A New Method for β-Delayed Neutron-Emission Probability Measurements

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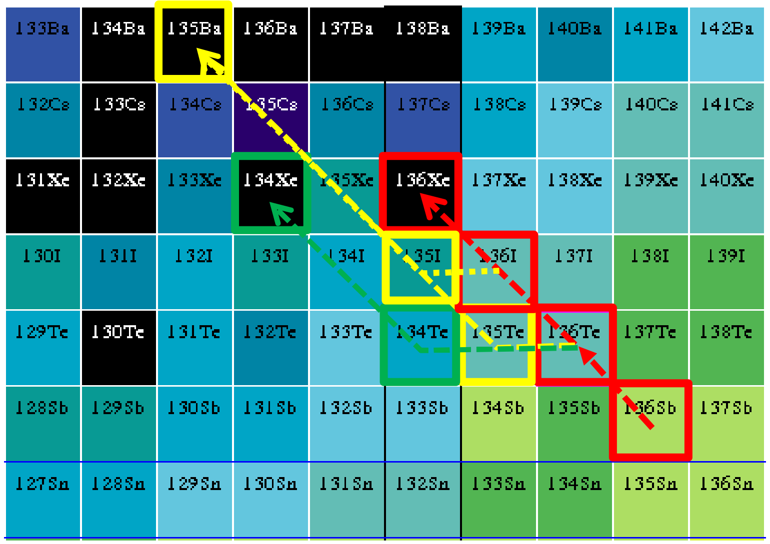
Abstract

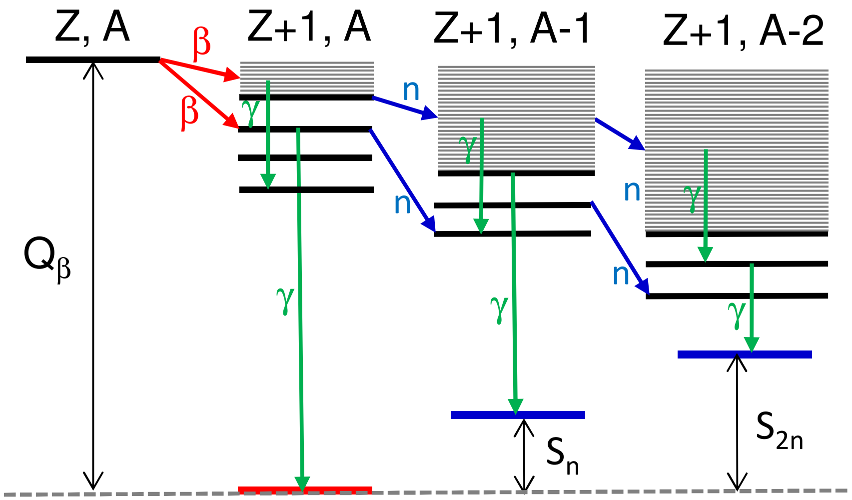
- We propose a new method for measuring **β-delayed single- and multi-neutron emission probabilities** ($\mathbf{P_{xn}}$) (and also **mass**, **Q-values** and $\mathbf{T_{1/2}}$), in the following way:
  - Use in-flight separated fission fragments from the FRS
  - Implant and store them in the Cryogenic Stopping Cell (CSC) for decay
  - Identify and count the precursors and decay daughters simultaneously with the MR-TOF-MS
- Method is **direct**, **essentially background free**, **model independent** and **complementary** to worldwide programs
- Especially suited for **multi-neutron** emission probabilities (x>1)
  - First measurements of n-rich fission fragments
  - Extended measurements towards neutron drip line and N~126 region

Motivation for βxn measurements (1/2)

- **r-process nucleosynthesis**[1]
  - Detours in β-decay chains
  - More neutrons during freeze-out
- **Nuclear physics models**[2]
  - Calculations of n-γ competition
  - Optical models for neutron transmission in the nucleus
  - Nuclear energy level schemes
- **Nuclear reactor operation**[3]
  - Next generation reactors
  - New fuel types
  - Accelerator Driven Systems
- **Worldwide βxn programs**[3]
  - Mostly using n, β, γ detectors
  - Usually no direct recoil identification



133Ba	134Ba	135Ba	136Ba	137Ba	138Ba	139Ba	140Ba	141Ba	142Ba
132Cs	133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	139Cs	140Cs	141Cs
131Xe	132Xe	133Xe	134Xe	135Xe	136Xe	137Xe	138Xe	139Xe	140Xe
130I	131I	132I	133I	134I	135I	136I	137I	138I	139I
129Te	130Te	131Te	132Te	133Te	134Te	135Te	136Te	137Te	138Te
128Sb	129Sb	130Sb	131Sb	132Sb	133Sb	134Sb	135Sb	136Sb	137Sb
127Sn	128Sn	129Sn	130Sn	131Sn	132Sn	133Sn	134Sn	135Sn	136Sn



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[1] R. Surman et al., JPS Conf. Proc. , 010010 (2015)

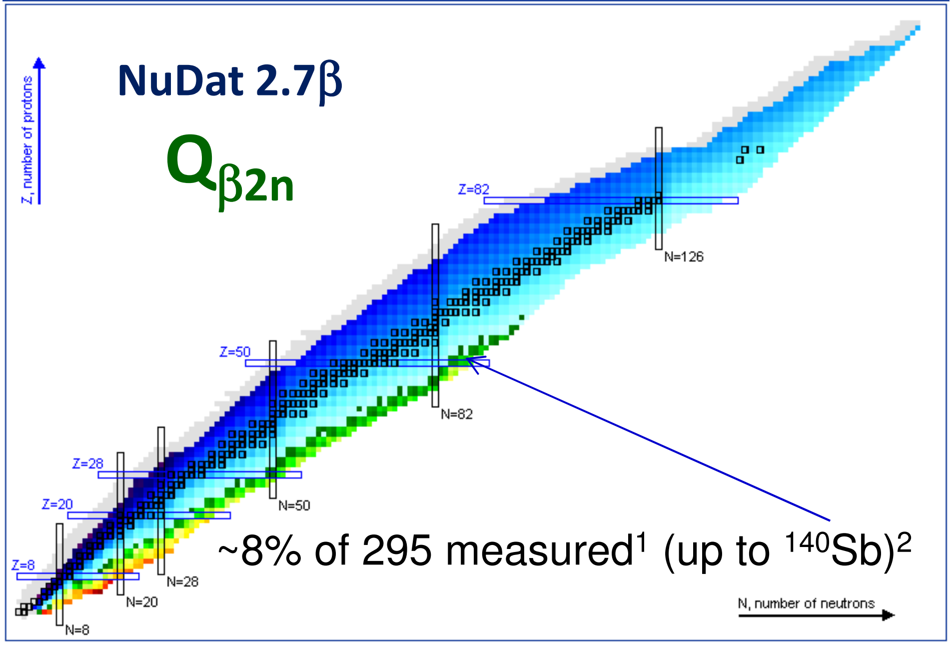
[2] M. R. Mumpower et al., Physical Review C 94, 064317 (2016)

[3] IAEA CRP on a Reference Database for Beta-Delayed Neutron Emission (2013-2017)

Motivation for βxn measurements (2/2)

Limited P_{xn} data (x>1)

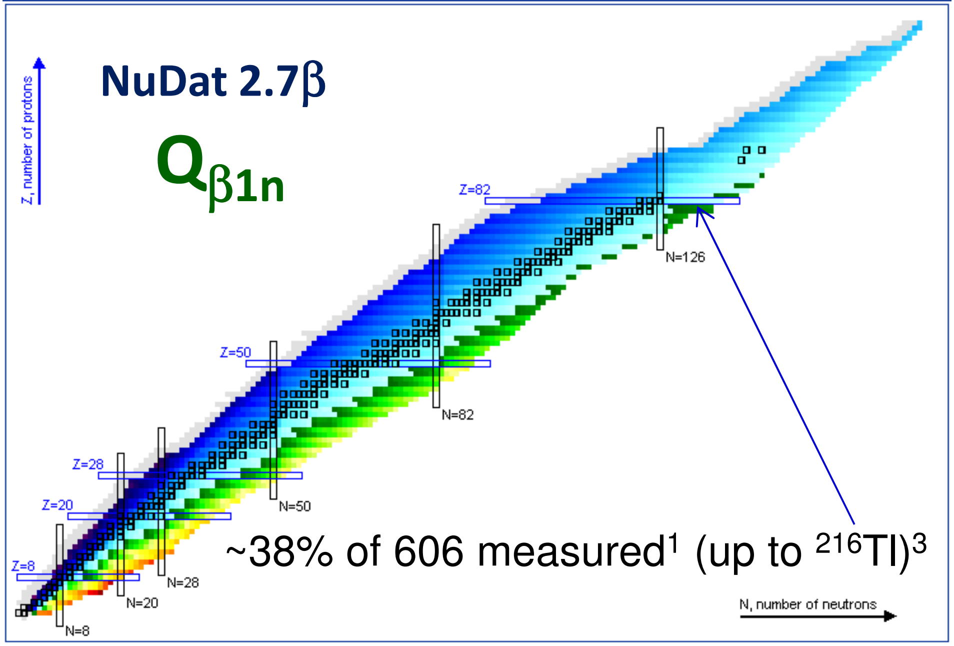
- Only **3(!) P_{2n}** values appear in data bases in fission fragment region: **^{86}Ga, ^{98}Rb, ^{100}Rb**
- **P_{2n}(^{136}Sb)** measurements (β2n coincidence) at TETRA@ALTO (2011) and BELEN@JYFL (2014)
- **P_{2n}(^{140}Sb)** published recently (βγ coincidence) at WAS3ABi+EURICA@RIKEN (2017)



