Neutron-induced cross section measurements using the Liquid Lithium Target at SARAF

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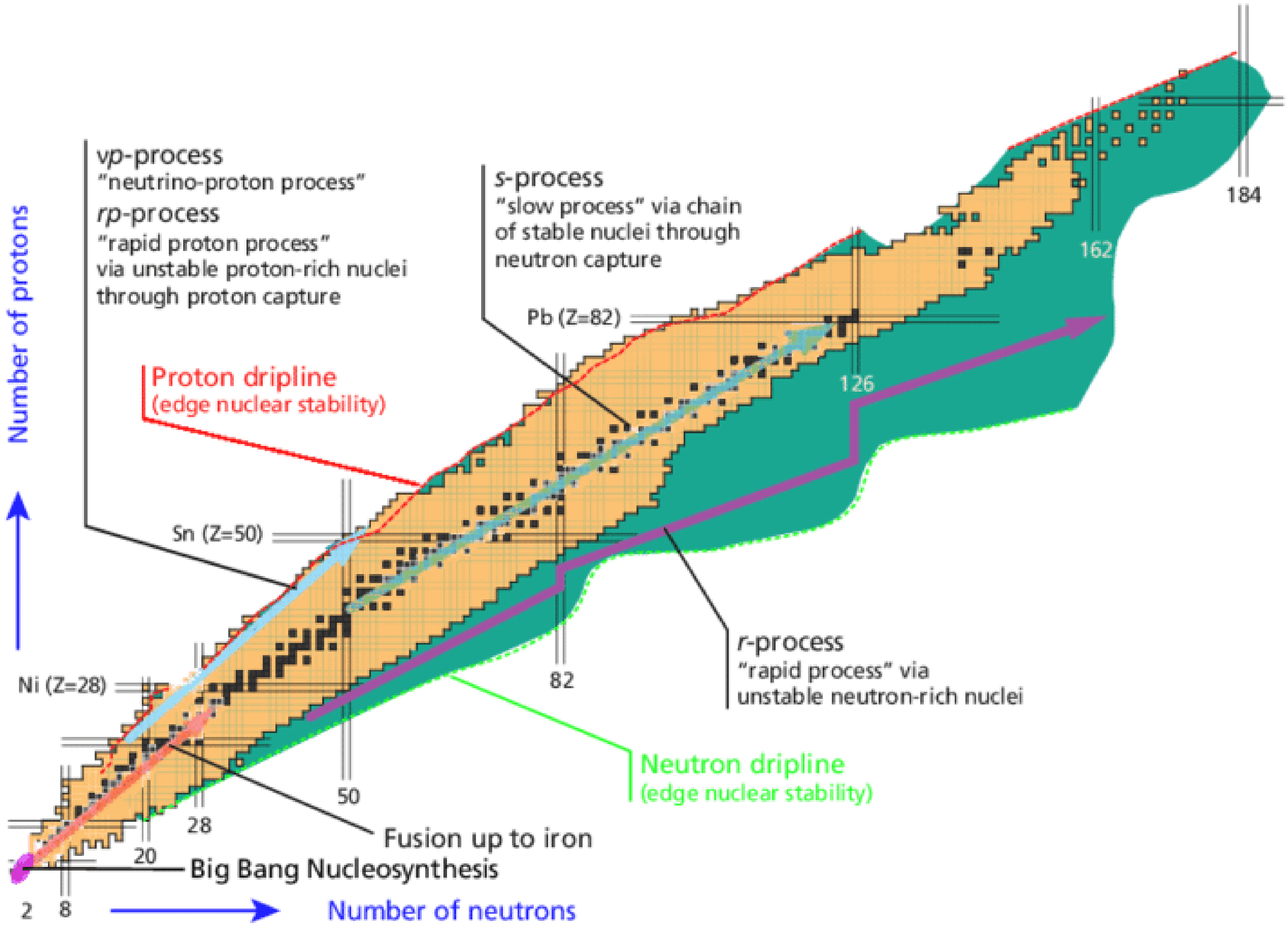
NPA-X

CERN 5/9/2022

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Main stellar nucleosynthesis processes

