Key aspects for the production of the ideal actinide target for the production of superheavy elements

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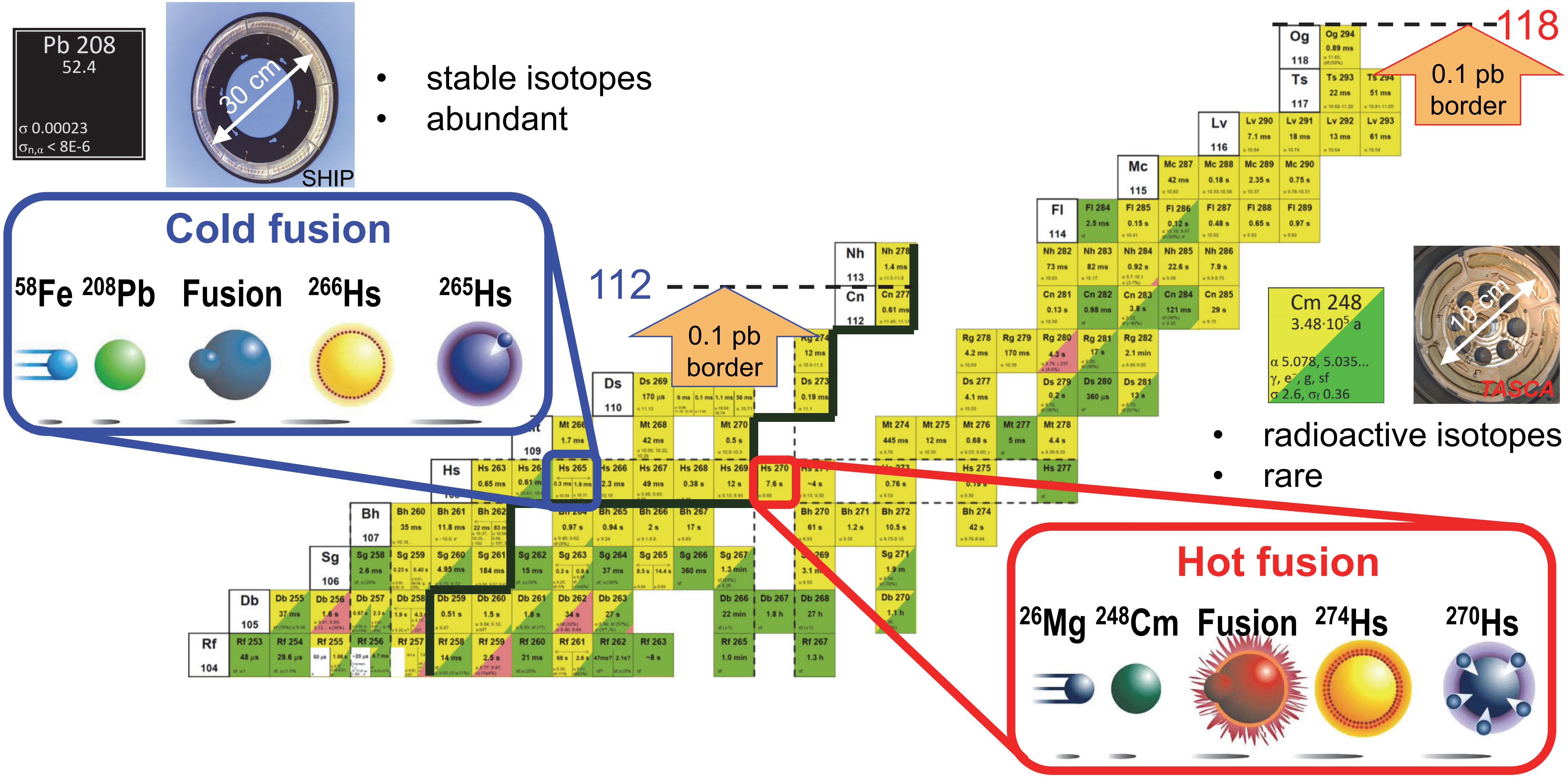
Production of the heaviest elements

Pb 208
52.4
σ 0.00023
$\sigma_{n,\alpha} < 8E-6$

- stable isotopes
- abundant



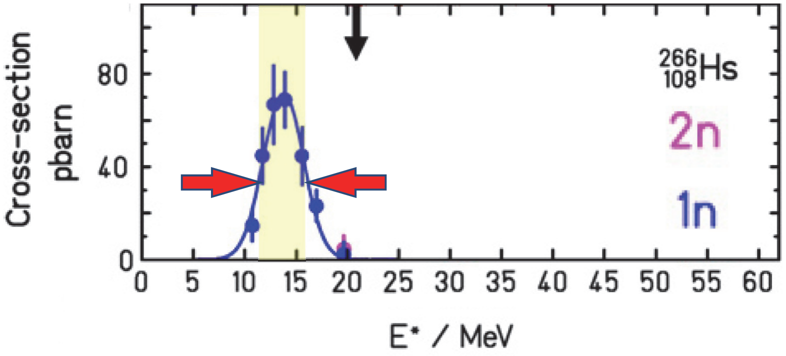
- radioactive isotopes
- rare

Excitation functions

- Considerations limited to those of isotope production
- Neglects constraints from, e.g., recoil separator acceptance
- Neglects energy loss of EVR inside target, too