NuDat 2.7β

$Q_{\beta 2n}$

~8% of 295 measured[1] (up to ^{140}Sb)[2]



NuDat 2.7β

$Q_{\beta 1n}$

~38% of 606 measured[1] (up to ^{216}Tl)[3]

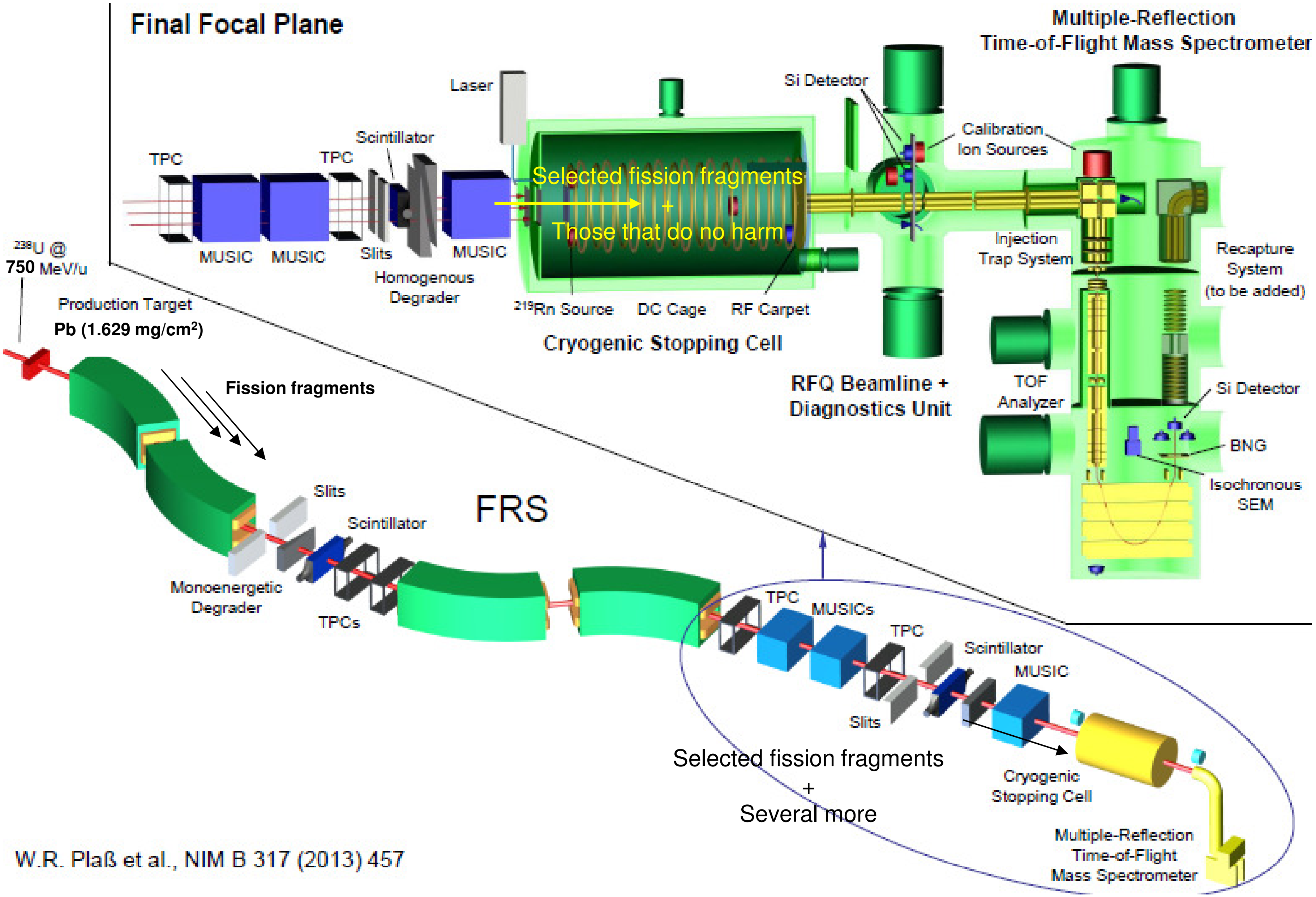
[1] I. Dillmann et al., AIP Conference Proceedings 332 ,1594 (2014)

[2] B. Moon et al., Phys. Rev. C , 95, 044322 (2017)

[3] R. Caballero-Folch et al., Phys. Rev. Lett. , 117, 012501 (2016)

- Given the importance of P_{xn} measurements, it is worthwhile to pursue a complementary method, which relies on direct identification and counting of βxn decay daughter isotopes

Method Overview (1/3)