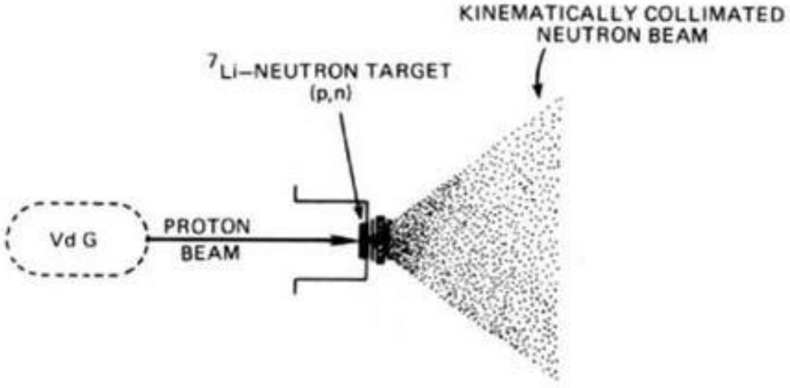


Rodríguez, Tomás. (2014). J Phys. Conf. Ser. 503. 012038.

^{7}Li(p,n)^{7}Be as a neutron source

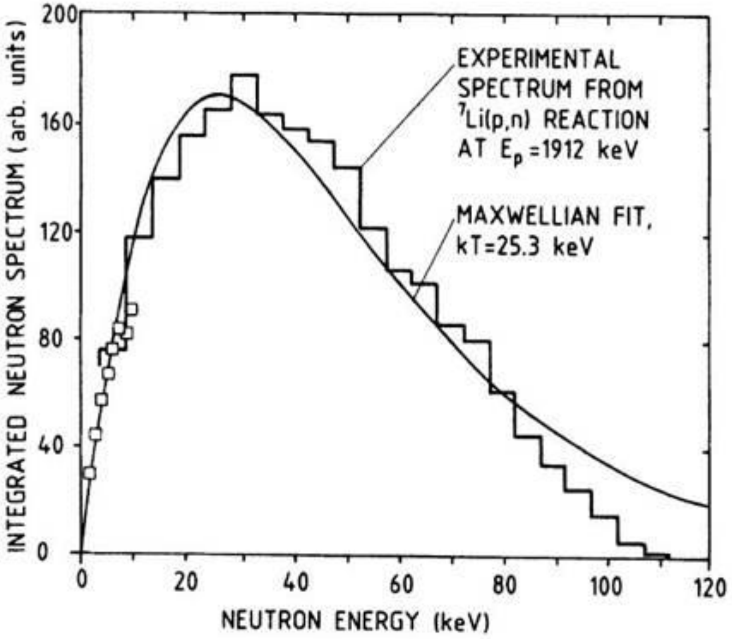
Q= -1.644 MeV

$E_{th}(p)$= 1.881 MeV → $E_n \approx 27$ keV



$$\frac{dN}{dE_n} \propto E_n \exp(-E_n / kT)$$

Thick target integral spectrum:



W. Ratynski and F. Käppeler,
PRC 37, 595 (1988)

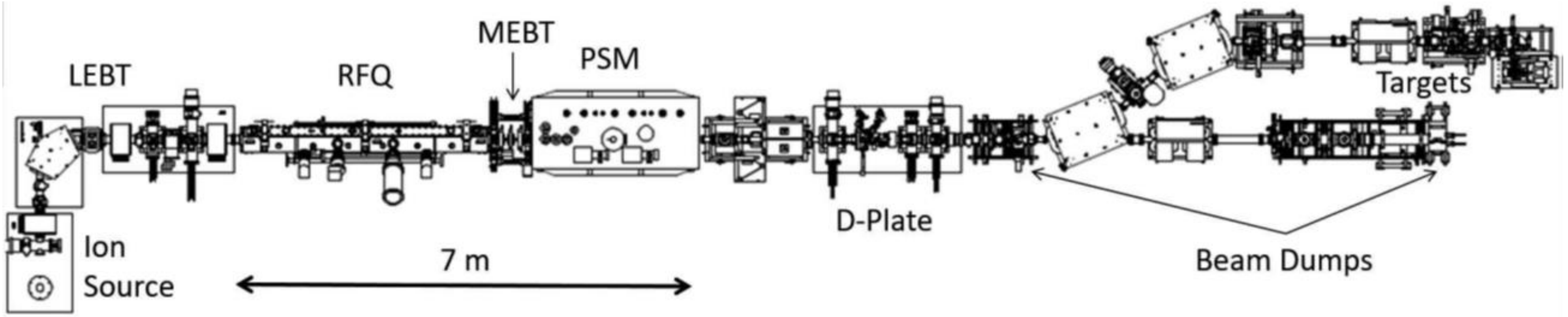
- For E_p=1912 keV → quasi-Maxwellian energy flux distribution with kT≈25 keV
- Neutron emission: forward cone with ~ ±60° opening angle

$$MACS = \frac{2}{\sqrt{\pi}} \frac{1}{(kT)^2} \int \sigma(E) \cdot E \cdot \exp(-E/kT) \cdot dE$$

