Trap System for Measuring Neutron Capture Cross Section of Short-lived Isotopes

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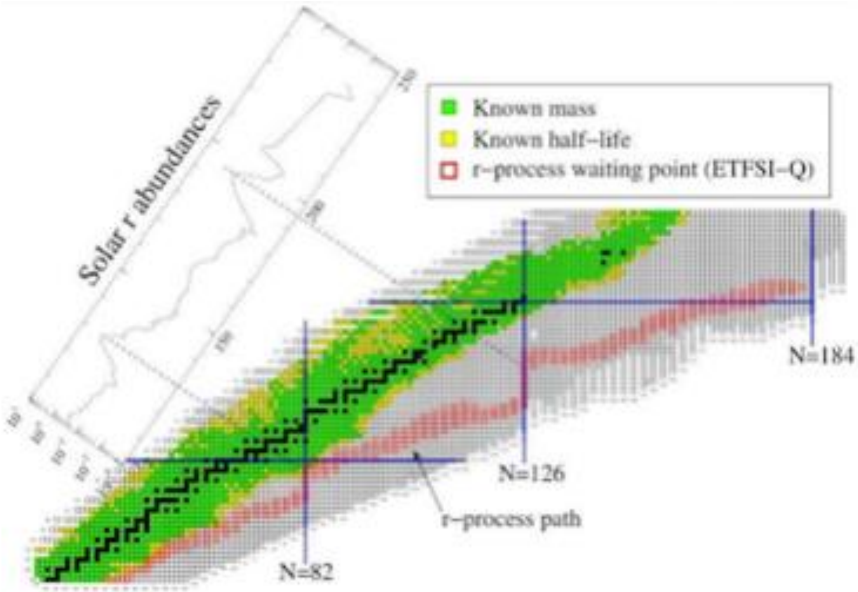
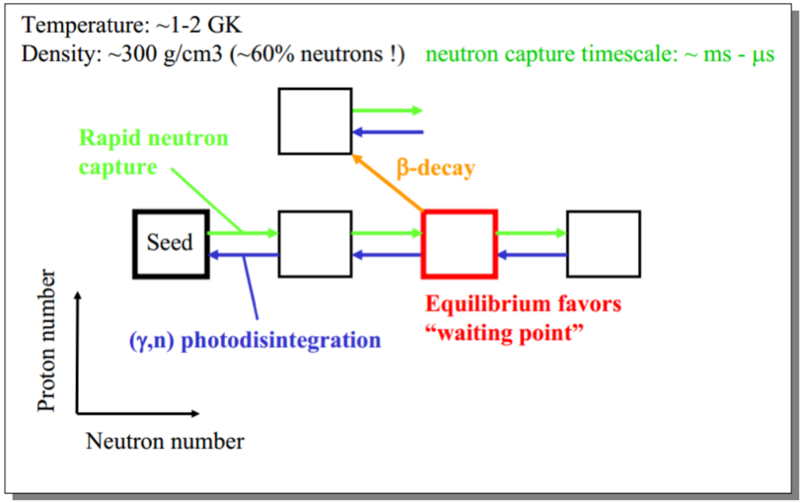
[4]Soreq Nuclear Research Center, Yavne, Israel

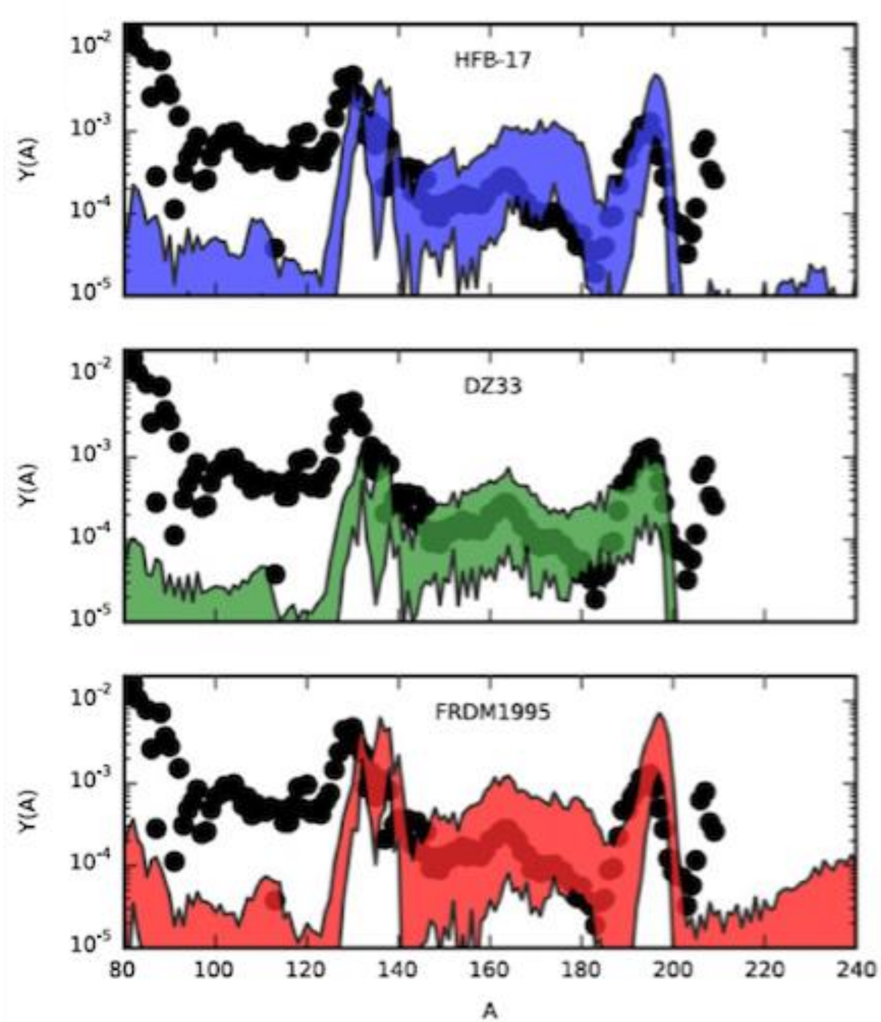
Nuclear Physics in Astrophysics - X

The ~~Problem~~ Challenge





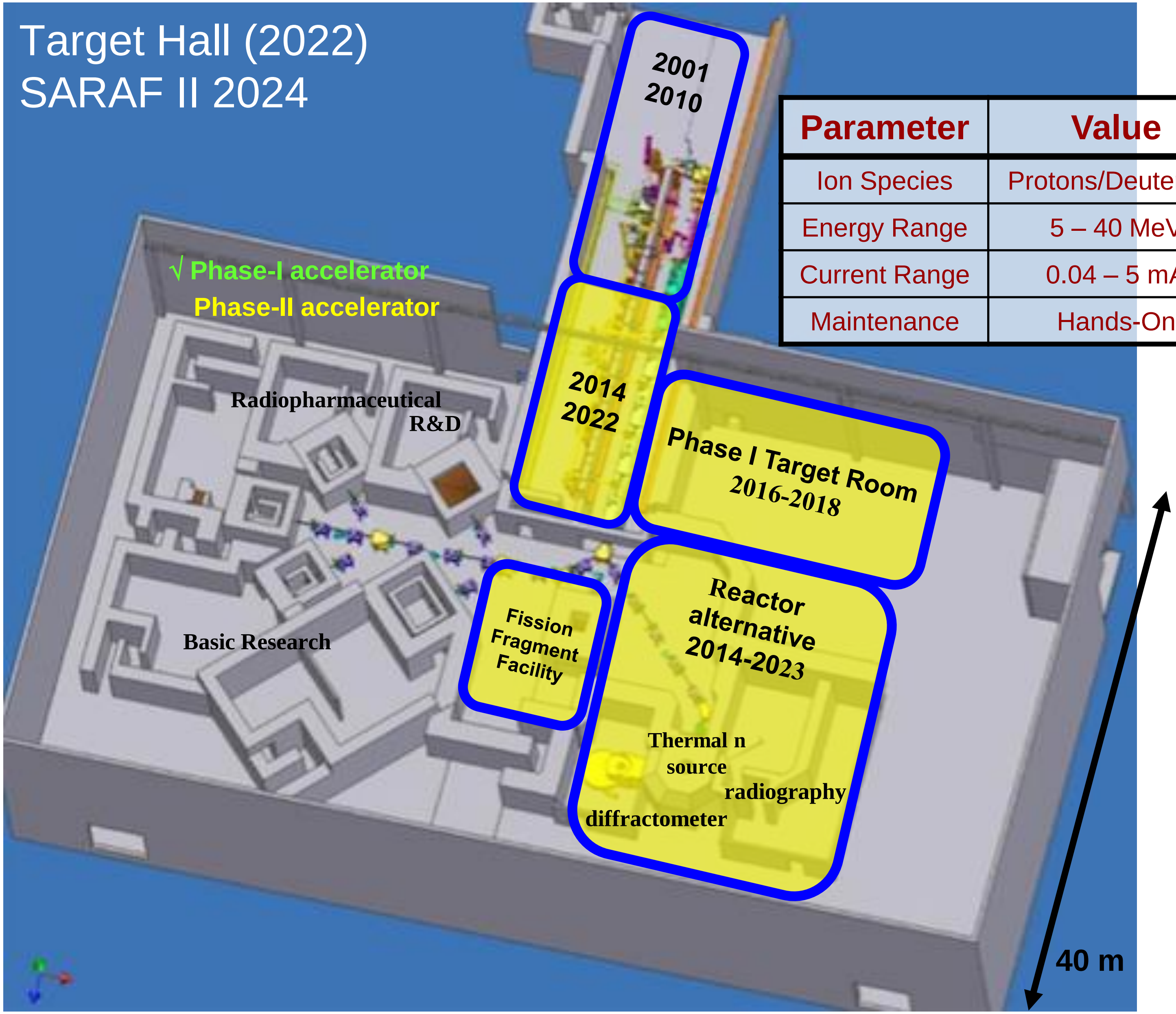
Effect of uncertain neutron capture rates



Progress in Particle and Nuclear Physics 86 (2016) 86–126

<u>Experimental Challenge</u>: Target and projectile are **unstable**.