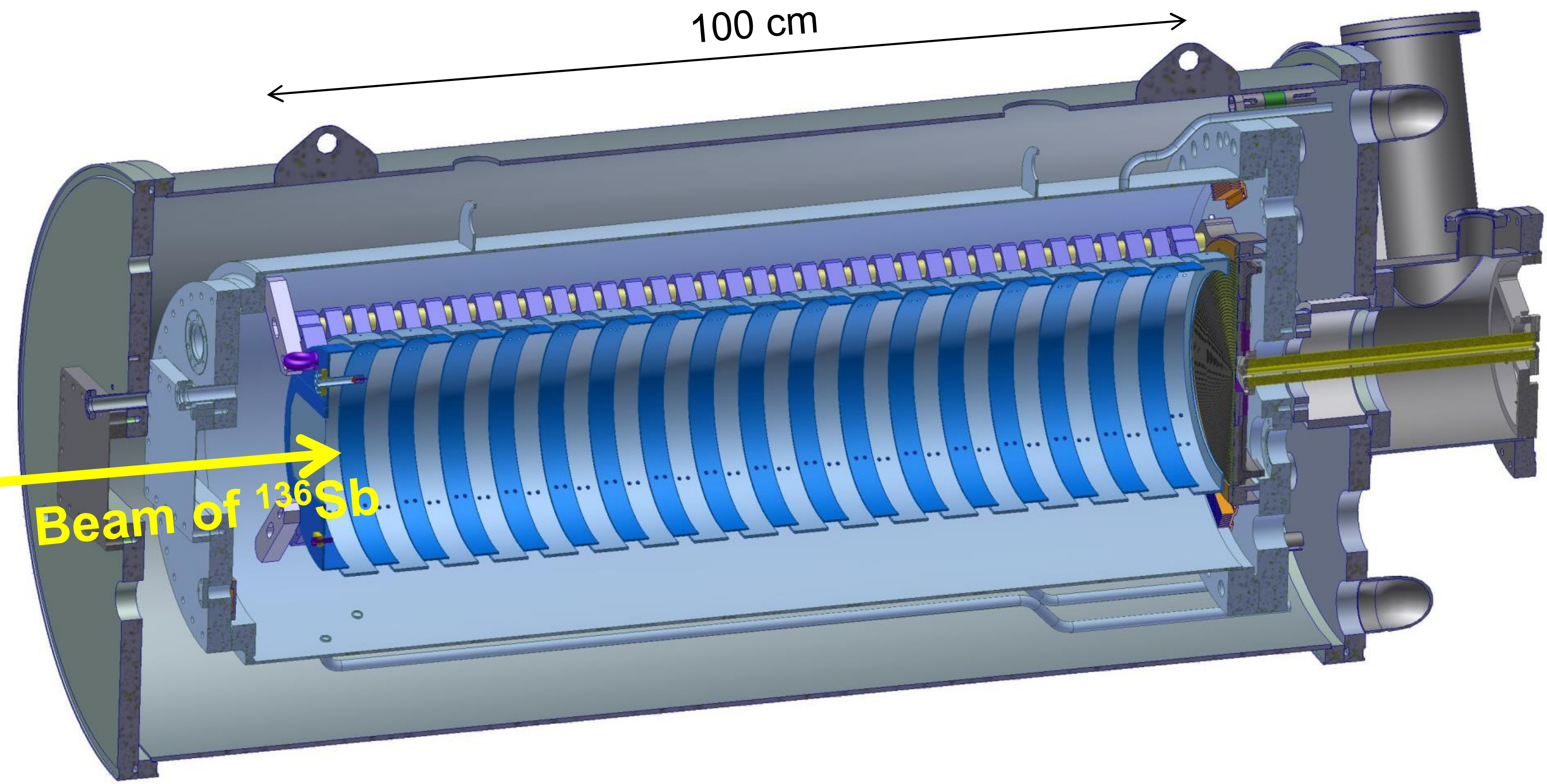


Selected fission fragments
+
Those that do no harm

Selected fission fragments
+
Several more

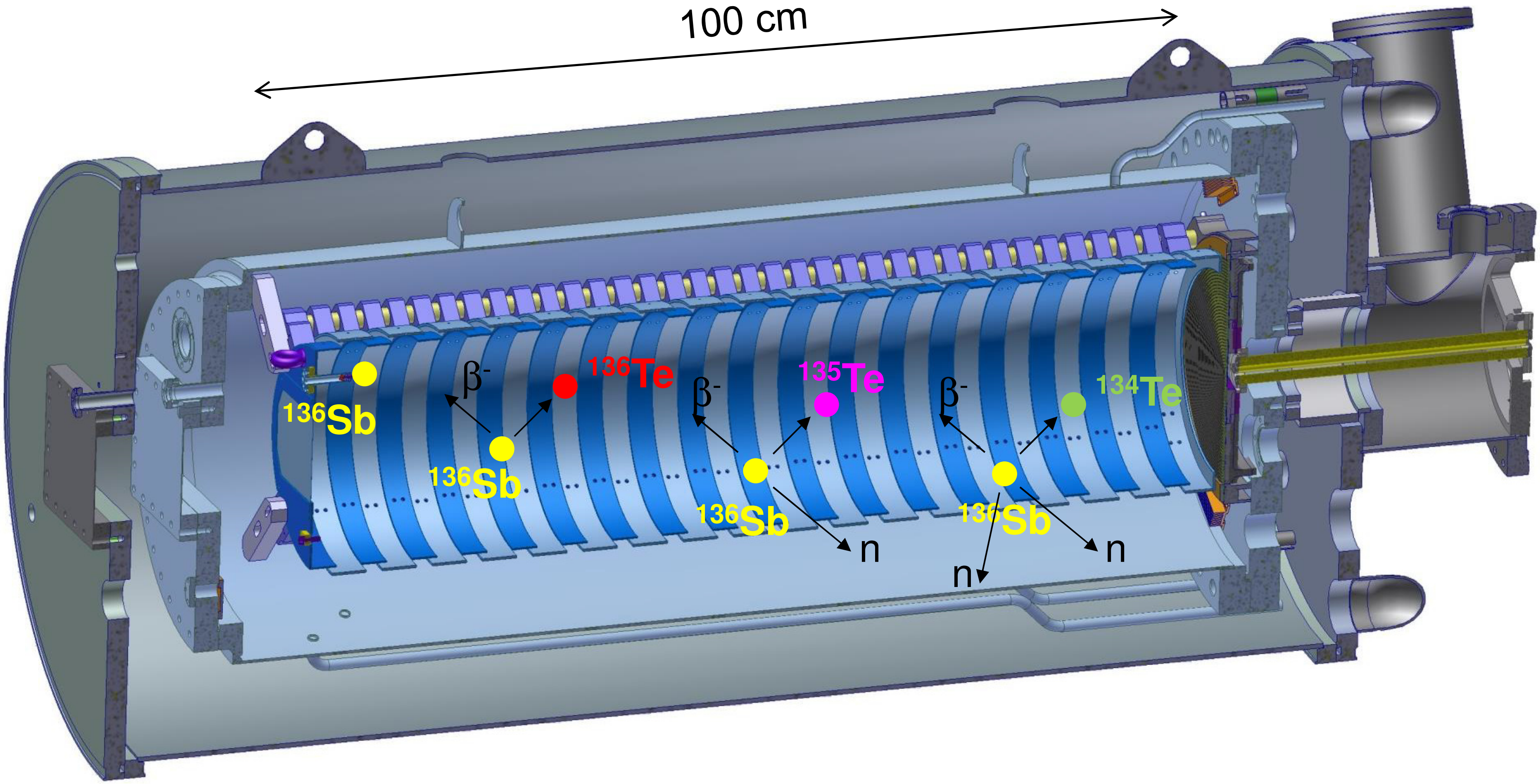
W.R. Plaß et al., NIM B 317 (2013) 457

Method Overview (2/3)



- Precursor beam implantation for 5-10 msec, at a selected frequency (1 Hz or less)
- Between beam spills, precursors decay according to open branches and P_{xn} values (x=0,1,2)
- Before next beam spill, precursors and decay daughters are extracted towards MR-TOF-MS

Method Overview (2/3)



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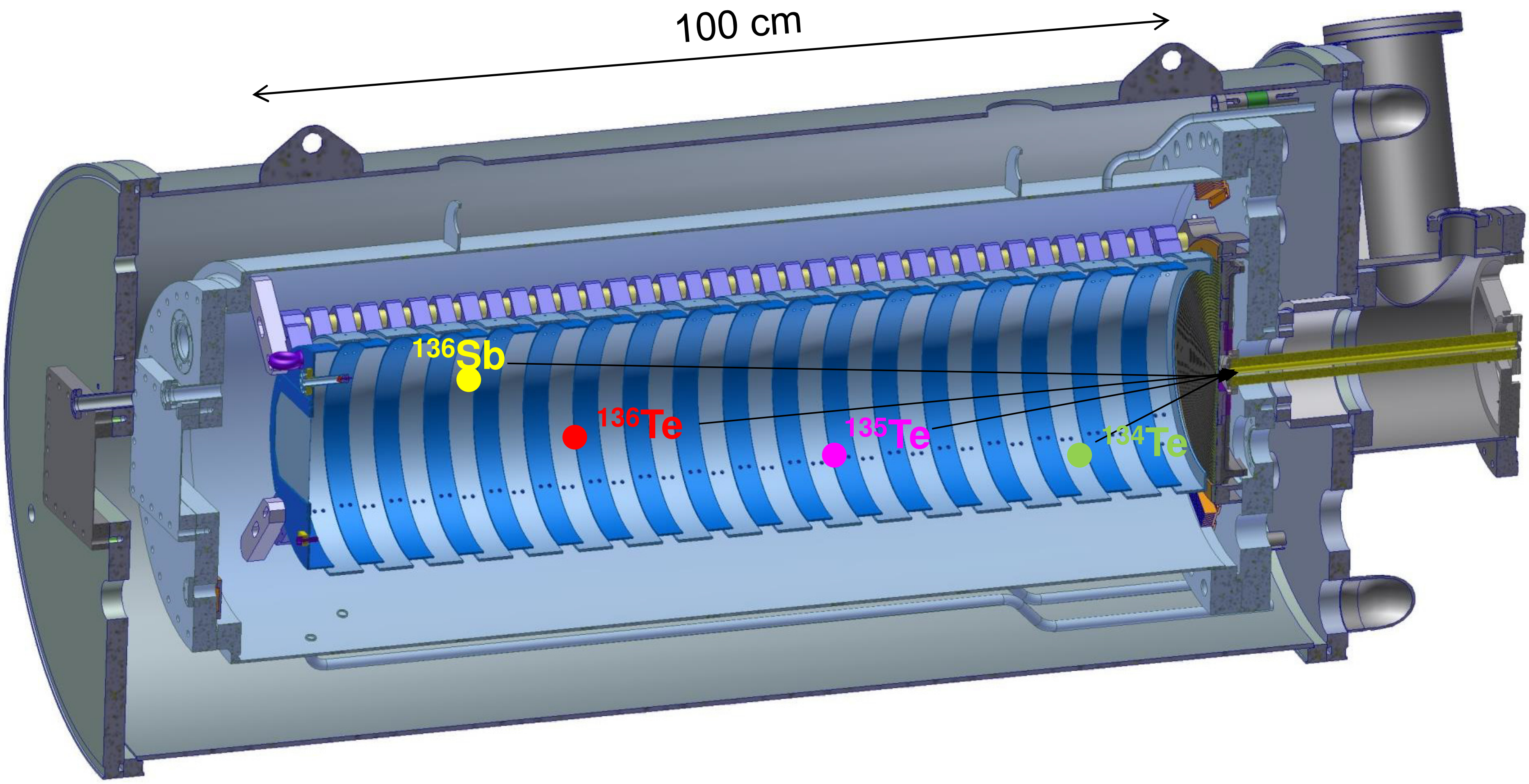
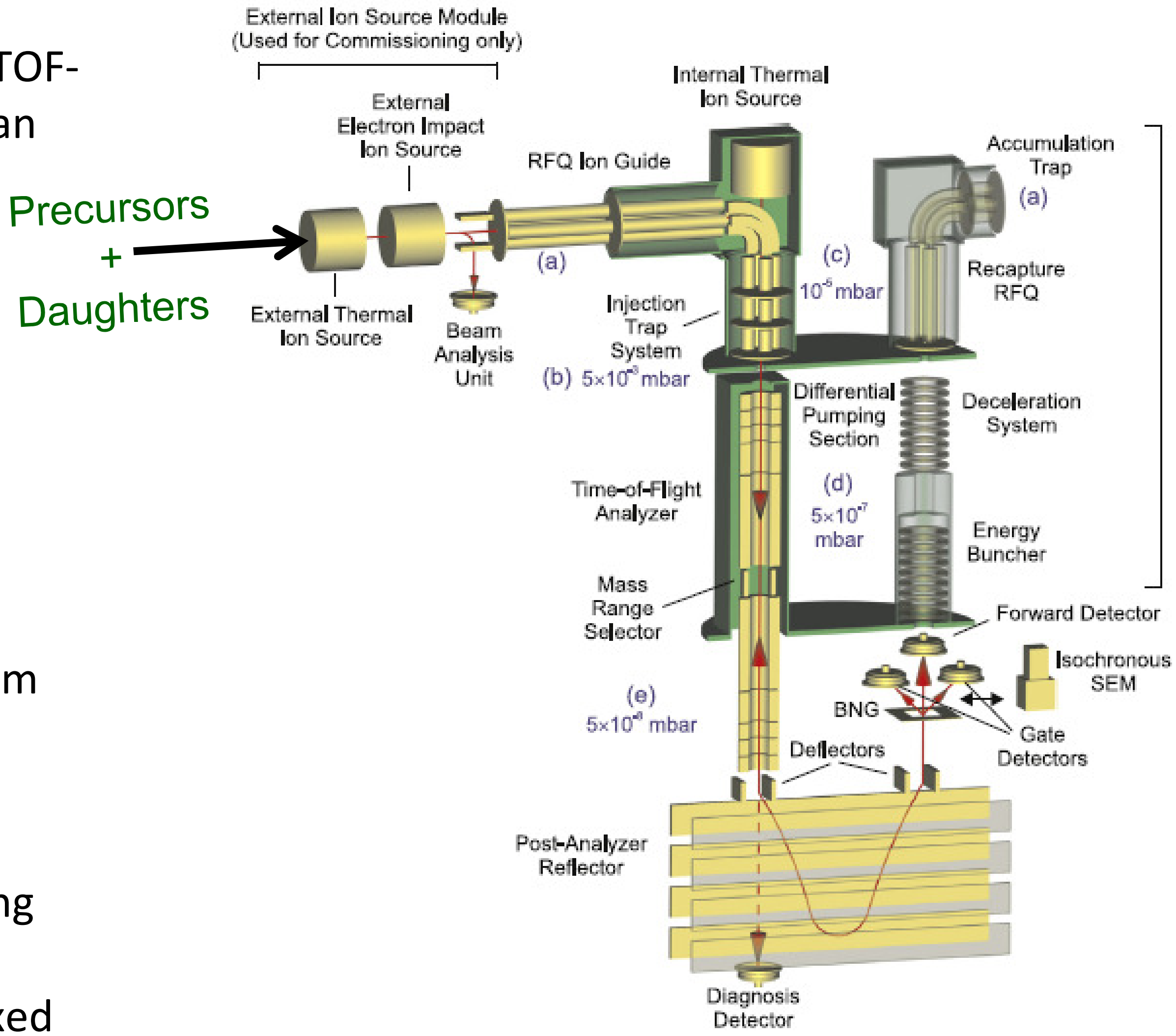
Method Overview (2/3)