Cold fusion

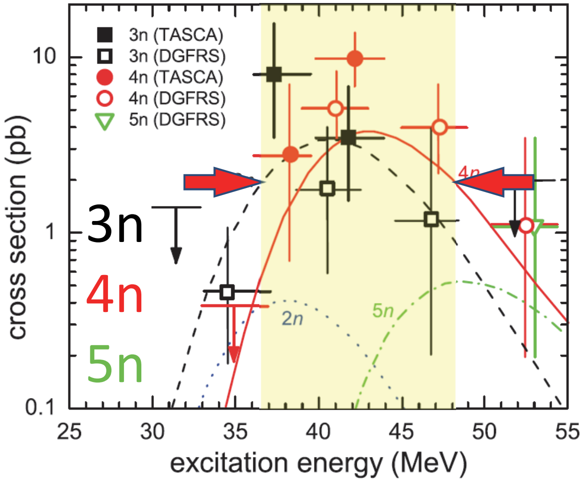
$^{58}Fe + ^{208}Pb \rightarrow ^{266}Hs^{*}$



Hofmann *et al*., Rep. Prog. Phys. 61 (1998) 639

Hot fusion

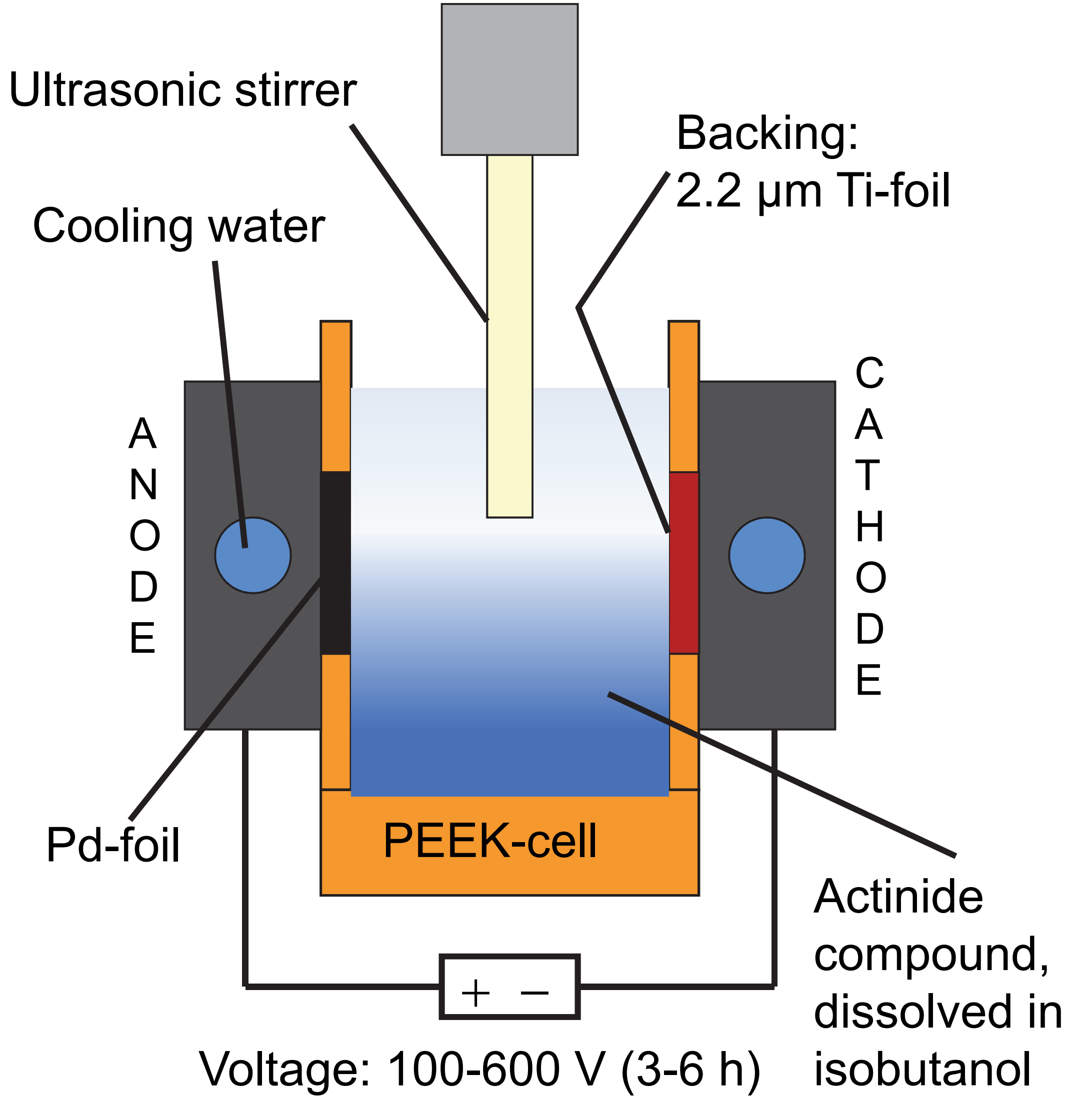
$^{48}Ca + ^{244}Pu \rightarrow ^{292}Fl^{*}$