Soreq Applied Research Accelerator Facility (SARAF): Phase I

2 mA ≈ 10^{16} protons/sec

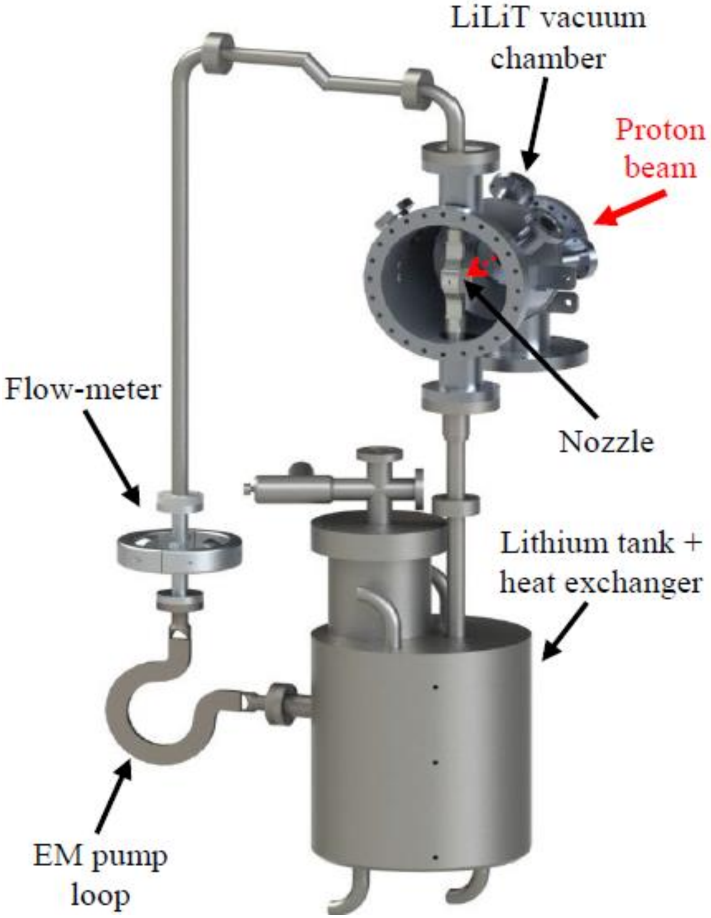
2 mA @ 2 MeV --> 4 kW beam power



I. Mardor *et al.*, EPJ A **54**, 91 (2018)

Liquid Lithium Target (LiLiT)