- Precursor beam implantation for 5-10 msec, at a selected frequency (1 Hz or less)
- Between beam spills, precursors decay according to open branches and P_{xn} values (x=0,1,2)
- Before next beam spill, precursors and decay daughters are extracted towards MR-TOF-MS

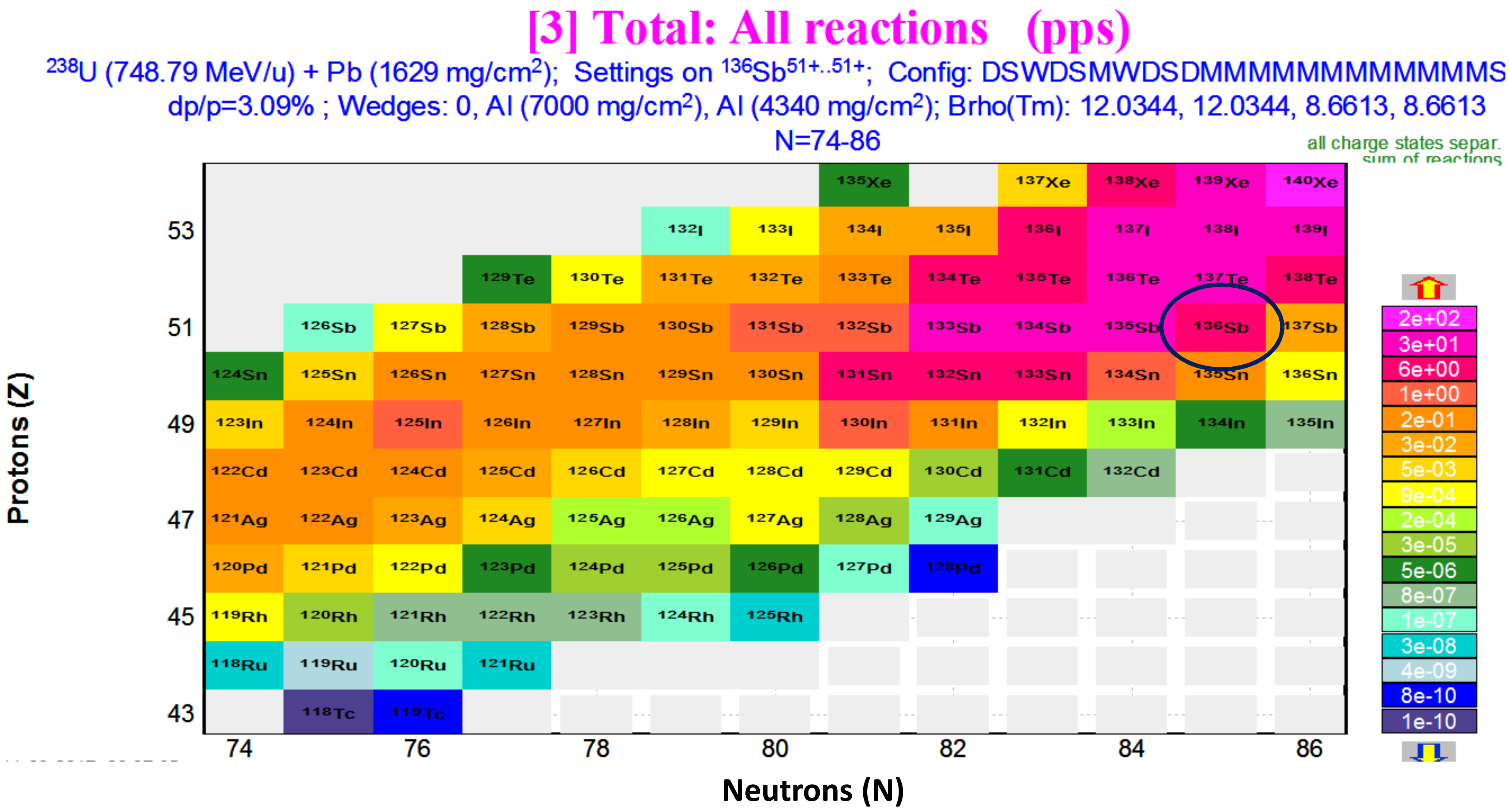
Method Overview (3/3)

- Recoils (and the precursors) are identified and counted by their masses via the Ion Catcher MR-TOF-MS (isobars and even isomers can be resolved within 10’s ms)
- $\mathbf{P_{xn} = N_{xn}/(N_{0n}+N_{1n}+\ldots+N_{xn})}$ where N_{xn} is the amount of βxn decay daughters
- **Masses** will be measured by MR-TOF-MS
- $\mathbf{Q_{\beta xn}}$ for all **x** will be inferred from precursor and decay daughters mass differences
- $\mathbf{T_{1/2}}$ can be deduced from varying CSC containment times, or from precursor-daughter ratios for fixed containment times



T. Dickel et al., NIM A 777, 172 (2016)

Implant precursors in CSC (1/3)