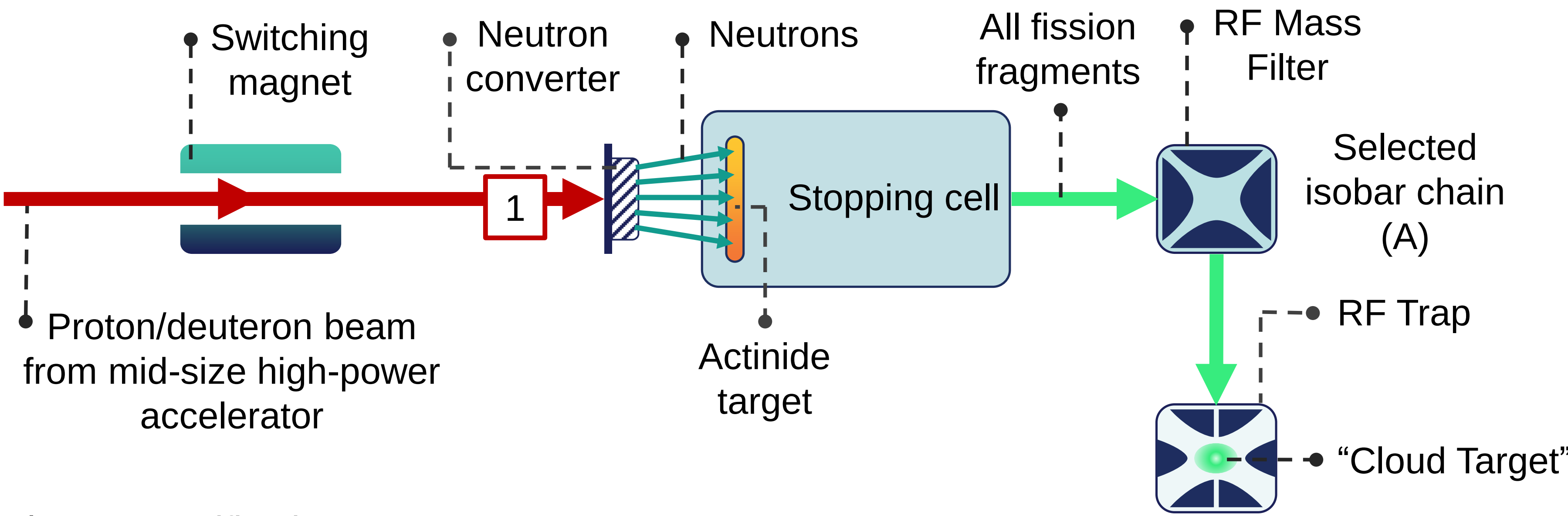
Soreq Applied Research Accelerator Facility (SARAF)



Parameter	Value	Comment
Ion Species	Protons/Deuterons	M/q ≤ 2
Energy Range	5 – 40 MeV	Variable energy
Current Range	0.04 – 5 mA	CW (and pulsed)
Maintenance	Hands-On	Very low beam loss

SARAF II
Under construction at
Soreq Nuclear Research
Center
Yavne, Israel

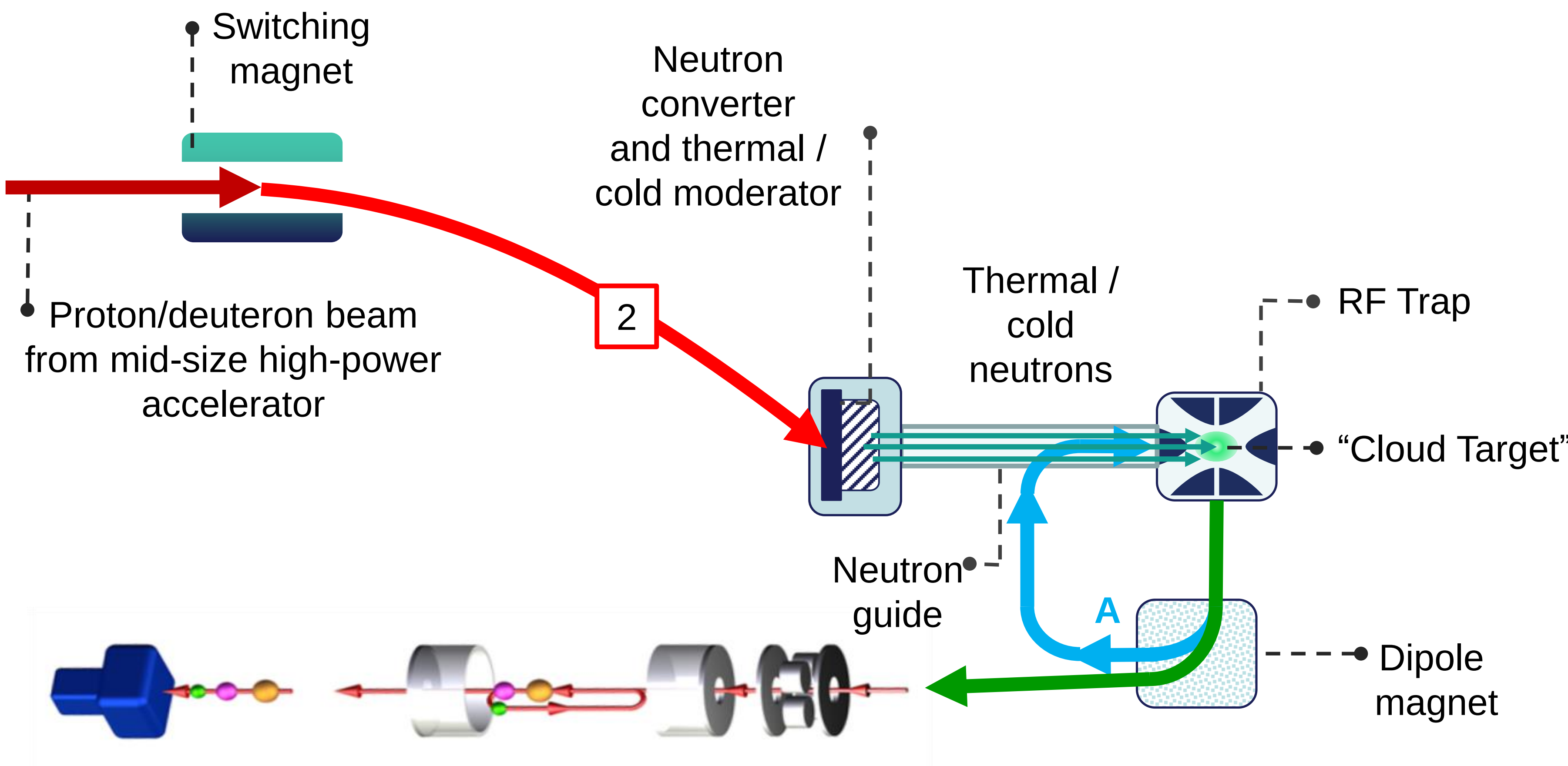
SARaf exOtic Nuclide fAcility (SARONA)

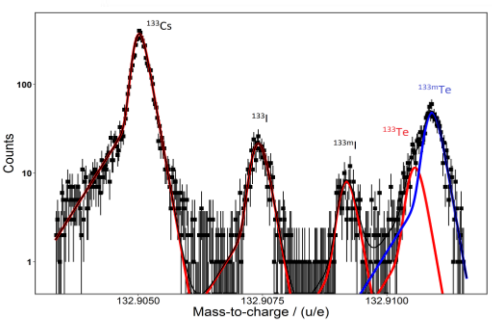


<u>Final Trap Specifications</u>

- "Cloud Target": **~10^{10} ions** with same A, in the region **A ~ 85-155** (fission products)
- Trapping duration: **~300 s**
- Trap volume can/should be cylindrical. **Transverse** dimensions of **a few mm**. **Longitudinal** can be longer, up to **~ 10's cm**
- Trap should enable irradiation by **cold/thermal neutrons** (~1-25 meV)
- Trap should contain ion kinetic energy of up to **~100's eV**
  - ***β*-decay** (A daughters of short-lived FPs) **and (n,*γ*)** (A+1 daughter)
- A+1 ions should be ejected in a **particular direction (axial or radial)**, towards a mass spectrometer

SARaf exOtic Nuclide fAcility (SARONA)