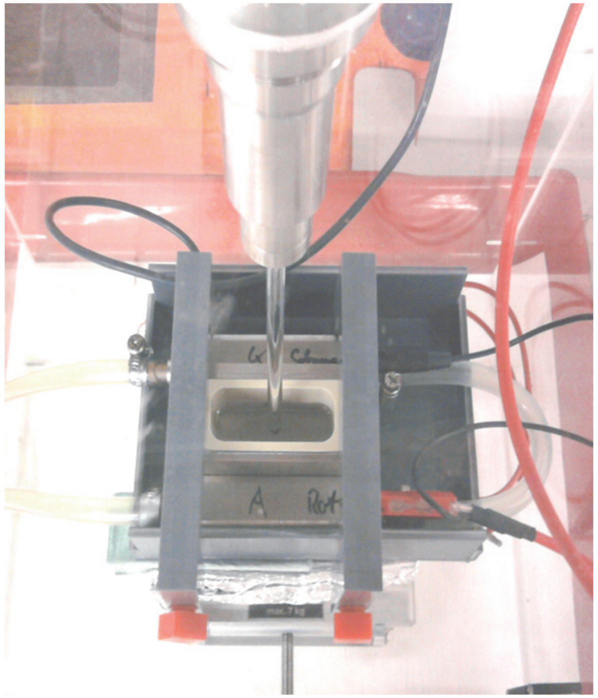
Gates *et al*., Phys. Rev. C 83 (2011) 054618

	Cold fusion		Hot fusion	
Ex. function FWHM / MeV	4.8	(1n)	11.5	(3n + 4n)
E_{lab} range in target / MeV	5.7		13.8	
Optimal areal density / mg·cm^{-2}	0.51	(Pb met.)	1.47	(^{244}Pu as PuO_2)
Typical density / mg·cm^{-2}	0.45	(SHIP)	≤0.84	(DGFRS, TASCA, BGS, GARIS)
Fraction of optimum / %	88		≤57	

Production of actinide targets: molecular plating



Voltage: 100-600 V (3-6 h)



Own studies of MP process:
Vascon *et al.*,
-NIMA 696 (2012) 180
-NIMA 714 (2013) 163
-Appl. Rad. Isot. (2015)
-JRNC 305 (2015) 913

Current process:
Runke *et al.*,
-JRNC 299 (2014) 1081

- Used for 50+ yrs.
- Yields: up to 90%
- Layer thickness up to ≤ 1 mg/cm^2 in a single step
- Chemical composition of layer not fully known

Parker & Falk,
Nucl. Instrum. Meth. 16 (1962) 355

Trautmann & Folger,
Nucl. Instrum. Meth. A282 (1989) 102

Eberhardt *et al.*,
Nucl. Instrum. Meth. A 590 (2008) 134

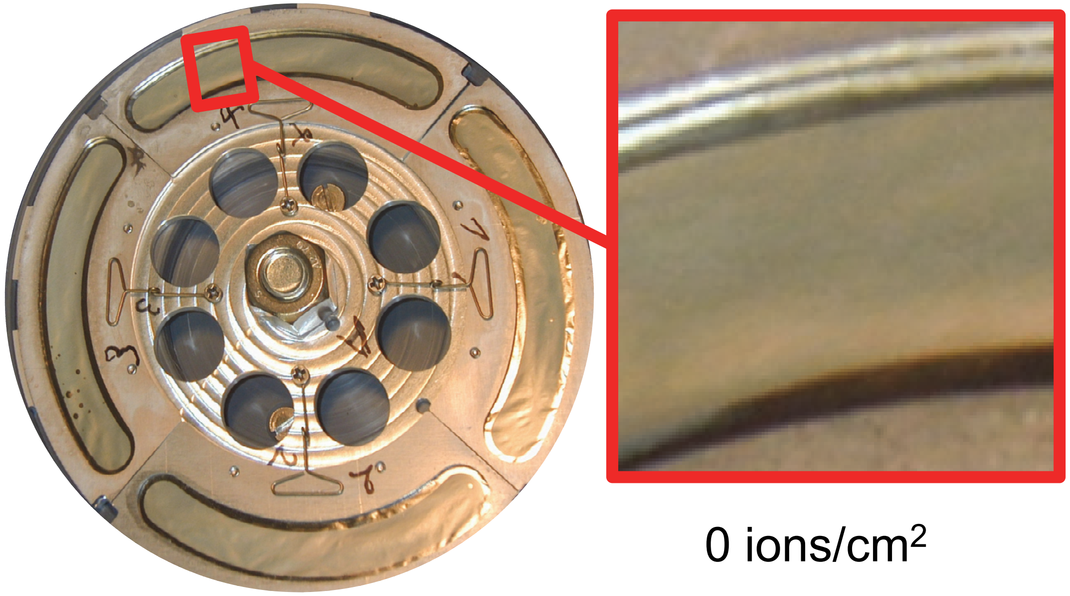
Target irradiation

Jäger et al., J. Radioanal. Nucl. Chem. Nucl. 299 (2014) 1073

TASCA target wheel:

- four segments of $(515\pm52)\ \mu g\cdot cm^{-2}$ ^{249}Cf as Cf_2O_3 (in total 12.4 mg ^{249}Cf)
- wheel diameter: 100 mm. Area: 6 cm^2 per segment

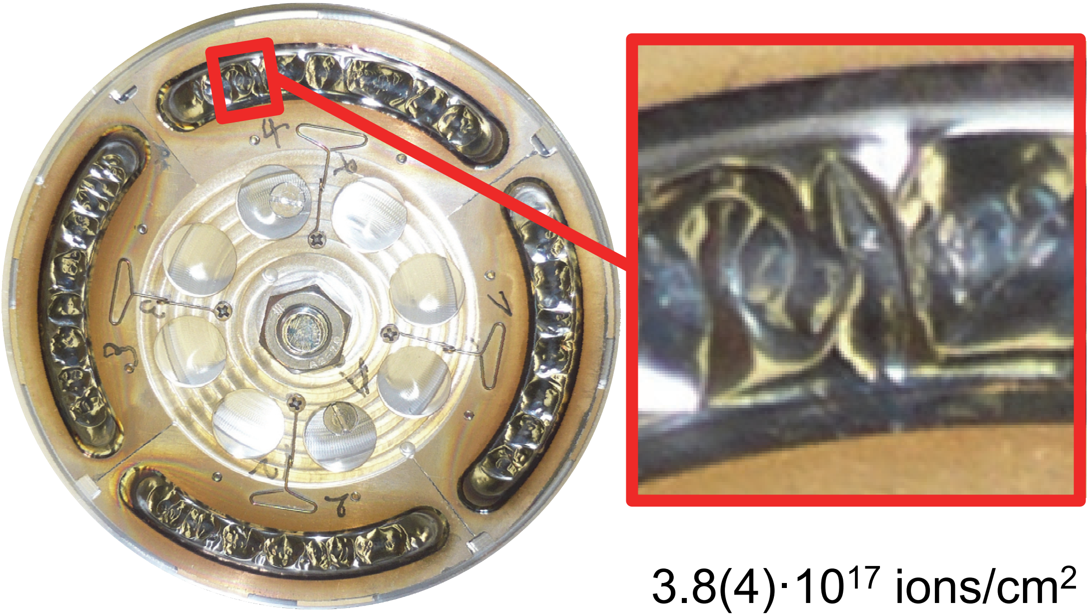
Fresh target



0 ions/cm^2

After irradiation ($9.2\cdot10^{18}$ ^{48}Ca ions)

(intensity: $\approx3\text{-}6\cdot10^{12}\ s^{-1}$ // $\approx0.5\text{-}1.0\ \mu A_{part}$))



$3.8(4)\cdot10^{17}$ ions/cm^2

Runke *et al.*, J. Radioanal. Nucl. Chem. 299 (2014) 1081

Towards the optimum target

The ideal situation

Self-supporting, elementally pure, monoisotopic, ideally thick target

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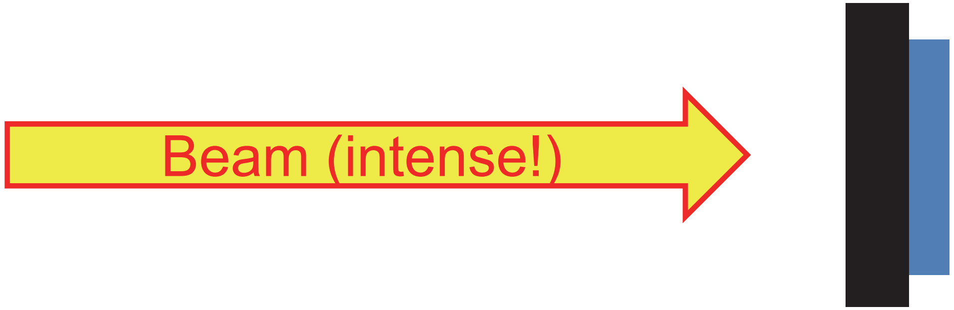
The real situation

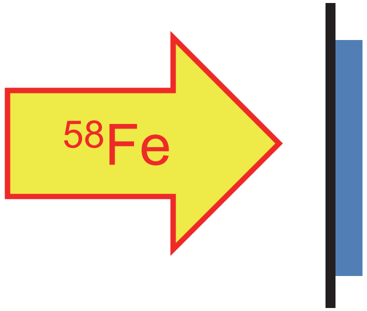


Target backing	→ add. target element	⇒ nuclear reaction byproducts	
	→ energy loss	⇒ target heating	⇒ limits lifetime
	→ energy straggling	⇒ spread in E_{lab} entering target	⇒ limits yield
Chemical compound target	→ add. target elements	⇒ nuclear reaction byproducts	
Contaminants in target	→ add. target elements	⇒ nuclear reaction byproducts	
Finite target thickness			⇒ limits yield