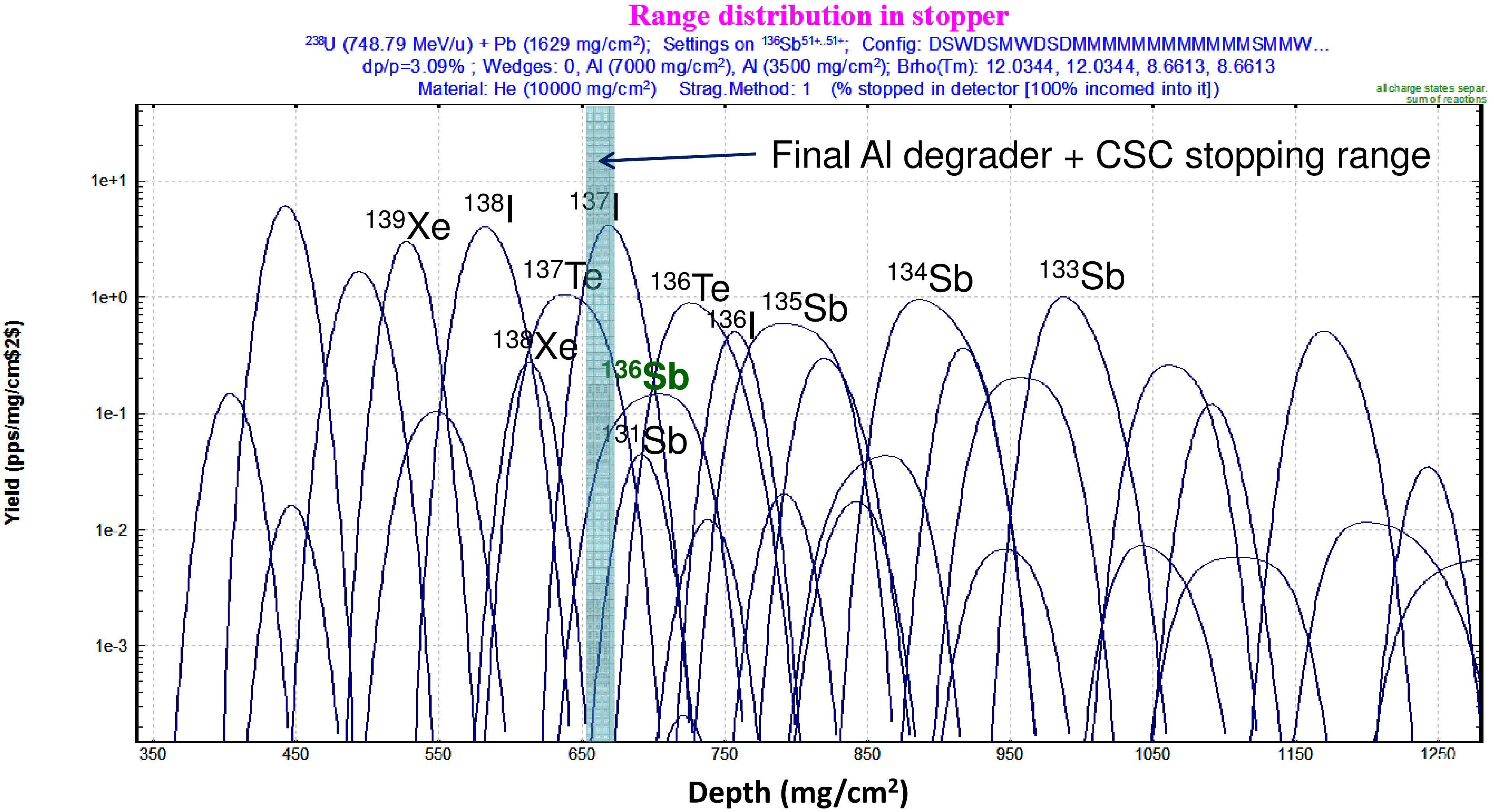
[3] Total: All reactions (pps)

^{238}U (748.79 MeV/u) + Pb (1629 mg/cm^2); Settings on ^{136}Sb$^{51+..51+}$; Config: DSWDSMWDSDMMMMMMMMMMMS
dp/p=3.09% ; Wedges: 0, Al (7000 mg/cm^2), Al (4340 mg/cm^2); Brho(Tm): 12.0344, 12.0344, 8.6613, 8.6613
N=74-86

all charge states separ.
sum of reactions

Implant precursors in CSC (2/3)

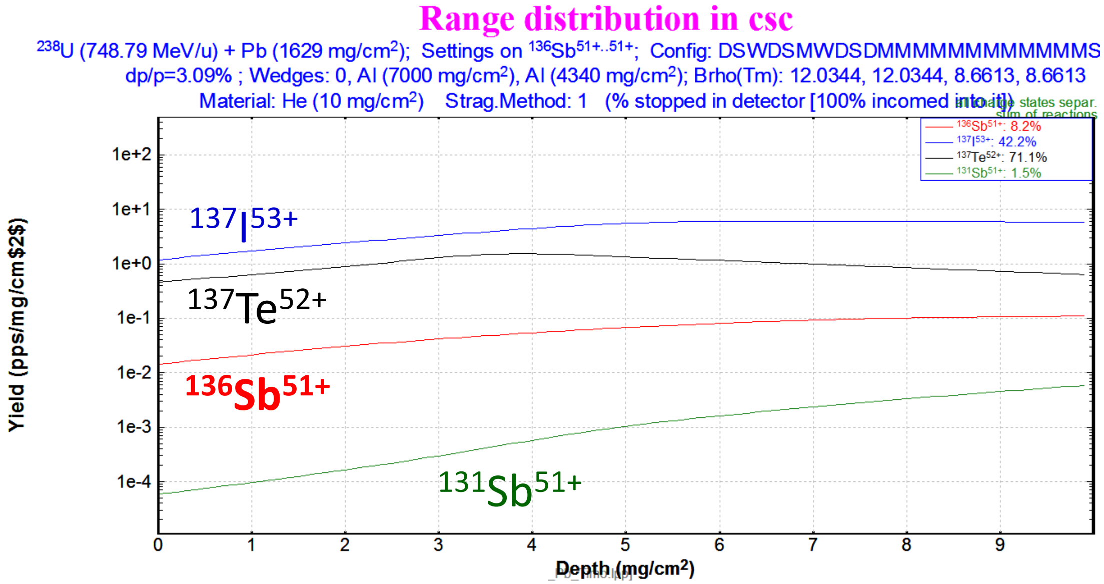
- Key to required purity: **Combination** of FRS and CSC
  - Thin (10 mg/cm^2) CSC provides crucial additional separation, by **not** stopping potential background sources



Final Al degrader + CSC stopping range

In practice, only **^{136}Sb**, ^{137}I, ^{137}Te & ^{131}Sb are stopped in the CSC

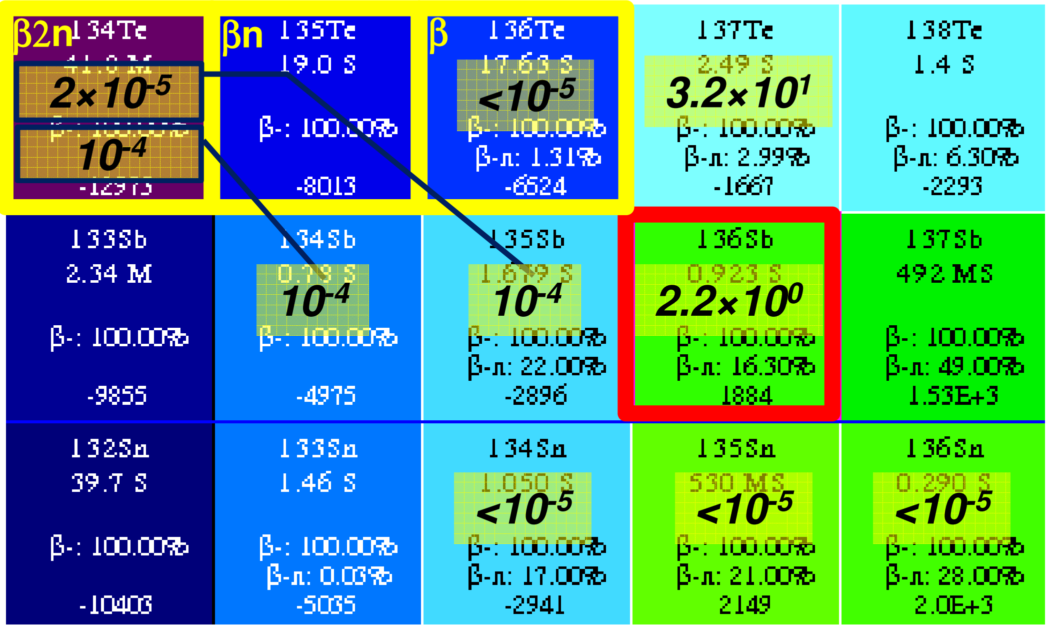
Implant precursors in CSC (3/3)



- Another isotopes 'source': **Upstream neutron removal**
  - Δdepth ~ A/Z^2 **~ 1%** (~135/136)
  - Only neutron removal recoils from **last 1 gr before CSC**, will be stopped in CSC (10mg = 1% of 1gr)
  - At relevant energies, **CS_{-n}~ 50 mb**
  - Effect at **10^{-4} level**

- Harmful beam induced background risks
  1. **βxn decay daughters:** can be isolated and subtracted by varying CSC storage time
  2. **Lower isotope, isotone and isobar**: decay products (**while in CSC**) might mask precursor's βn and β2n decay products