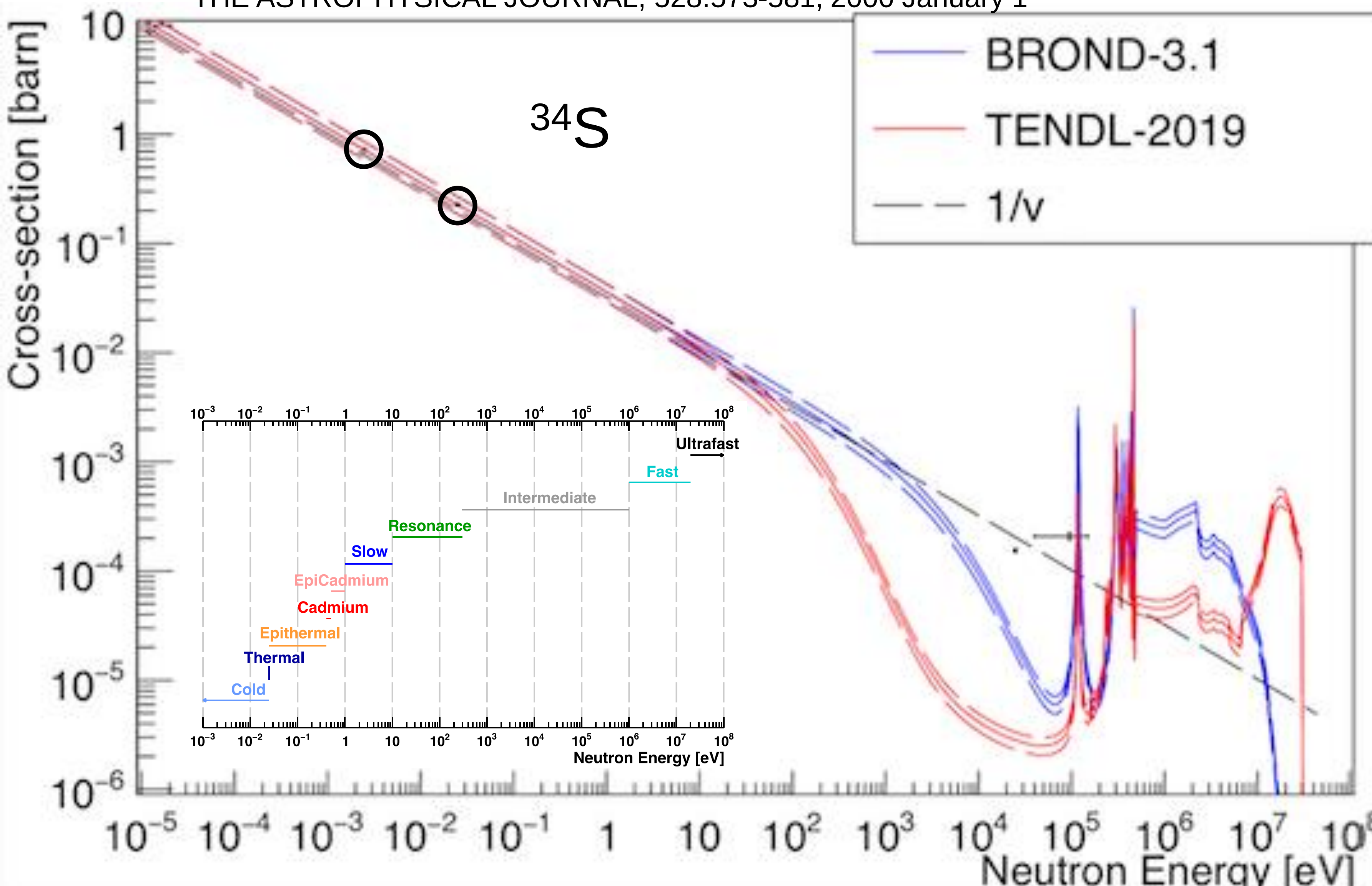




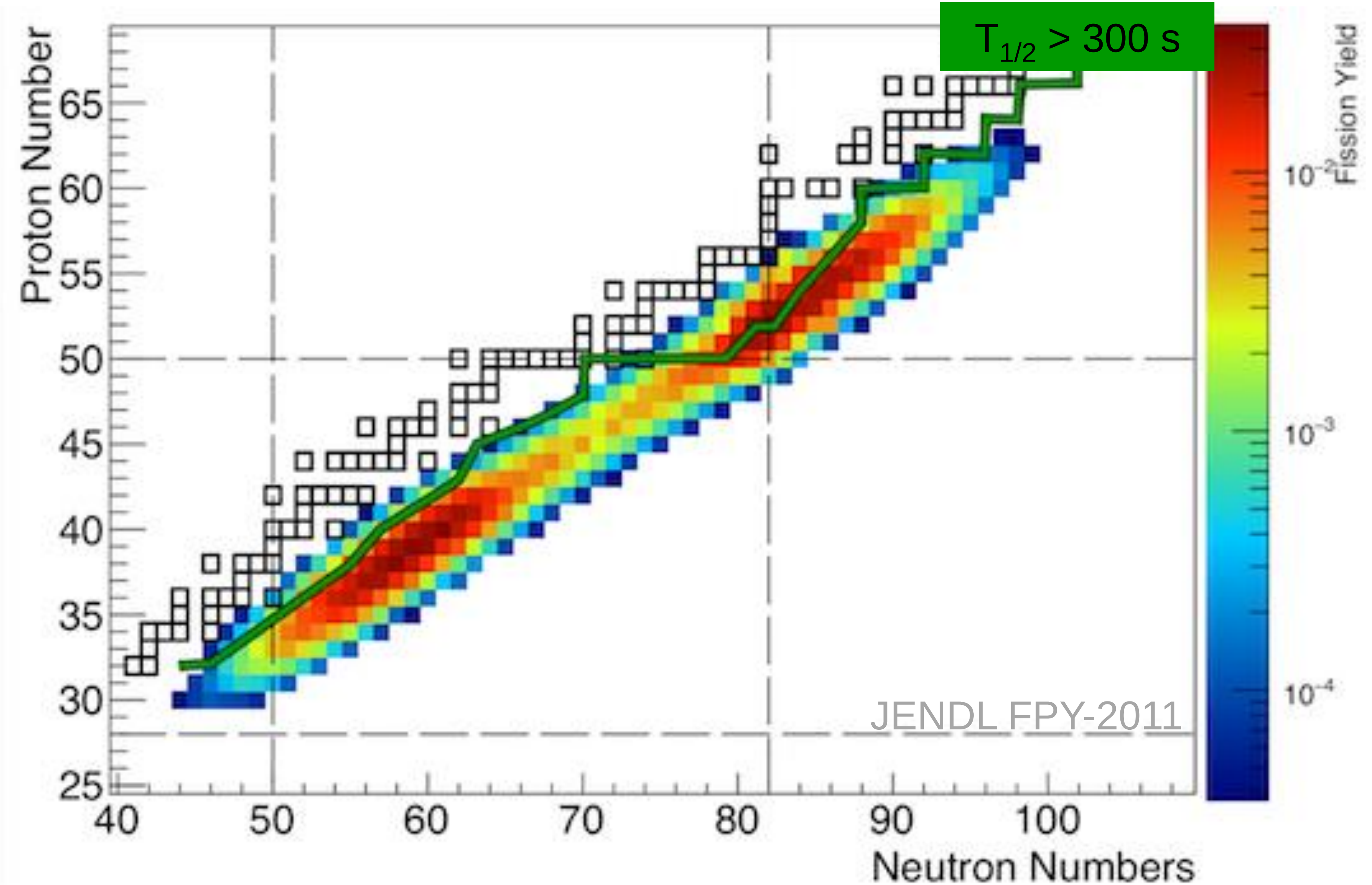
T. Dickel *et al.*, EPJ Web of Conferences 260, 11021 (2022)