Beam power: ~2 kW



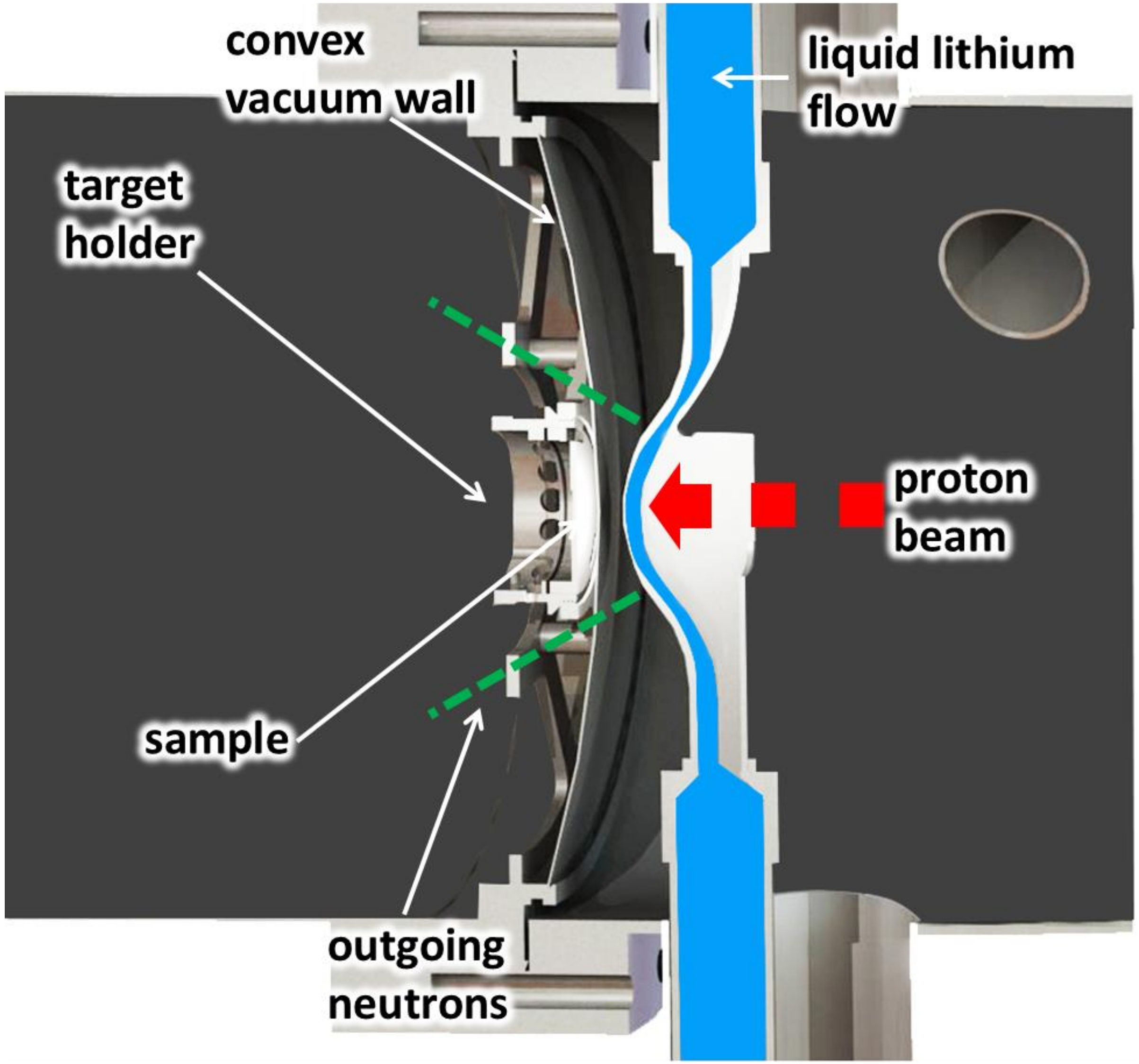
Peak power areal density: ~2.5 kW/cm^2

Peak power volume density: ~0.5 MW/cm^3

S. Halfon *et al.*, RSI **84**, 12350 (2013)

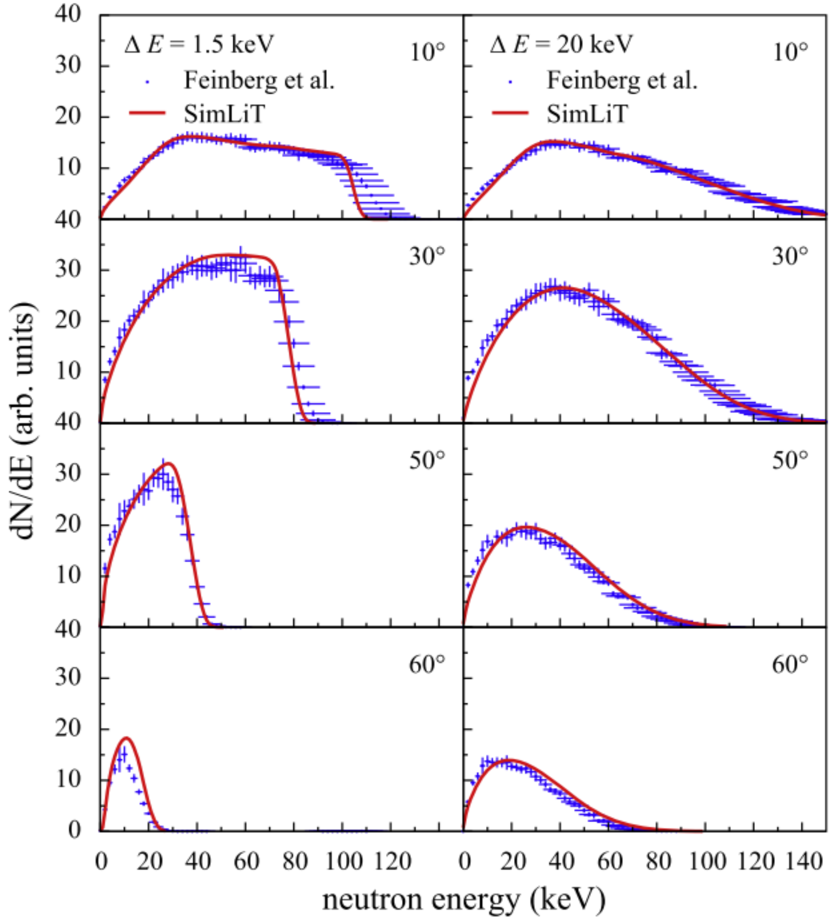
S. Halfon *et al.*, RSI **85**, 056105 (2014)