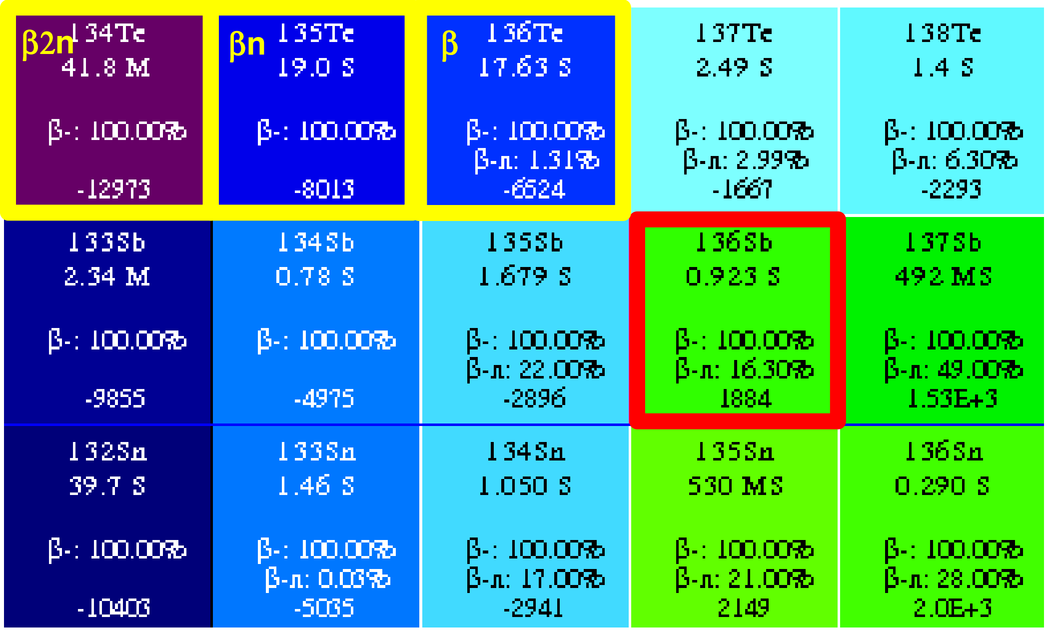
P_{xn} specificity limit is at 10^{-4} level



β2n 134Te 41.0 M 2×10^{-5} 10^{-4} -12975	βn 135Te 19.0 S β-: 100.00% -8013	β 136Te 17.63 S $<10^{-5}$ β-: 100.00% β-n: 1.31% -6524	137Te 2.49 S 3.2×10^{1} β-: 100.00% β-n: 2.99% -1667	138Te 1.4 S β-: 100.00% β-n: 6.30% -2293
133Sb 2.34 M β-: 100.00% -9855	134Sb 0.78 S 10^{-4} β-: 100.00% -4975	135Sb 1.679 S 10^{-4} β-: 100.00% β-n: 22.00% -2896	136Sb 0.923 S 2.2×10^{0} β-: 100.00% β-n: 16.30% 1884	137Sb 492 MS β-: 100.00% β-n: 49.00% 1.53E+3
132Sn 39.7 S β-: 100.00% -10403	133Sn 1.46 S β-: 100.00% β-n: 0.03% -5035	134Sn 1.050 S $<10^{-5}$ β-: 100.00% β-n: 17.00% -2941	135Sn 530 MS $<10^{-5}$ β-: 100.00% β-n: 21.00% 2149	136Sn 0.290 S $<10^{-5}$ β-: 100.00% β-n: 28.00% 2.0E+3

Identify and count recoils (1/2)

- Recoils (and the precursor) are identified and counted by their masses via the Ion Catcher MR-TOF-MS (isobars and even isomers can be resolved within 10's ms)
- **$P_{xn} = N_{xn}/(N_{0n}+N_{1n}+…+N_{xn})$** where N_{xn} is the amount of βxn recoils
- There will be **no CSC chemical effects** on P_{xn} evaluation because:
- All counted recoils are **isotopes of the same element**



β2n 134Te 41.8 M β-: 100.00% -12973	βn 135Te 19.0 S β-: 100.00% -8013	β 136Te 17.63 S β-: 100.00% β-n: 1.31% -6524	137Te 2.49 S β-: 100.00% β-n: 2.99% -1667	138Te 1.4 S β-: 100.00% β-n: 6.30% -2293
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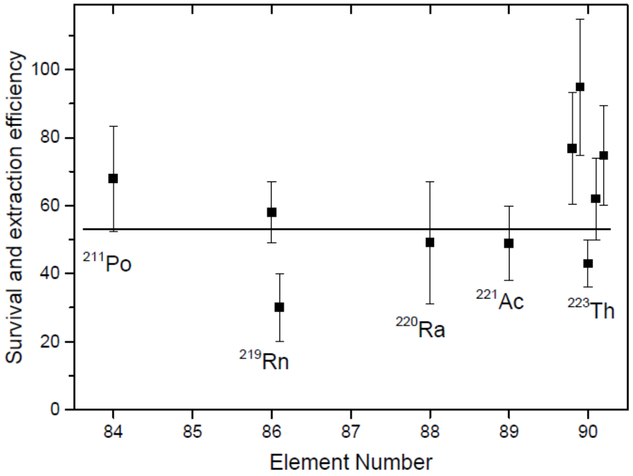
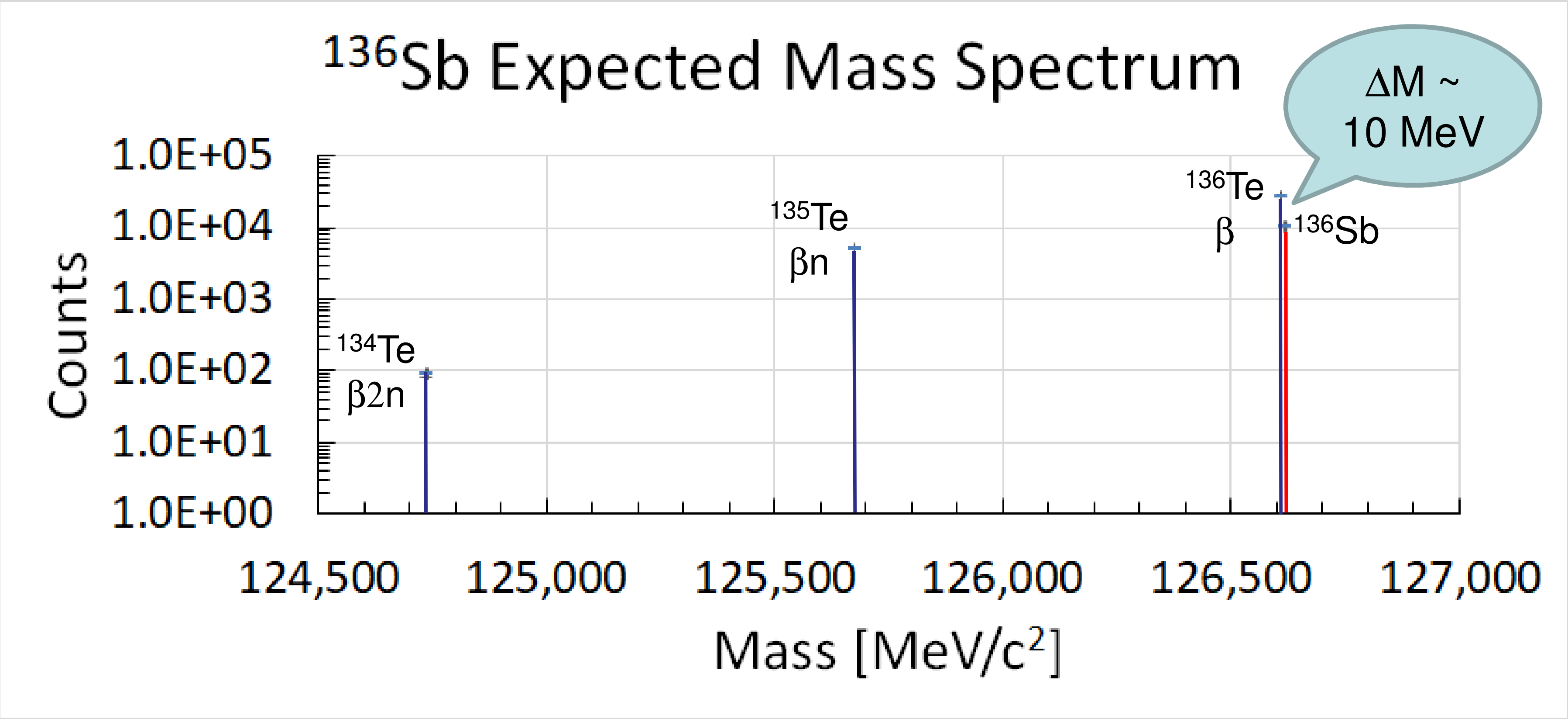
132Sn 39.7 S β-: 100.00% -10403	133Sn 1.46 S β-: 100.00% β-n: 0.03% -5035	134Sn 1.050 S β-: 100.00% β-n: 17.00% -2941	135Sn 530 MS β-: 100.00% β-n: 21.00% 2149	136Sn 0.290 S β-: 100.00% β-n: 28.00% 2.0E+3

It was established in previous experiments that CSC survival and extraction efficiency is **essentially element independent**, including comparison of a **noble element (Rn)**, and one of the **most reactive** ones **(Th)**