Target heating

Cold fusion

$^{58}\text{Fe} + {}^{208}\text{Pb} \rightarrow {}^{266}\text{Hs}^*$



			dE
Backing	40 μg/cm^2	C	1.2 MeV
Target	450 μg/cm^2	PbS	5.7 MeV
	(380 μg/cm^2	^{208}Pb)	
Total			**6.9 MeV**
			6.9 W·μA$_{\text{particle}}^{-1}$

Further reading:
Lommel *et al.*, Nucl. Instrum. Meth. A 561 (2006) 107
Heßberger, Nucl. Instrum. Meth. B 204 (2003) 59

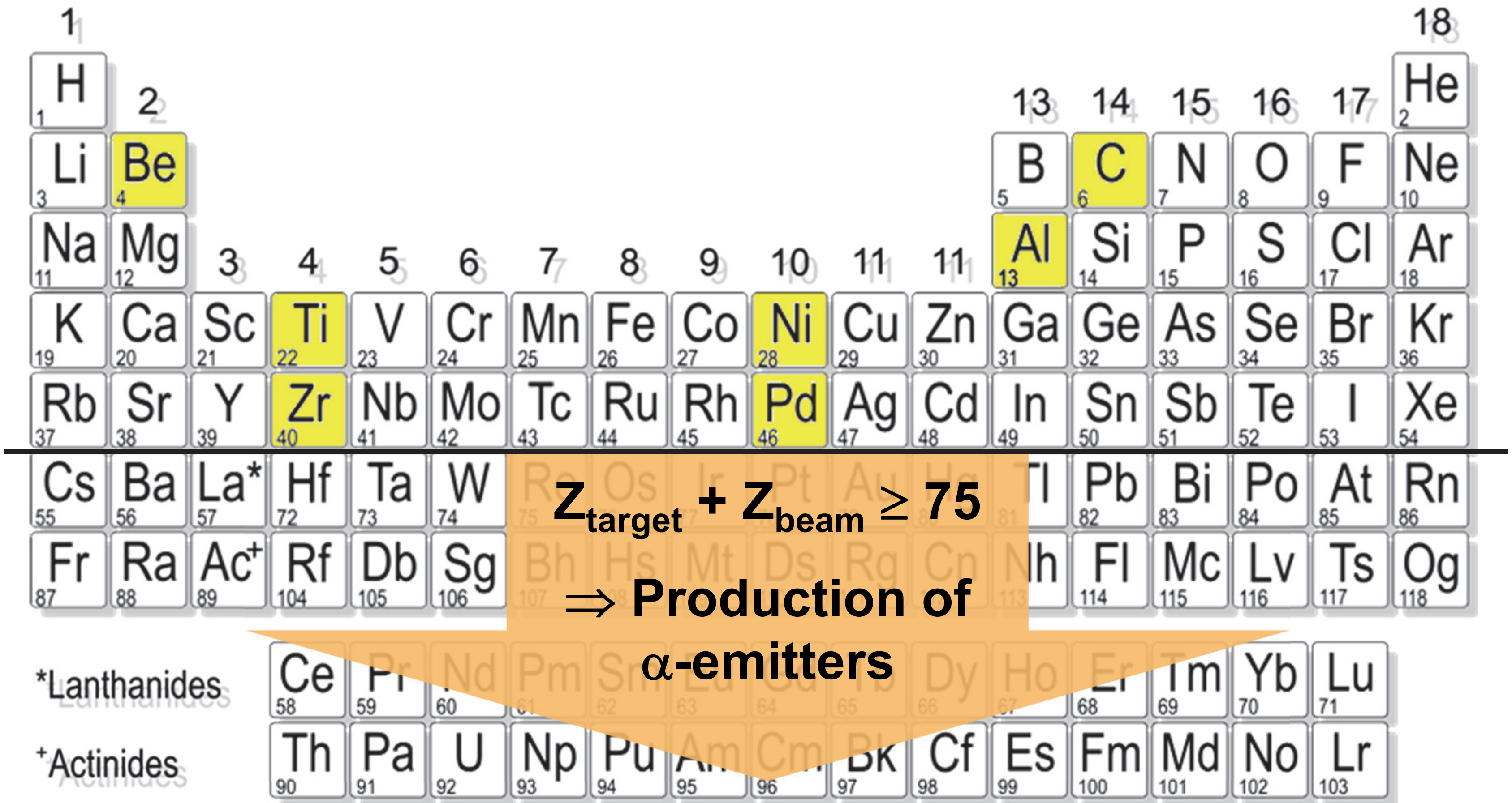
Hot fusion

$^{48}\text{Ca} + {}^{244}\text{Pu} \rightarrow {}^{292}\text{Fl}^*$

			dE
Backing	2.2 μm	Ti	13.4 MeV
Target	900 μg/cm^2	PuO_2	7.3 MeV
	(800 μg/cm^2	^{244}Pu)	
Total			**20.7 MeV**
			20.7 W·μA$_{\text{particle}}^{-1}$