Neutron Cross Section

R. Reifarth, K. Schwarz and F. Käppeler
THE ASTROPHYSICAL JOURNAL, 528:573-581, 2000 January 1

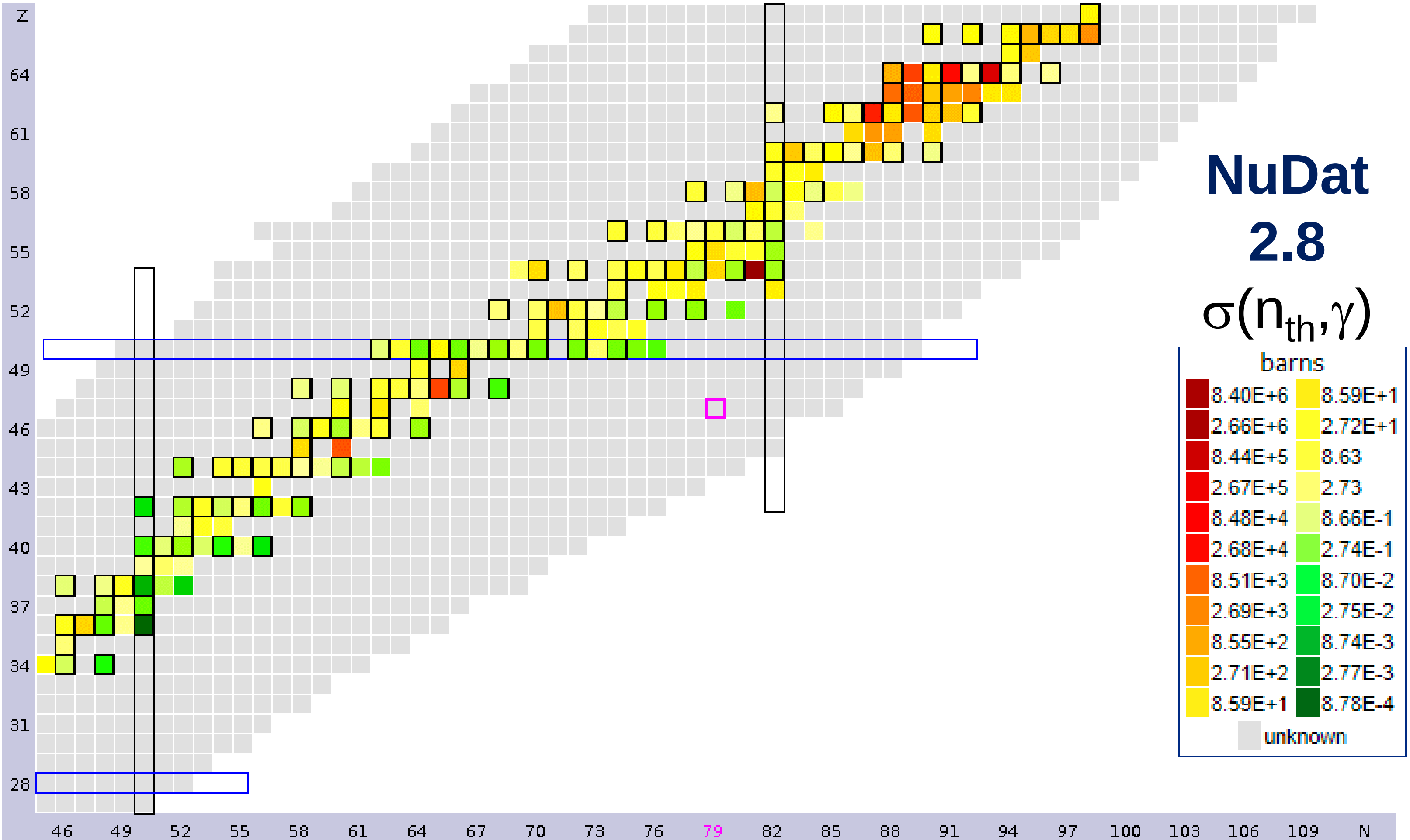


Fission Yields of ^{238}U at 14 MeV



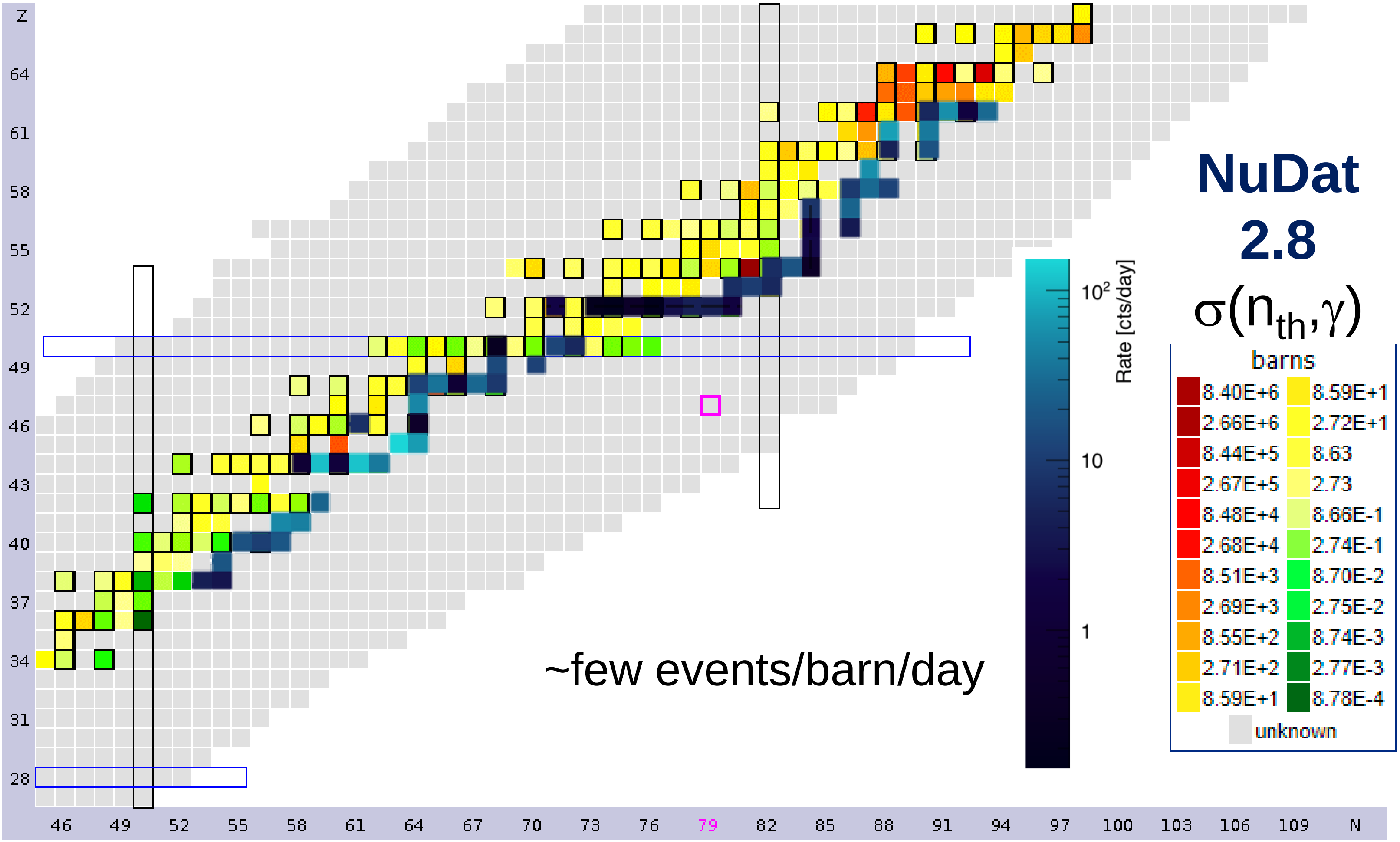
https://wwwndc.jaea.go.jp/cgi-bin/FPYfig

Comparison to measured $\sigma(n_{th},\gamma)$ so far



- Cross section values are from TALYS
- TALYS gives σ for thermal neutrons
- We assume σ(cold) ~ 2·σ(thermal) ($1/E^{1/2}$ trend)

Comparison to measured $\sigma(n_{th},\gamma)$ so far



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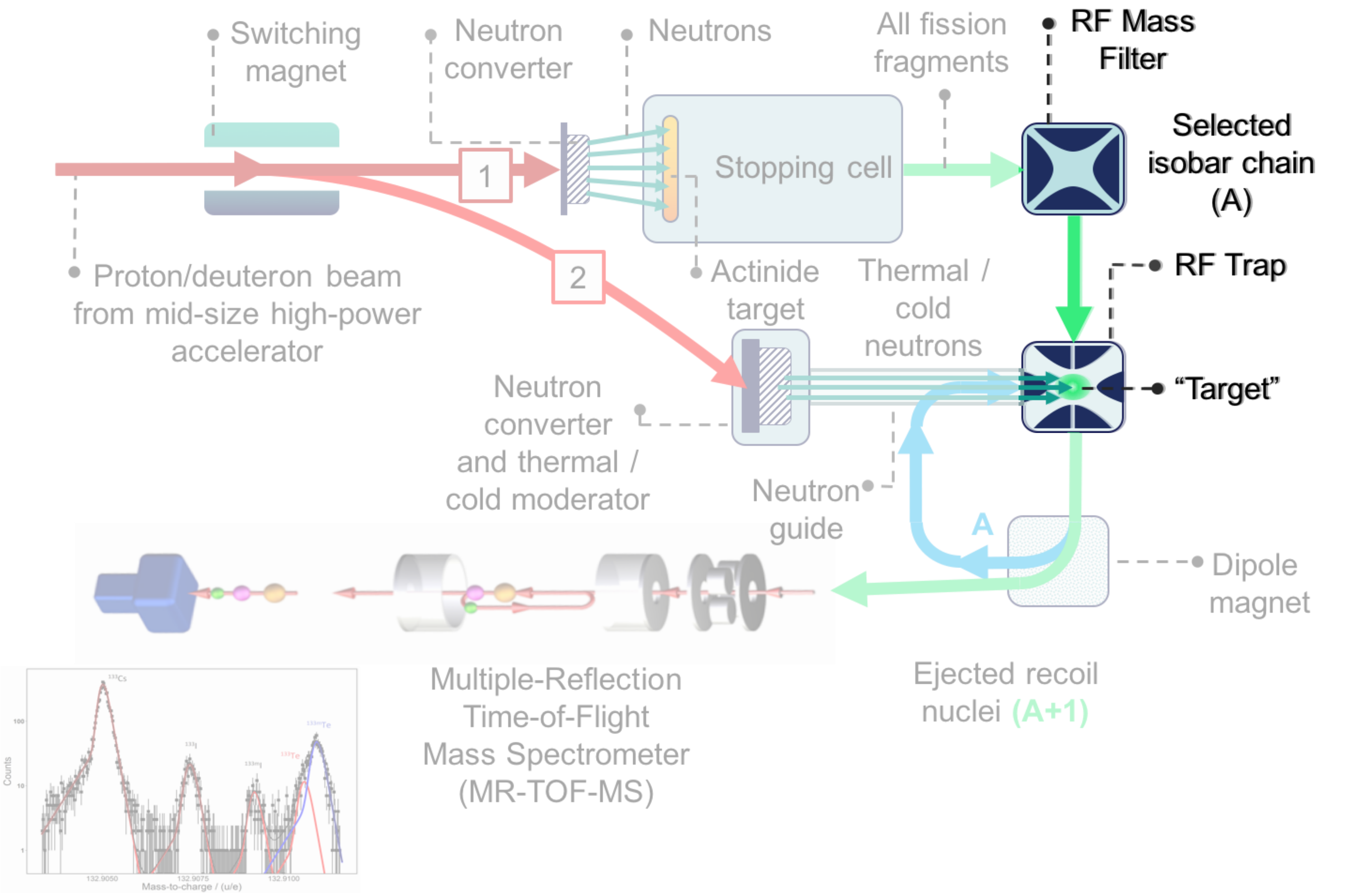
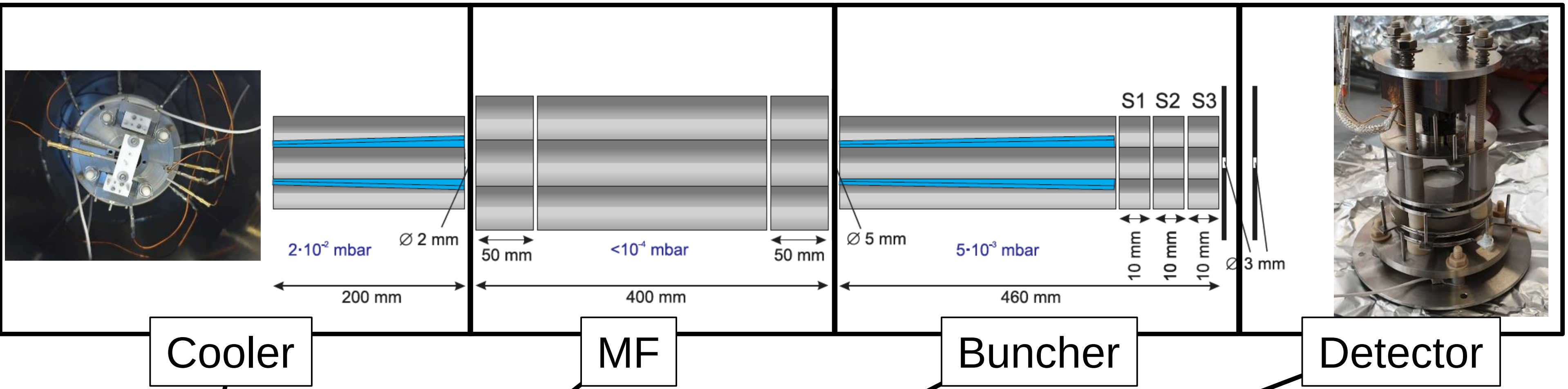
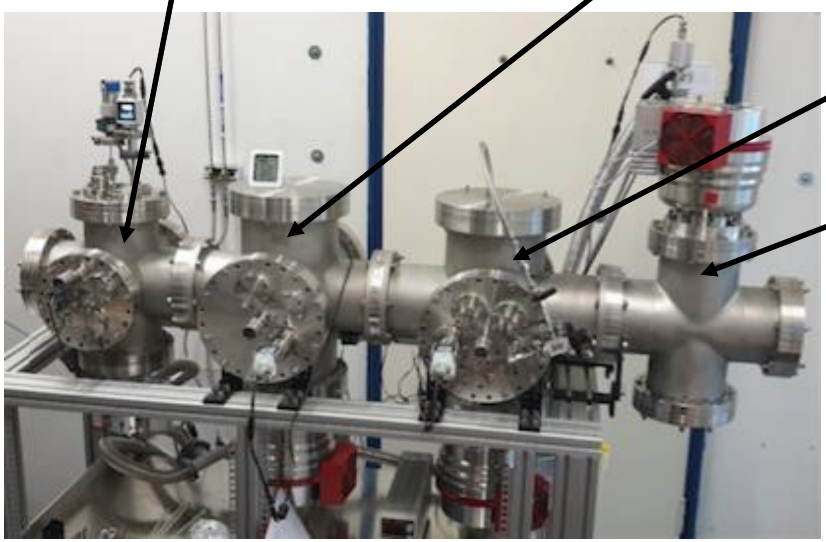
NG-Trap