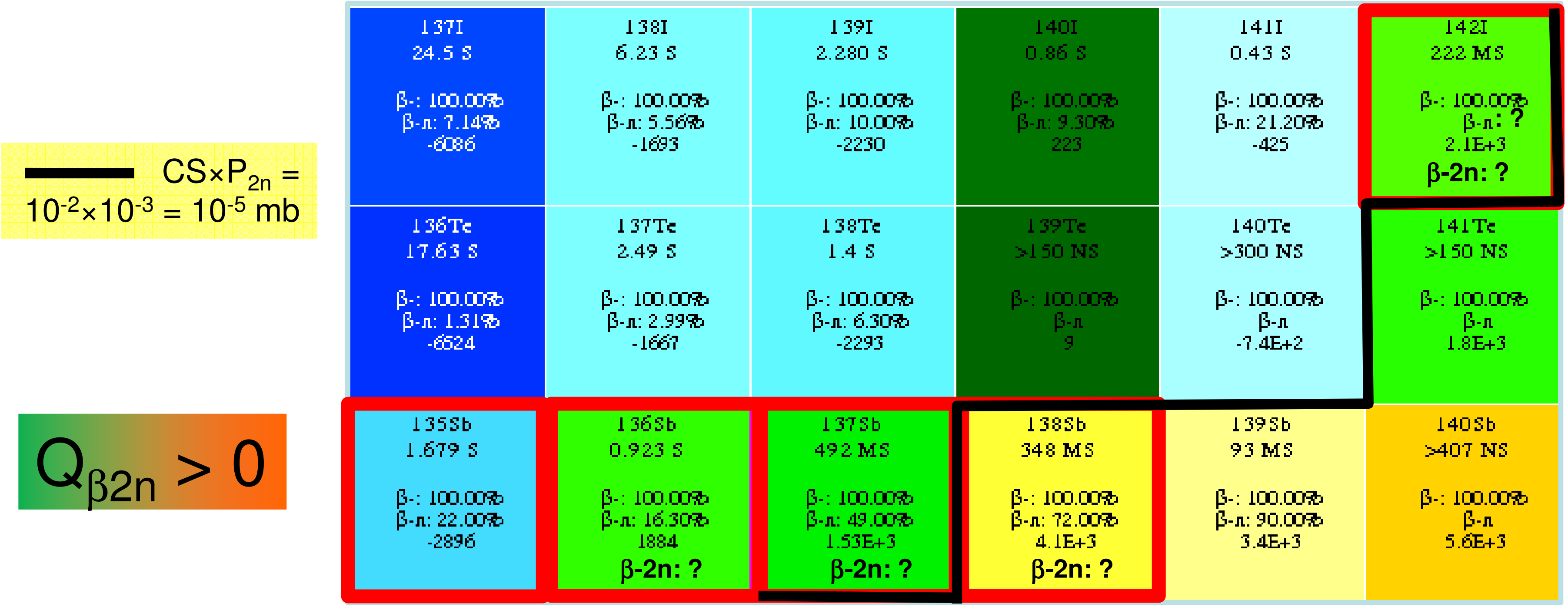
Identify and count recoils (2/2)



- Major method advantage:
  - P_{xn} measurement efficiency is independent of x

Proposed first experiments (1/2)

- Start with n-rich isotopes with the highest current GSI rate, with $Q_{\beta 2n} > 0$
- Attempt to look for those with significant physics impact
- Repeat known P_{1n} (and also P_{2n}) measurements
- Focus on isotopes that can generate 10's of β2n daughters in a few shifts
- As FOM, define 'effective cross section' – production cross section × P_{2n}



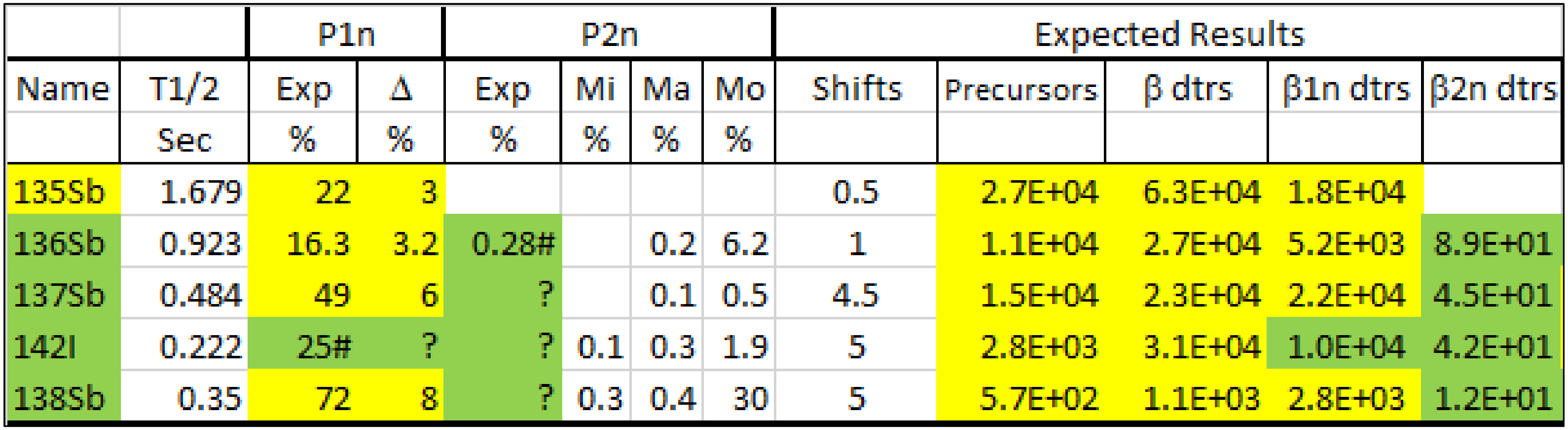
$CS \times P_{2n} = 10^{-2} \times 10^{-3} = 10^{-5}$ mb

$Q_{\beta 2n} > 0$

137I 24.5 S β-: 100.00% β-n: 7.14% -6086	138I 6.23 S β-: 100.00% β-n: 5.56% -1693	139I 2.280 S β-: 100.00% β-n: 10.00% -2230	140I 0.86 S β-: 100.00% β-n: 9.30% 223	141I 0.43 S β-: 100.00% β-n: 21.20% -425	142I 222 MS β-: 100.00% β-n: ? 2.1E+3 **β-2n: ?**
136Te 17.63 S β-: 100.00% β-n: 1.31% -6524	137Te 2.49 S β-: 100.00% β-n: 2.99% -1667	138Te 1.4 S β-: 100.00% β-n: 6.30% -2293	139Te >150 NS β-: 100.00% β-n 9	140Te >300 NS β-: 100.00% β-n -7.4E+2	141Te >150 NS β-: 100.00% β-n 1.8E+3
135Sb 1.679 S β-: 100.00% β-n: 22.00% -2896	136Sb 0.923 S β-: 100.00% β-n: 16.30% 1884 **β-2n: ?**	137Sb 492 MS β-: 100.00% β-n: 49.00% 1.53E+3 **β-2n: ?**	138Sb 348 MS β-: 100.00% β-n: 72.00% 4.1E+3 **β-2n: ?**	139Sb 93 MS β-: 100.00% β-n: 90.00% 3.4E+3	140Sb >407 NS β-: 100.00% β-n 5.6E+3

Proposed first experiments (2/2)

Objective	Motivation
Implement and demonstrate a **novel** P_{xn} **measurement method**	• **Complementary** to worldwide programs • Important for **confidence** in existing and new data
4 improved accuracy $\mathbf{P_{1n}}$ for $^{135\text{-}138}$**Sb**	• **4 more** $\mathbf{P_{2n}}$ measurements in **fission fragment region**
4 new $\mathbf{P_{2n}}$ for $^{136\text{-}138}$**Sb**, ^{142}**I** and **1 new** $\mathbf{P_{1n}}$ for ^{142}**I**	• **Systematics** of an isotope chain and a nearby isotope
1 improved mass and $\mathbf{Q_{bxn}}$ values for ^{137}**Sb** **2 new masses** and $\mathbf{Q_{bxn}}$ values for ^{138}**Sb**, ^{142}**I** **Simultaneous** with $\mathbf{P_{xn}}$ measurements	• $\mathbf{P_{xn}}$ of **Sb**: **highest impact** on **r-process** • $\mathbf{P_{xn}}$ of $^{135(137)}$**Sb**: **1st(2nd) priority** lists of **IAEA** • ^{142}**I**: **heaviest, highest Z** β2n precursor measured yet