(with 1.5 μm Ti backing: 16.5 MeV)

Classical backings



$Z_{target} + Z_{beam} \geq 75$

$\Rightarrow$ **Production of α-emitters**

Classical backings

Element	dE/dX* (MeV·mg^{-1}·cm^{-2})	typ. Thickness	dE* (MeV)	m_p (°C)	Therm. expansion (μm·m^{-1}·K^{-1})
$_4$Be	17.4	10 μm	32.1	1278	11.3
$_6$C	19.0	40 – 200 μg·cm^{-2} (0.18 – 0.89 μm)	0.8 – 3.8	3500	7.1
$_{13}$Al	15.9	1 μm	8.6	660	23.1
$_{22}$Ti	13.7	1.5 – 2.2 μm	9.3 – 13.6	1660	8.6
$_{28}$Ni	12.7	1 μm	11.3	1453	13.4
$_{40}$Zr	10.4	1 μm	6.8	1852	5.7
$_{46}$Pd	9.8	1 μm	11.8	1552	11.8

* 250 MeV ^{48}Ca

Gas-filled sep.: O_2-traces (commercial He: 0.5 – 5 ppm)

⇒ **Backing destruction via C + O_2 → CO (g) / CO_2 (g)?**

At ***TASCA***: 100-200 mL/min He-flow rate

0.2 L/min, 1 ppm O_2 ⇒ 0.4 mmol O per month

C-backing 100 μg·cm^{-2}: 0.6 mmol C

⇒Use cleanest gas!

Further reading:
Lommel *et al*., Nucl. Instrum. Meth. A 590 (2008) 141

Influence of target thickness (I): Rate of detected Mc EVRs at DGFRS from ^{48}Ca + ^{243}Am

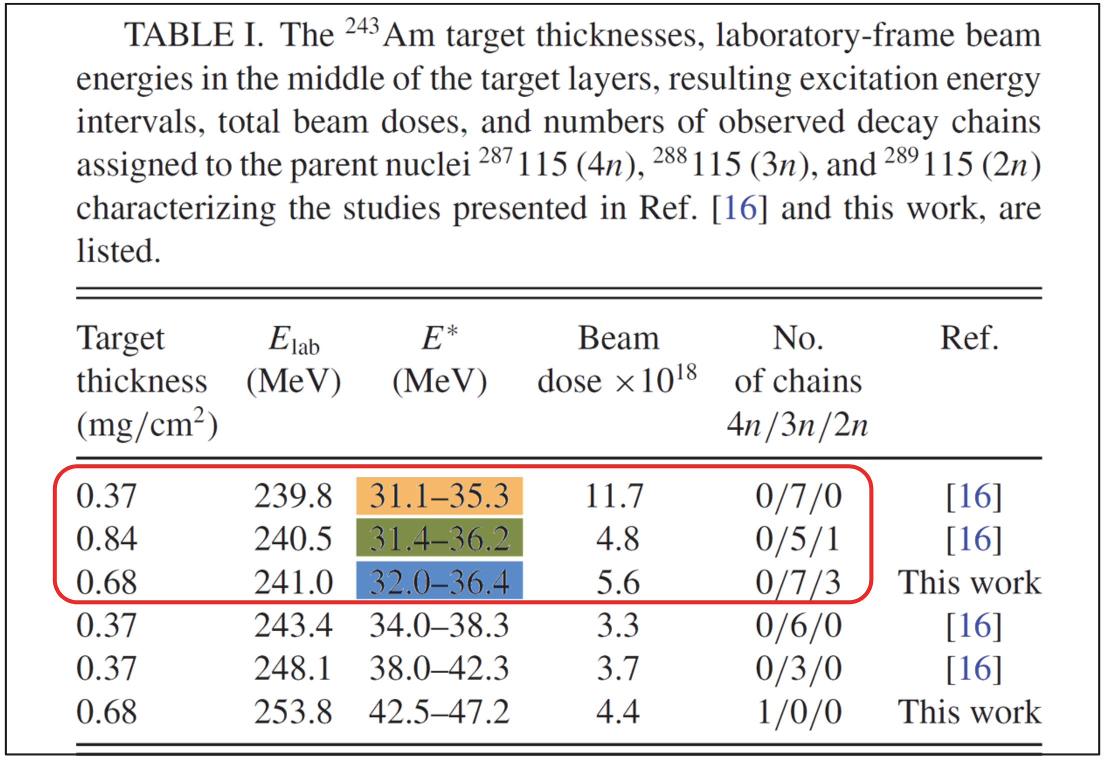
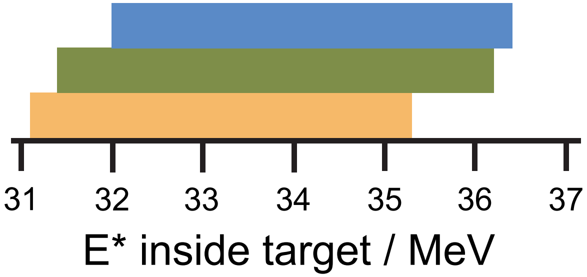


