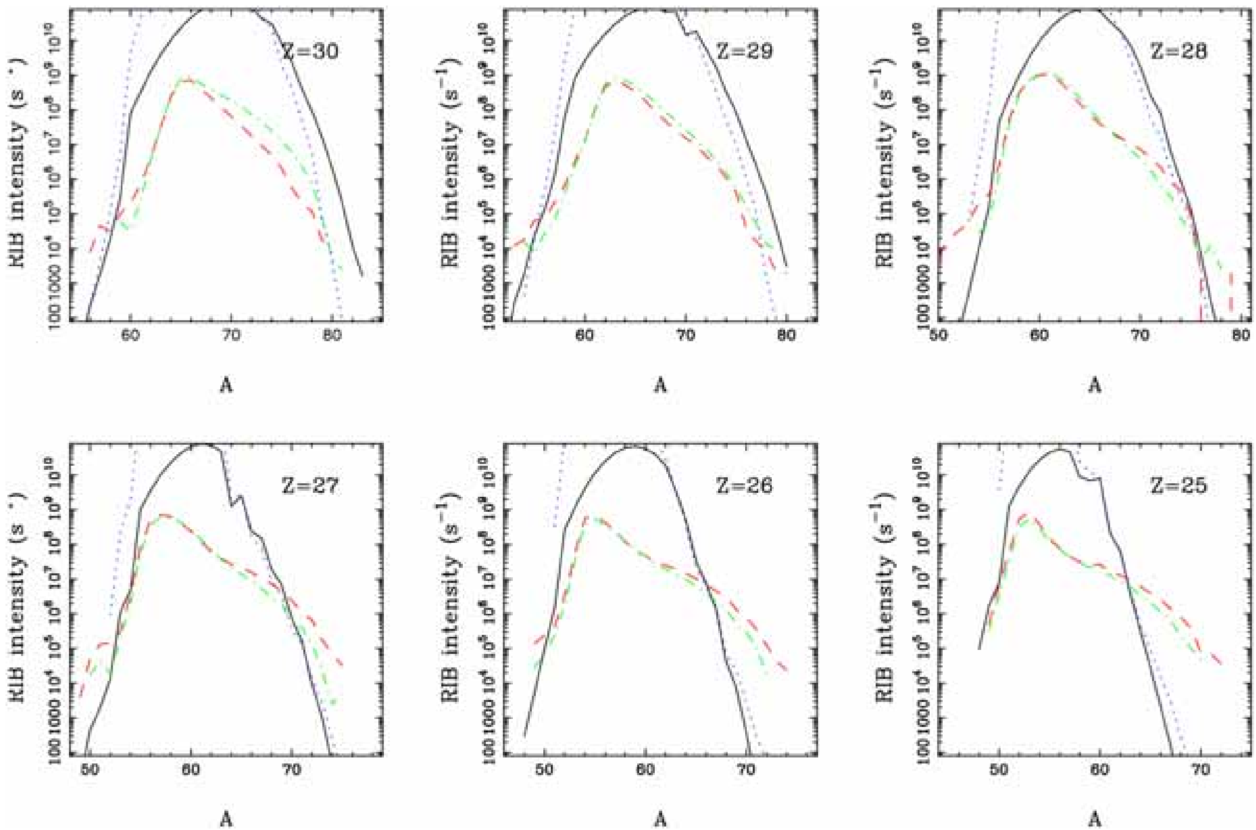
Bold numbers: Calculations by Mittig, Villari (previous figure).

This option requires heavy ions with high energies (→ expensive!).

Benefit only for light proton-rich nuclei (→ physics interest?)

Extraction from target not fully developed.