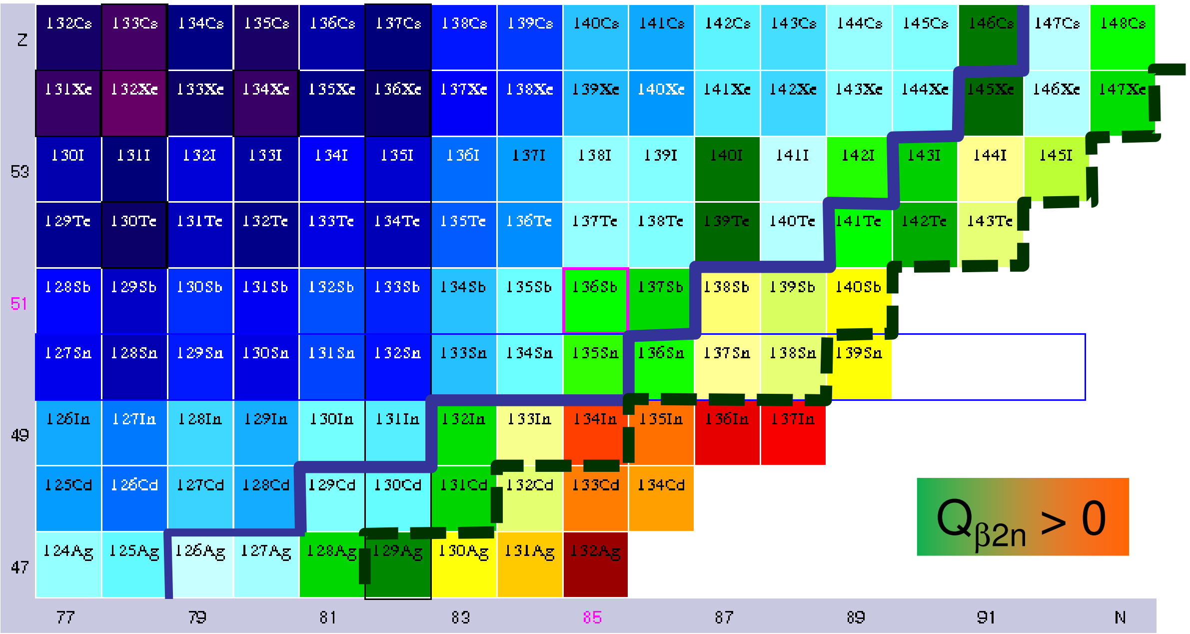
		P1n		P2n				Expected Results				
Name	T1/2	Exp	Δ	Exp	Mi	Ma	Mo	Shifts	Precursors	β dtrs	β1n dtrs	β2n dtrs
	Sec	%	%	%	%	%	%					
135Sb	1.679	22	3					0.5	2.7E+04	6.3E+04	1.8E+04	
136Sb	0.923	16.3	3.2	0.28#		0.2	6.2	1	1.1E+04	2.7E+04	5.2E+03	8.9E+01
137Sb	0.484	49	6	?		0.1	0.5	4.5	1.5E+04	2.3E+04	2.2E+04	4.5E+01
142I	0.222	25#	?	?	0.1	0.3	1.9	5	2.8E+03	3.1E+04	1.0E+04	4.2E+01
138Sb	0.35	72	8	?	0.3	0.4	30	5	5.7E+02	1.1E+03	2.8E+03	1.2E+01

Green – new measurement, **Yellow** – improved accuracy measurement, **#** - evaluation, **?** – no existing value
Mi, **Ma**, **Mo** – P_{2n} theoretical predictions of **Mi**ernik, **Ma**rketin et al, **Mo**ller et al.

- **~40 β2n events for $^{136\text{-}137}$Sb and ^{142}I ➔** ~15% stat. uncertainty, similar to expected syst. uncertainty
- **~10 β2n events for ^{138}Sb**, the estimated minimum for unambiguous identification in MR-TOF-MS.

FAIR Phase-1 - P_{xn} near drip line and N~126

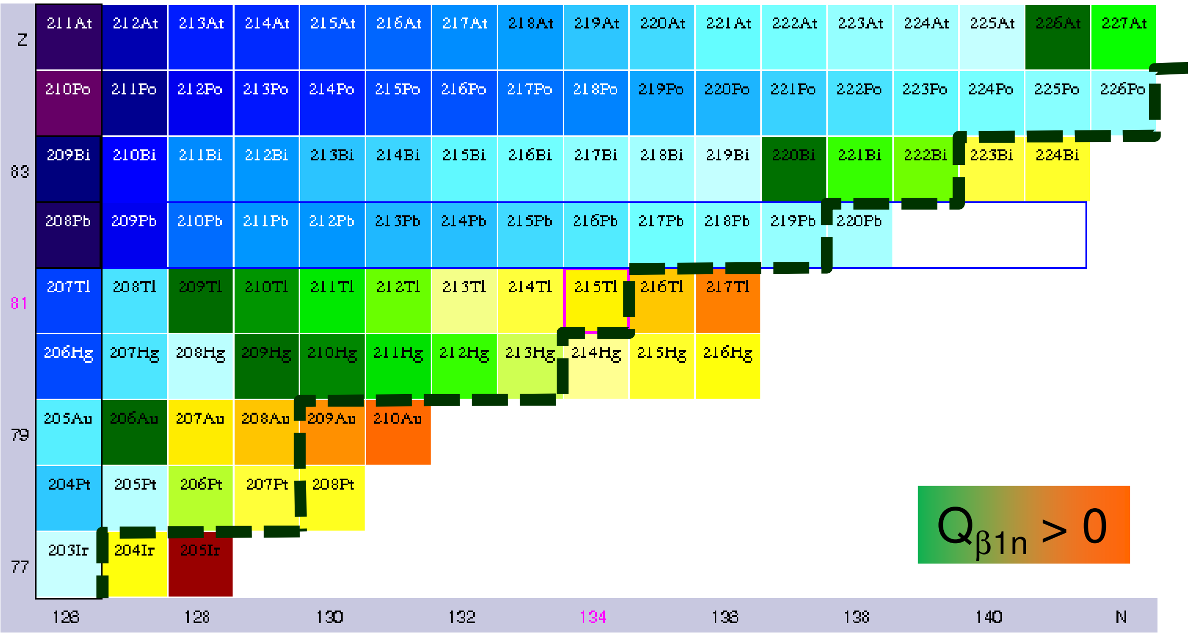
- Phase-0 ▬▬▬
  - CS×P_{2n} = 10^{-2}×10^{-3} = 10^{-5} mb
- Phase-1 ▬ ▬ ▬ ▬
  - CS×P_{2n} = 10^{-5}×10^{-3} = 10^{-8} mb
  - Conservative, since P_{2n} increases with N



Z																	
	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	139Cs	140Cs	141Cs	142Cs	143Cs	144Cs	145Cs	146Cs	147Cs	148Cs
	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe	137Xe	138Xe	139Xe	140Xe	141Xe	142Xe	143Xe	144Xe	145Xe	146Xe	147Xe
53	130I	131I	132I	133I	134I	135I	136I	137I	138I	139I	140I	141I	142I	143I	144I	145I	
	129Te	130Te	131Te	132Te	133Te	134Te	135Te	136Te	137Te	138Te	139Te	140Te	141Te	142Te	143Te		
51	128Sb	129Sb	130Sb	131Sb	132Sb	133Sb	134Sb	135Sb	136Sb	137Sb	138Sb	139Sb	140Sb				
	127Sn	128Sn	129Sn	130Sn	131Sn	132Sn	133Sn	134Sn	135Sn	136Sn	137Sn	138Sn	139Sn				
49	126In	127In	128In	129In	130In	131In	132In	133In	134In	135In	136In	137In					
	125Cd	126Cd	127Cd	128Cd	129Cd	130Cd	131Cd	132Cd	133Cd	134Cd							
47	124Ag	125Ag	126Ag	127Ag	128Ag	129Ag	130Ag	131Ag	132Ag								
	77		79		81		83		85		87		89		91		N

- Phase-1 ▬ ▬ ▬ ▬
  - CS×P_{1n} = 10^{-6}×10^{-2} = 10^{-8} mb
  - Conservative, since P_{1n} increases with N

"Understanding the 3rd r-process peak by means of comprehensive measurements of **masses**, **lifetimes**, **neutron branchings**, dipole strength, and level structure along the N=126 isotones" (1st highlight of the NUSTAR MSV Phase I program)



Z																	
	211At	212At	213At	214At	215At	216At	217At	218At	219At	220At	221At	222At	223At	224At	225At	226At	227At
	210Po	211Po	212Po	213Po	214Po	215Po	216Po	217Po	218Po	219Po	220Po	221Po	222Po	223Po	224Po	225Po	226Po
83	209Bi	210Bi	211Bi	212Bi	213Bi	214Bi	215Bi	216Bi	217Bi	218Bi	219Bi	220Bi	221Bi	222Bi	223Bi	224Bi	
	208Pb	209Pb	210Pb	211Pb	212Pb	213Pb	214Pb	215Pb	216Pb	217Pb	218Pb	219Pb	220Pb				
81	207Tl	208Tl	209Tl	210Tl	211Tl	212Tl	213Tl	214Tl	215Tl	216Tl	217Tl						
	206Hg	207Hg	208Hg	209Hg	210Hg	211Hg	212Hg	213Hg	214Hg	215Hg	216Hg						
79	205Au	206Au	207Au	208Au	209Au	210Au											
	204Pt	205Pt	206Pt	207Pt	208Pt												
77	203Ir	204Ir	205Ir														
	126		128		130		132		134		136		138		140		N

THANK YOU