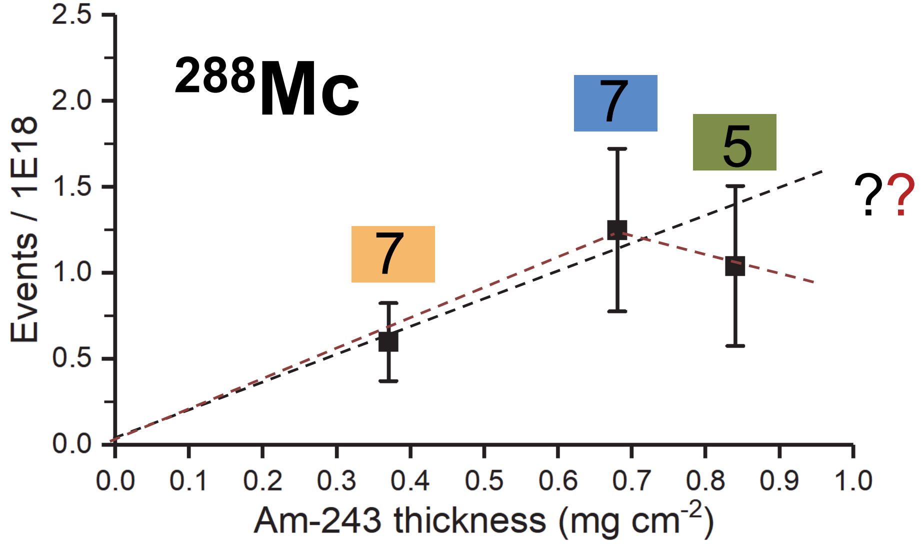
TABLE I. The ^{243}Am target thicknesses, laboratory-frame beam energies in the middle of the target layers, resulting excitation energy intervals, total beam doses, and numbers of observed decay chains assigned to the parent nuclei $^{287}115$ ($4n$), $^{288}115$ ($3n$), and $^{289}115$ ($2n$) characterizing the studies presented in Ref. [16] and this work, are listed.

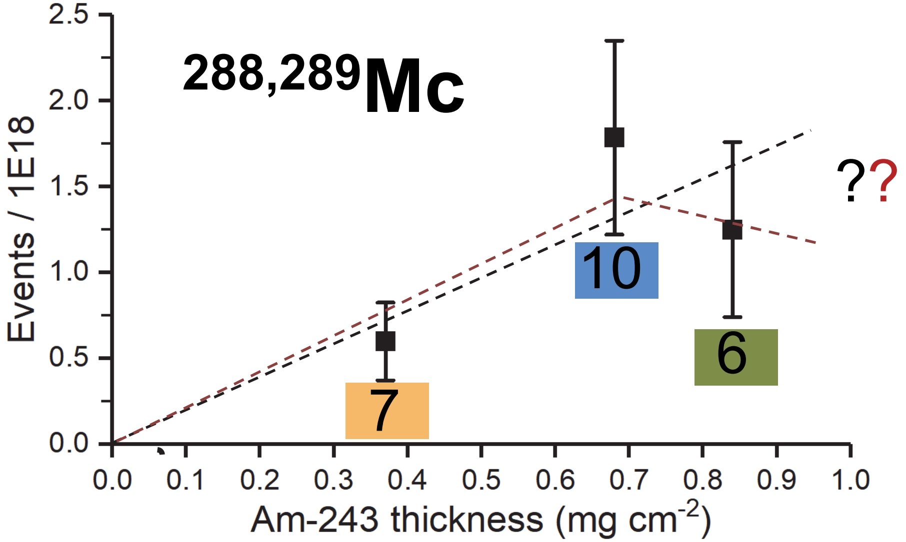
Target thickness (mg/cm^2)	E_{lab} (MeV)	E^* (MeV)	Beam dose $\times 10^{18}$	No. of chains $4n/3n/2n$	Ref.
0.37	239.8	31.1–35.3	11.7	0/7/0	[16]
0.84	240.5	31.4–36.2	4.8	0/5/1	[16]
0.68	241.0	32.0–36.4	5.6	0/7/3	This work
0.37	243.4	34.0–38.3	3.3	0/6/0	[16]
0.37	248.1	38.0–42.3	3.7	0/3/0	[16]
0.68	253.8	42.5–47.2	4.4	1/0/0	This work