Heavy-ion reactions at Fermi energy



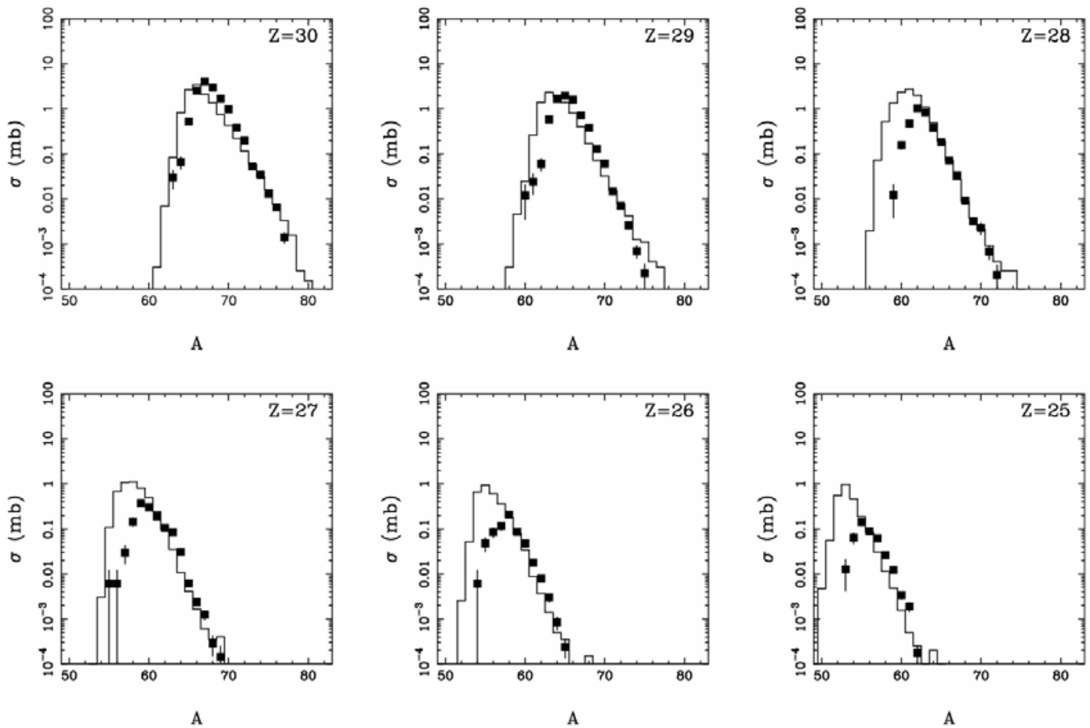
^{86}Kr + ^{64}Ni
^{82}Se + ^{64}Ni
E = 25 *A* MeV
I = 1 pμA

^{238}U + p
E = 1 GeV
I = 100 pμA

Calculations by M. Veselsky.

Calculation: benefit for extremely neutron-rich isotopes of light elements.

Heavy-ion reactions at Fermi energy (x sections)



^{86}Kr + ^{64}Ni
***E* = 25 *A* MeV**

Production inside 3 degrees.

Comparison of experimental data with model calculations.

Data and calculations by M. Veselsky.

Experiment does not extend far enough to confirm calculated benefit.
Highly relevant for fragmentation of neutron-rich ISOL beam (^{132}Sn)!

Conclusions

- **2 GeV ^{3}He beam fills gaps in the masses far below available targets. (typical gain factor 3 to 5)**
- **2 GeV ^{3}He beam enhances production of neutron-rich IMFs. (typical gain factor 5)**
- **Deuteron-converter option yields wider nuclide distribution compared to 1-GeV proton converter-target option. (enhanced yields at symmetry and extreme mass-asymmetry)**
- **Converter-catcher - ISOL scenario using heavy-ions separates heat load, provides projectiles where ISOL targets are not available, and allows higher production of light neutron-deficient nuclides. (expensive, physics interest?, extraction?)**
- **Heavy-ion reactions (deep-inelastic transfer) at Fermi energies (20 to 30 *A* MeV) provides benefit for neutron-rich isotopes with Z < 30. (Benefit in extreme wing of distribution predicted by model calculation.) Importance for choice of optimum energy in fragmentation of n-rich ISOL beam!**

(This report is available on **EURISOL WEB**, other publications on **www.gsi.de/charms**.)