Switching magnet
Neutron converter
Neutrons
All fission fragments
RF Mass Filter
Selected isobar chain (A)
1
2
Stopping cell
Proton/deuteron beam from mid-size high-power accelerator
Actinide target
Thermal / cold neutrons
RF Trap
"Target"
Neutron converter and thermal / cold moderator
Neutron guide
A
Dipole magnet
Multiple-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS)
Ejected recoil nuclei (A+1)
Counts
Mass-to-charge / (u/e)

NG-Trap Setup

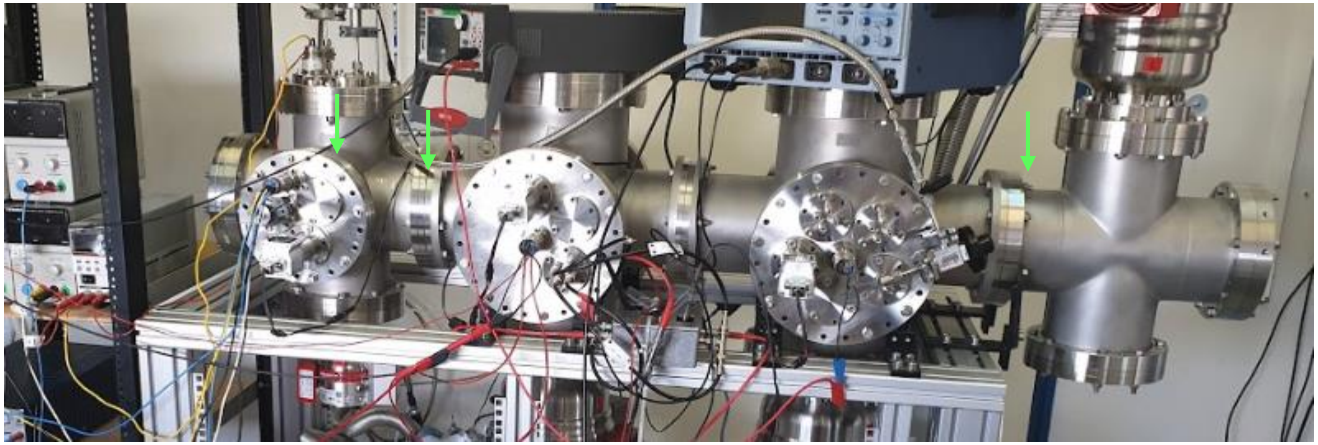


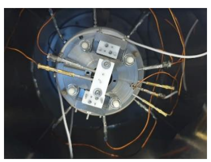


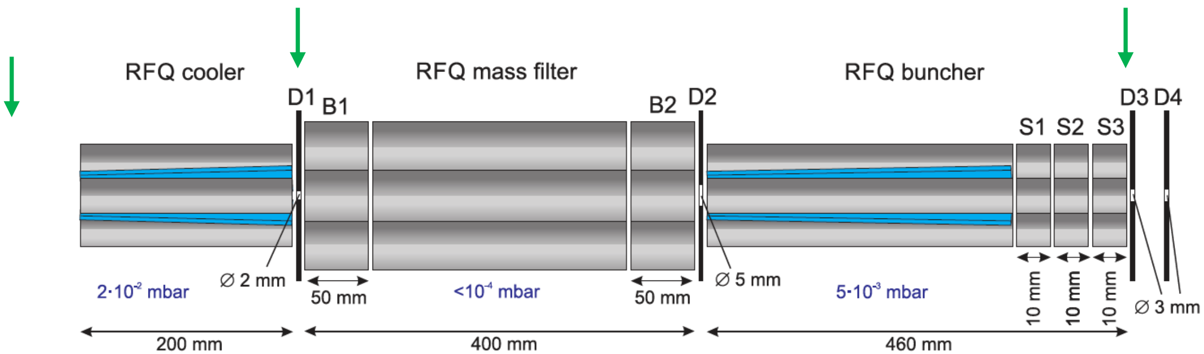
Parameter	Achieved*	Goal
Ion rate [ions/sec]	10^6	10^9
Ion capacity [ions]	$1.5\text{x}10^7$	10^{10}
Storage time [sec]	25	600

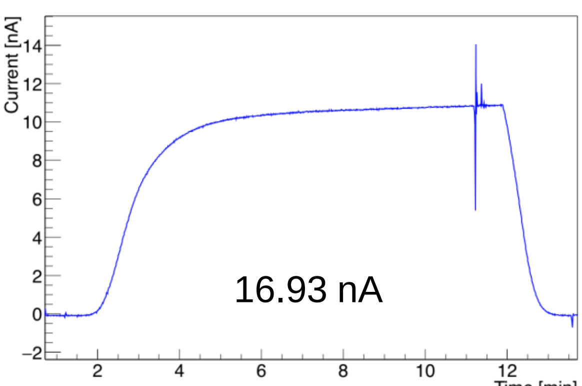
*E. Haettner *et al.*, A versatile triple radiofrequency quadrupole system for cooling, mass separation and bunching of exotic nuclei, Nucl. Inst. Meth. A 880 (2018) 138

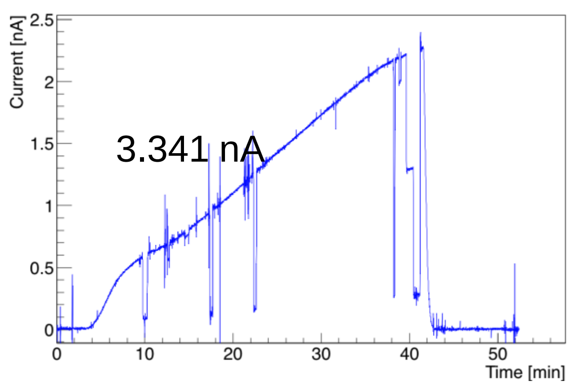
Progress

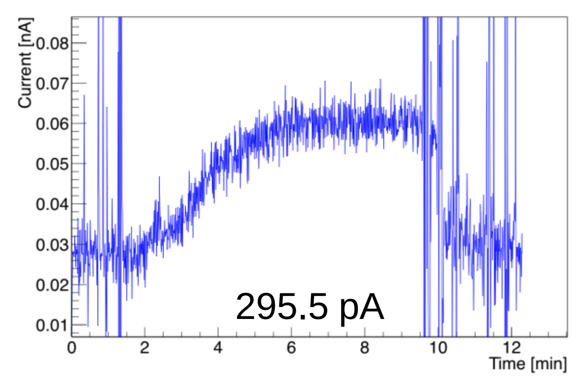





RFQ cooler
RFQ mass filter
RFQ buncher
D1
B1
B2
D2
D3
D4
S1
S2
S3
$2 \cdot 10^{-2}$ mbar
∅ 2 mm
50 mm
$<10^{-4}$ mbar
50 mm
∅ 5 mm
$5 \cdot 10^{-3}$ mbar
10 mm
10 mm
10 mm
∅ 3 mm
200 mm
400 mm
460 mm


Current [nA]
Time [min]
16.93 nA


Current [nA]
Time [min]
3.341 nA


Current [nA]
Time [min]
295.5 pA

Conclusion and outlook

- Optimise transport and trapping
- Continue simulations of all components
  - n-induced fission product (FP) generation
  - FP extraction and transport
  - NG-Trap RF simulations with space charge
  - neutron-ion kinematics
  - neutron flux enhancement via reflectors around trap
- Test concept by hydrogen capture on molecules
- Construction of a dedicated RF trap and demonstration
- Tests with a neutron beam and a target of stable ions (with high $\sigma(n,\gamma)$ values, e.g. $^{155,157}Gd$, ^{149}Sm)
- Installation and testing at SARAF-II