Backing: 1.5 μm Ti



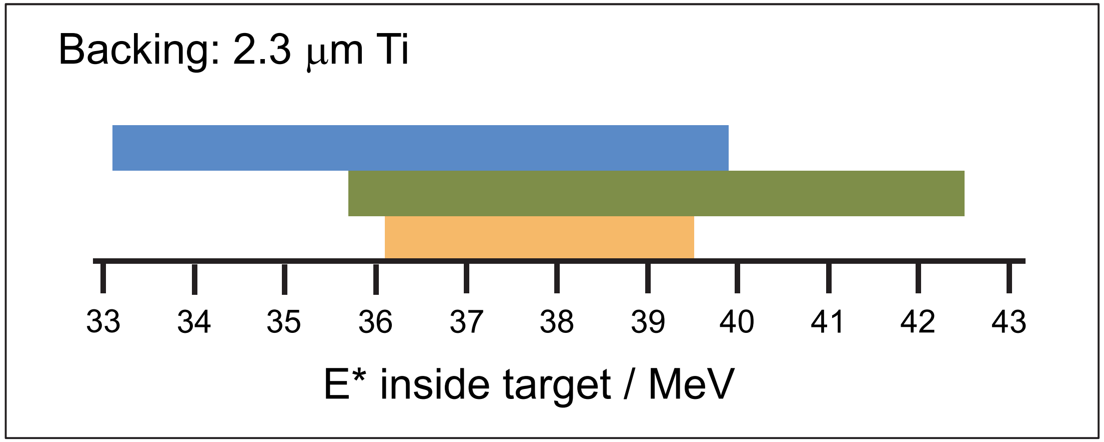
Oganessian *et al.*, Phys. Rev. C 87 (2013) 014302

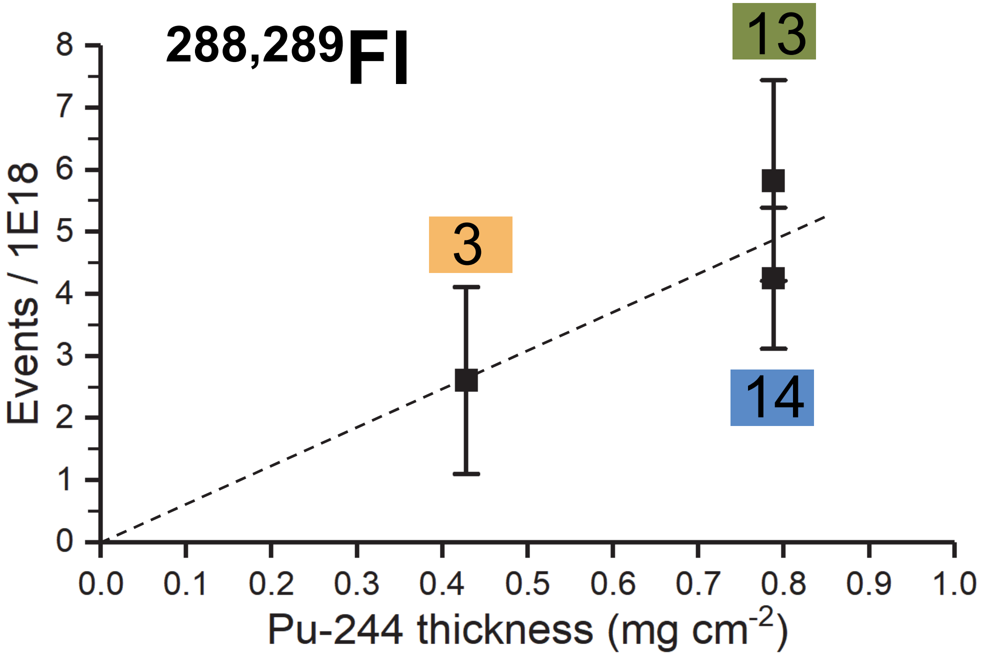




Influence of target thickness (I):
Rate of detected Fl EVRs at *TASCA* from ^{48}Ca + ^{244}Pu

Target thickness ^{244}Pu (mg cm^{-2})	E_{lab} c.o.t. (MeV)	E* (MeV)	Beam does x 10^{18}	No. of chains 4n / 3n	Ref.
0.43	**238.7**	**36.1-39.5**	**1.15**	**2 / 1**	**[1]**
0.79	**240.6**	**35.7-42.5**	**2.23**	**6 / 7**	**[2]**
0.79	**237.4**	**33.1-39.9**	**3.29**	**6 / 8**	**[2]**





[1] Düllmann *et al.*, Phys. Rev. Lett. 104 (2010) 252701
[2] Såmark-Roth *et al.*, Phys. Rev. Lett. 126 (2021) 032503 and to be submitted to Phys. Rev. C

Summary: the way to better (actinide) targets

Overall goal:

Developing target production methods that yield (actinide) films, which

- are sufficiently thick
- do not contain “problem“-contaminants
- adhere to the backing
- are beam-resistant
- can be reprocessed

Next talk by C.-C. Meyer

Our approach:

- Step 1: analyze the MP process
- Step 2: understand what happens to MP layers in beam
- Step 3: improve MP for thicker targets (or develop better methods)
- ….and: don’t forget the backing!

C.-C. Meyer

Ernst Artes

Lauren Reed

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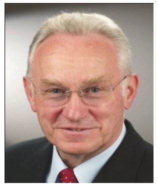
Mainz target makers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Discussions

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- B. Lommel
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- D. Rudolph