Experimental setup

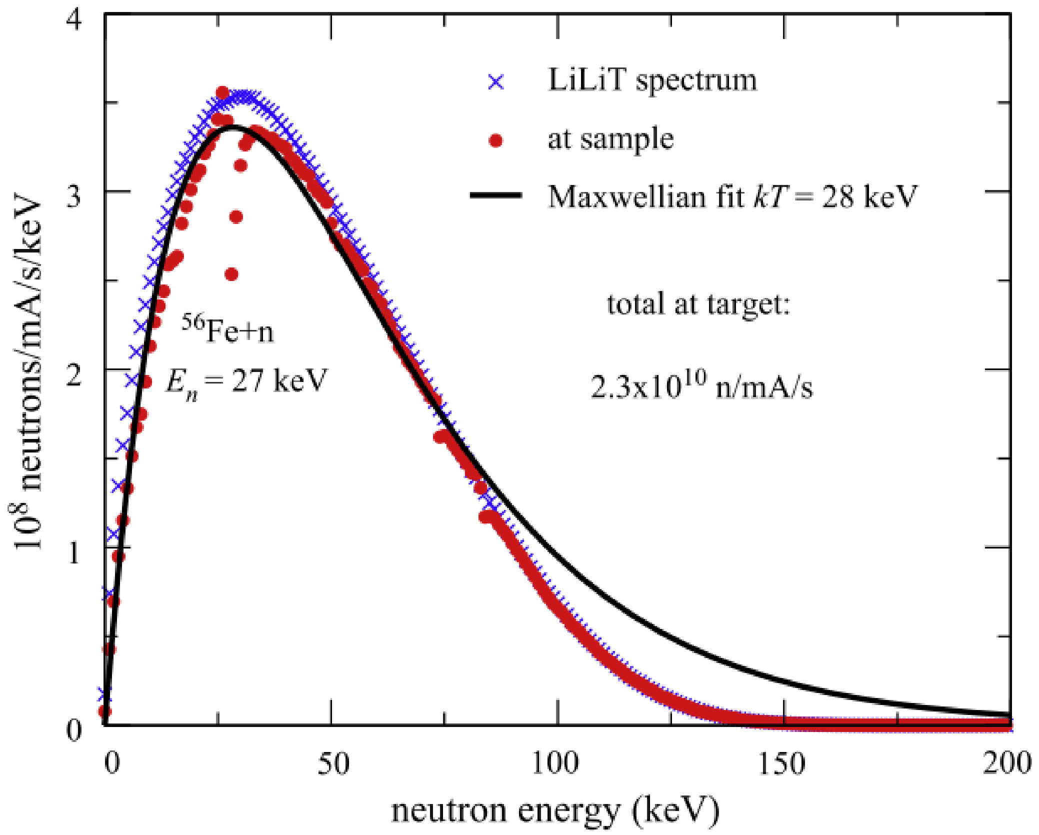


Neutron spectrum and transport simulation

SimLiT



SimLiT+GEANT4

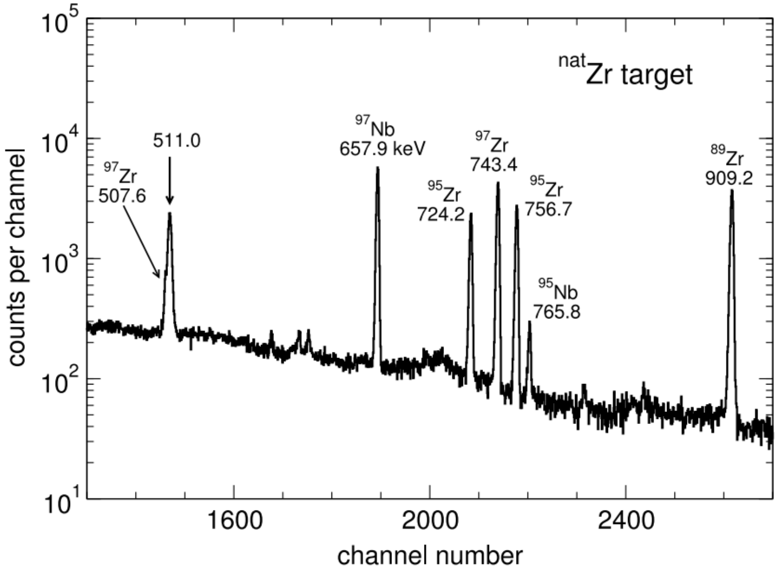


G. Feinberg *et al.*, PRC **85**, (2012)