Backup

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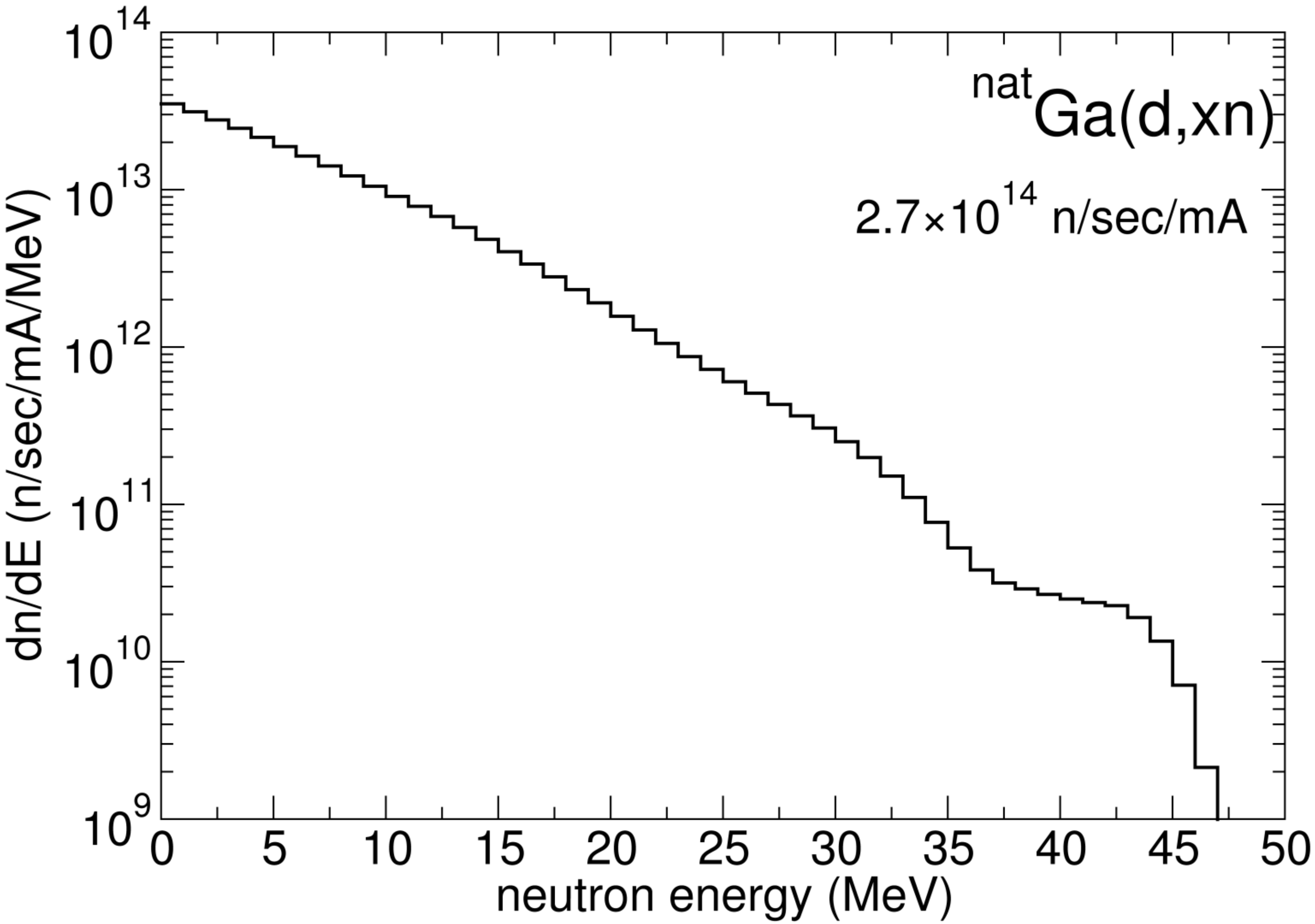
Energy Spectrum ^{nat}Ga



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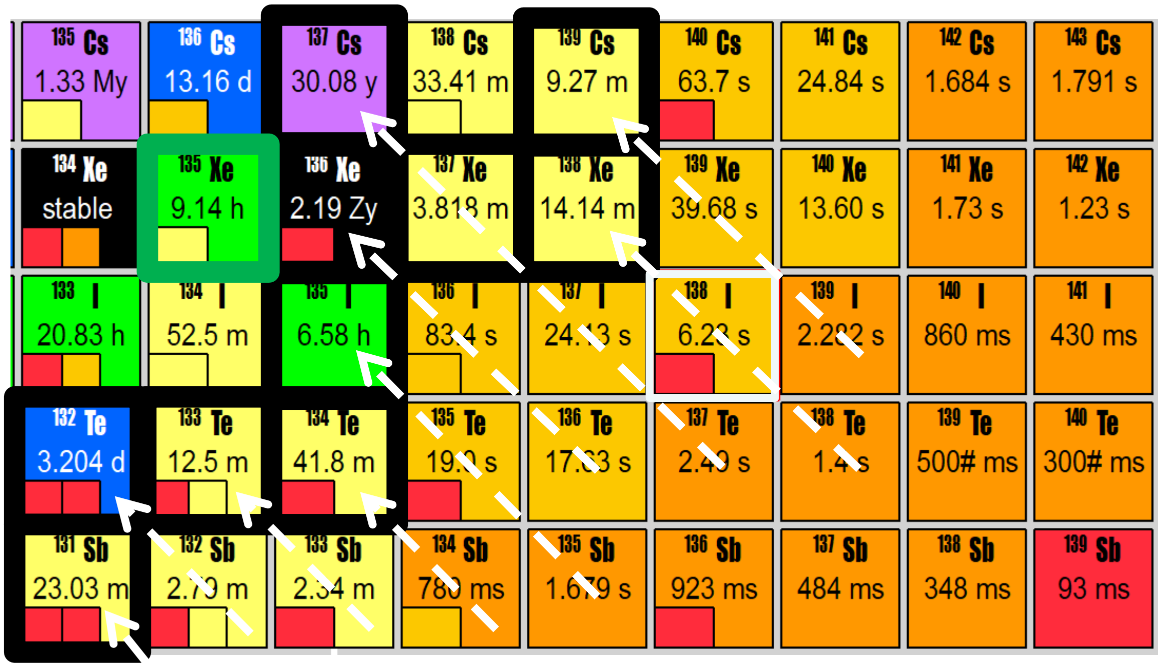
Status

Example of measured isotopes



- The more stable isotopes (in this case: ^{138}Cs, ^{136}Cs, ^{134}I, etc.) have IFY << 1%, so they will probably not be measured
- Special cases with extremely large $\sigma(n,\gamma)$ will be measured, e.g., ^{135}Xe, with $\sigma(n,\gamma)$ = 2.6e6 barn(!)

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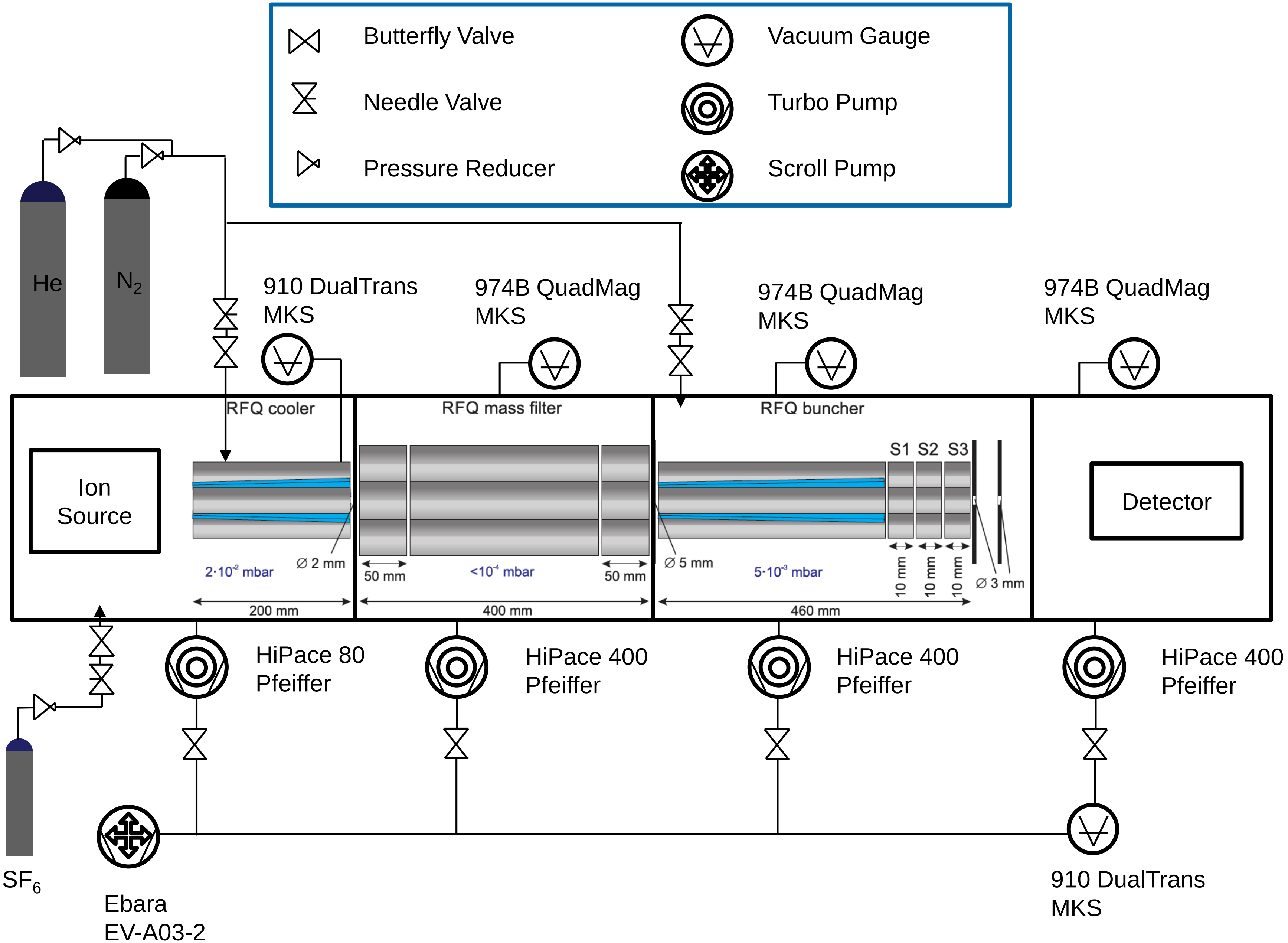
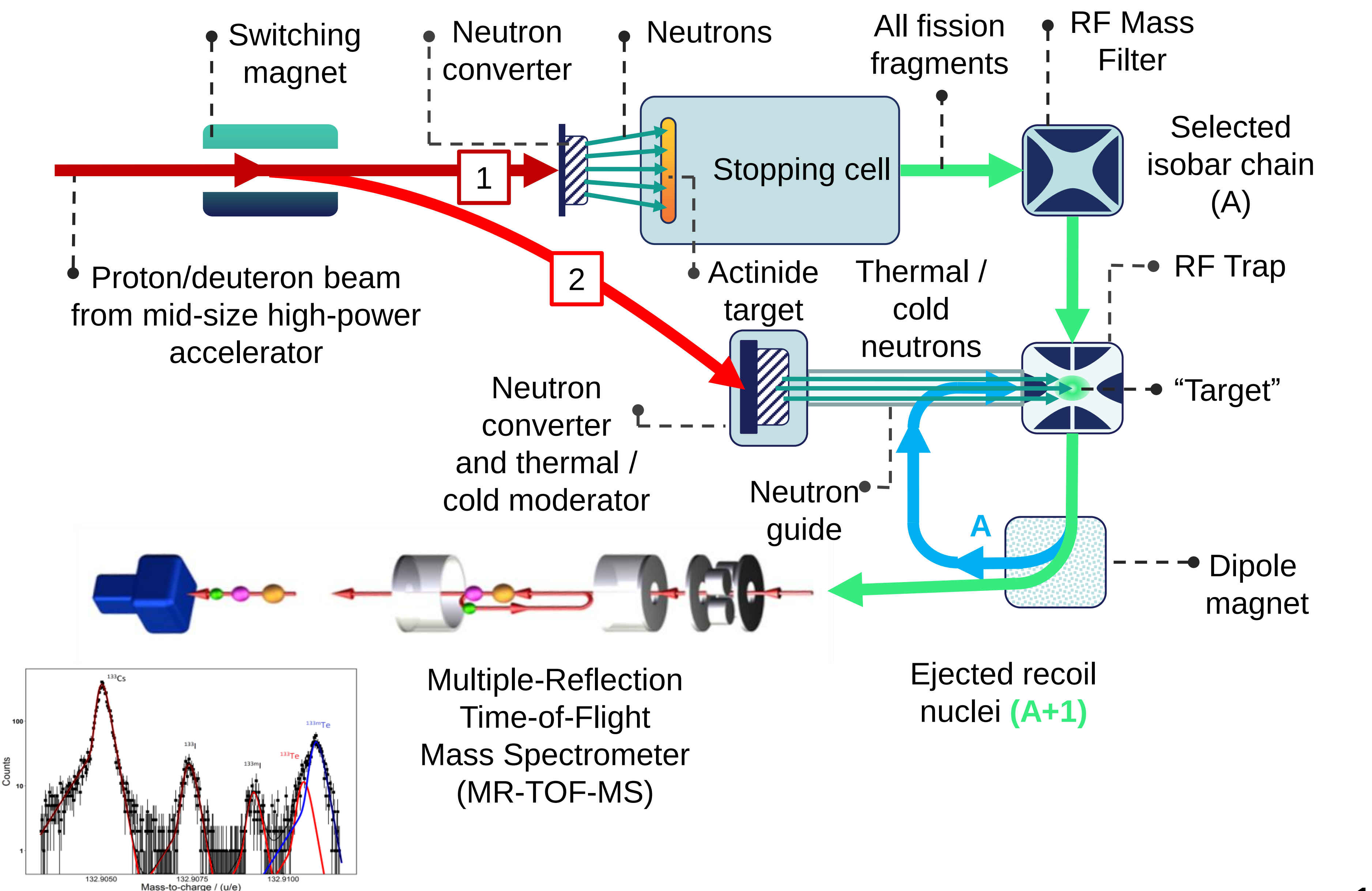
NG-Trap

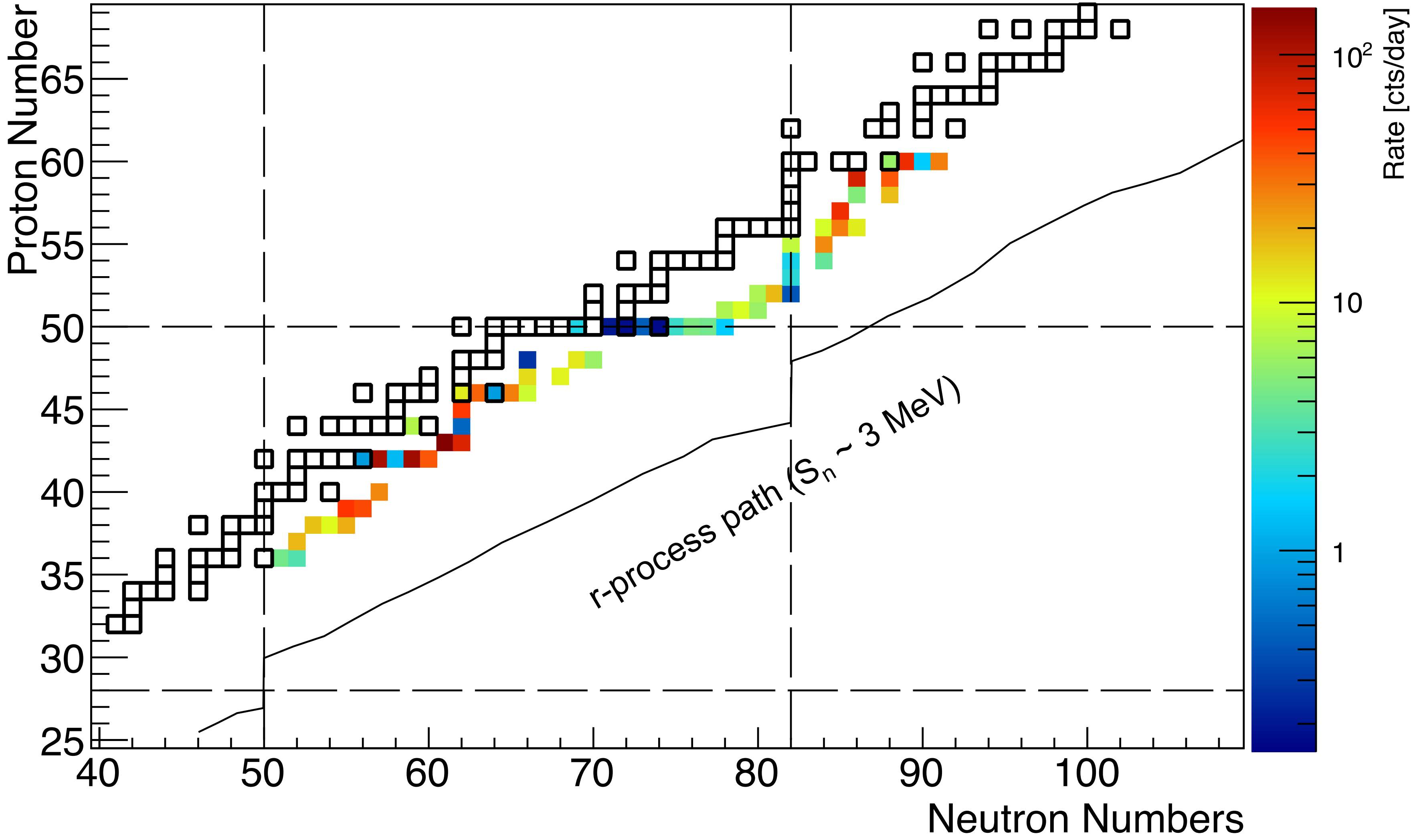


Butterfly Valve
Needle Valve
Pressure Reducer
Vacuum Gauge
Turbo Pump
Scroll Pump
He
N_2
910 DualTrans MKS
974B QuadMag MKS
974B QuadMag MKS
974B QuadMag MKS
RFQ cooler
RFQ mass filter
RFQ buncher
Ion Source
Detector
S1 S2 S3
$2\cdot10^{-2}$ mbar
∅ 2 mm
50 mm
$<10^{-4}$ mbar
50 mm
∅ 5 mm
$5\cdot10^{-3}$ mbar
10 mm
10 mm
10 mm
∅ 3 mm
200 mm
400 mm
460 mm
HiPace 80 Pfeiffer
HiPace 400 Pfeiffer
HiPace 400 Pfeiffer
HiPace 400 Pfeiffer
SF_6
Ebara EV-A03-2
910 DualTrans MKS

Project Sketch



Rate



- Cross section values are from TALYS
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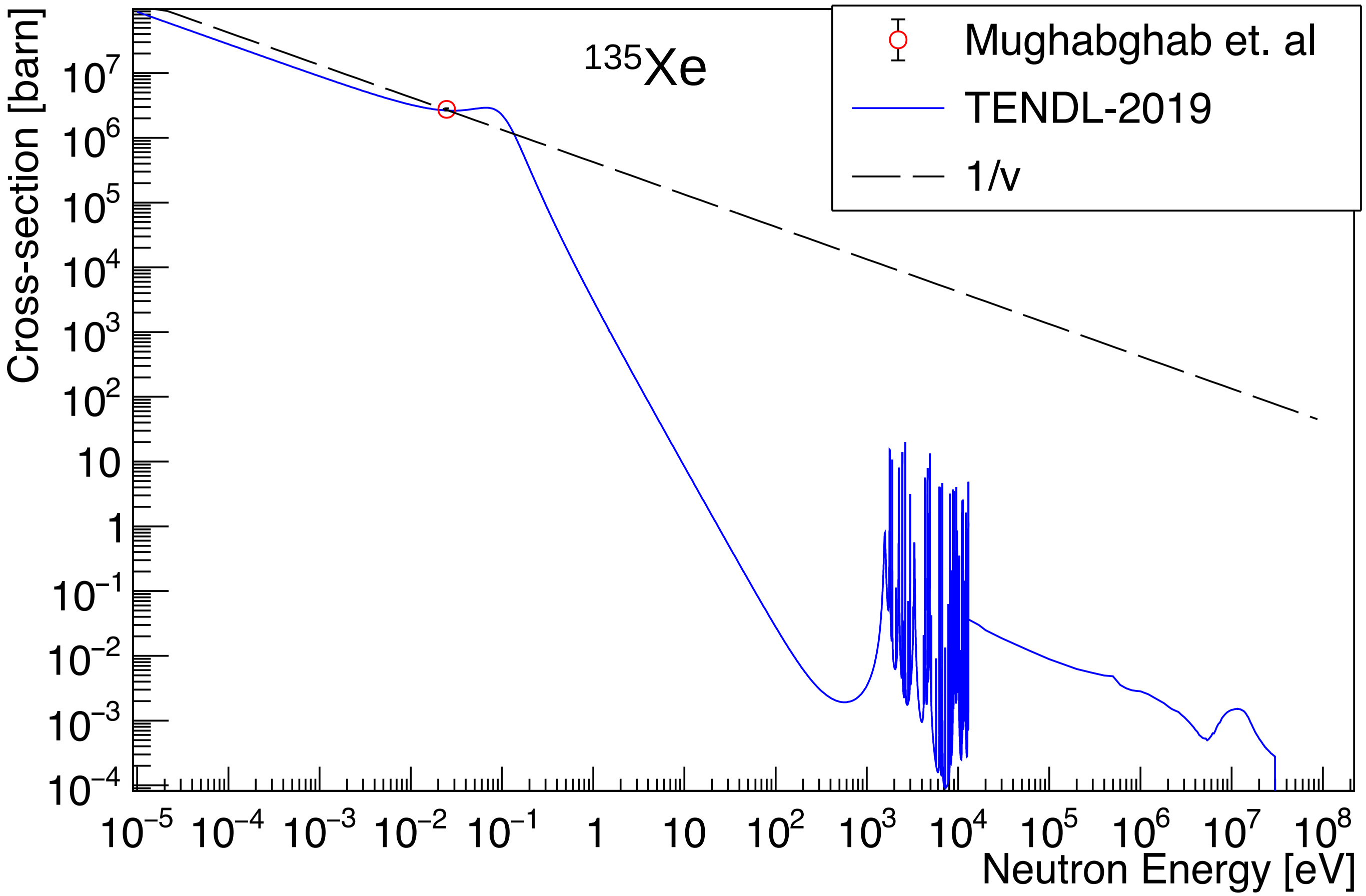
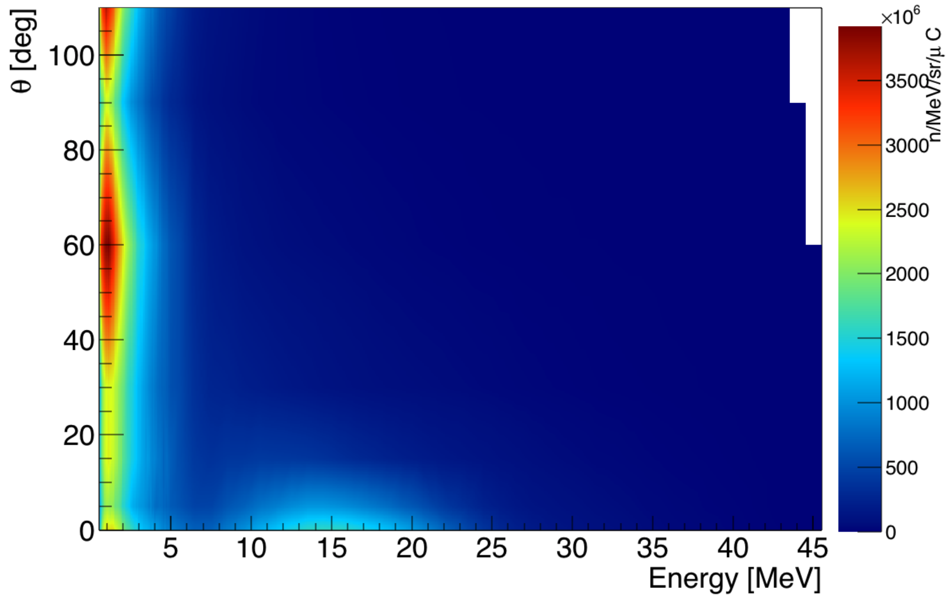
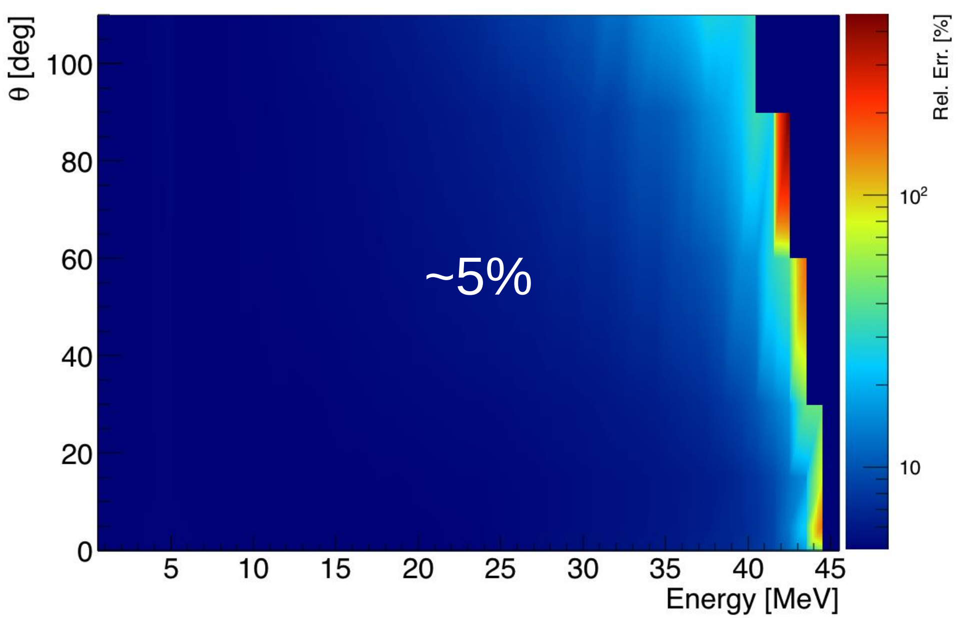
Resonance



^{135}Xe
Mughabghab et. al
TENDL-2019
1/v
Cross-section [barn]
Neutron Energy [eV]
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8}

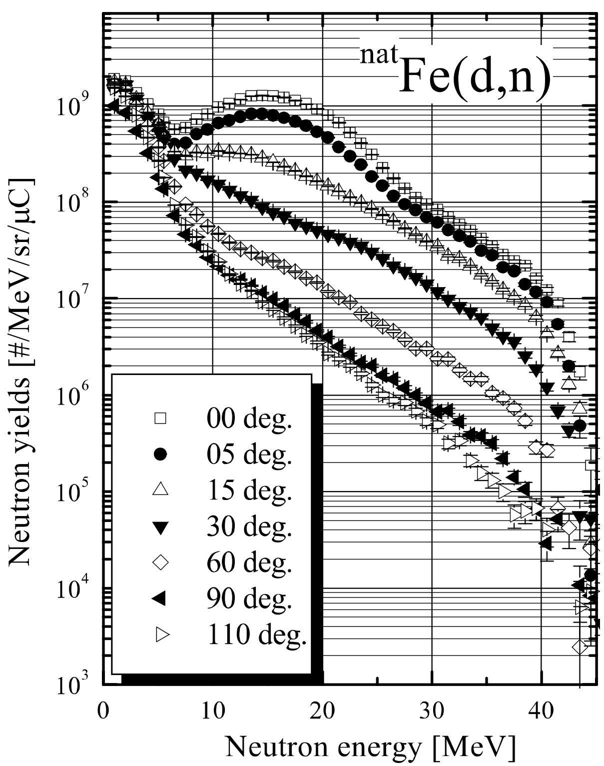
Neutrons





Fe shape is used and normalised to give the GaIn spectrum.

Itoga *et al.* 2006



Expected event rate

FP rate before mass filter	2.1E+09	FPs / sec			
IFY for relevant fission fragment	3.0E-02		Average CFY		
FP rate after mass filter	6.2E+07	FPs/sec			
Accumulation time	300	sec			
Fission fragments in 'target'	1.8E+10	FPs			
flux of cold n from guide on 'target'	1.10E+10	n/sec/cm2			
(n,g) CS on relevant fission fragments	1.00E+00	barn			
Conversion from barn to cm2	1.0E-24	cm2			
Accumulation factor	0.5	No CS measurment during accumulation			
# of events / sec	1.0E-04	events/sec			
# of events / hour	3.7E-01	events/hr			
resonance ejection efficiency	0.9				
MR-TOF efficiency	0.5				
# of measured events / hour/barn	1.6E-01	measured events/hr/barn			
# of measured events /day/barn	**4.0E+00**	**measured events/day/barn**			

- Evaluated σ(n,γ) for cold neutrons of neutron-rich isotopes range from ~1 barn to ~10's of barns
- Several isotopes have **extremely large** values, e.g., **$\sigma(^{135}Xe(nt_h,\gamma))$ = 2.6e6 barn**
- A very recent surprise[1]: **$\sigma(^{88}Zr(n_{th},\gamma))$ = 8.6e5 barn**. Prediction (TALYS) ~10 barn
- We may find more such 'surprises' Nature 565, 328 (2019)