M. Friedman *et al.*, NIM A **698**, (2013)

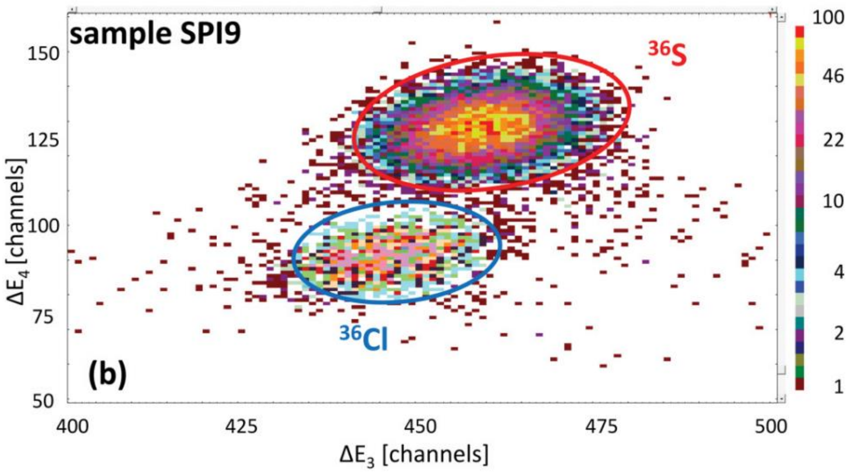
Product measurement

γ-spectroscopy



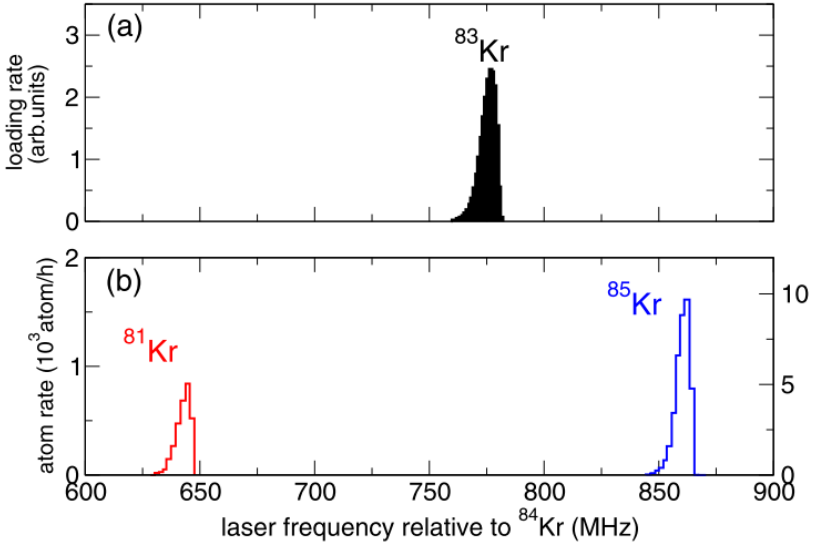
M. Tessler *et al.*, PLB **751**, (2015)

AMS



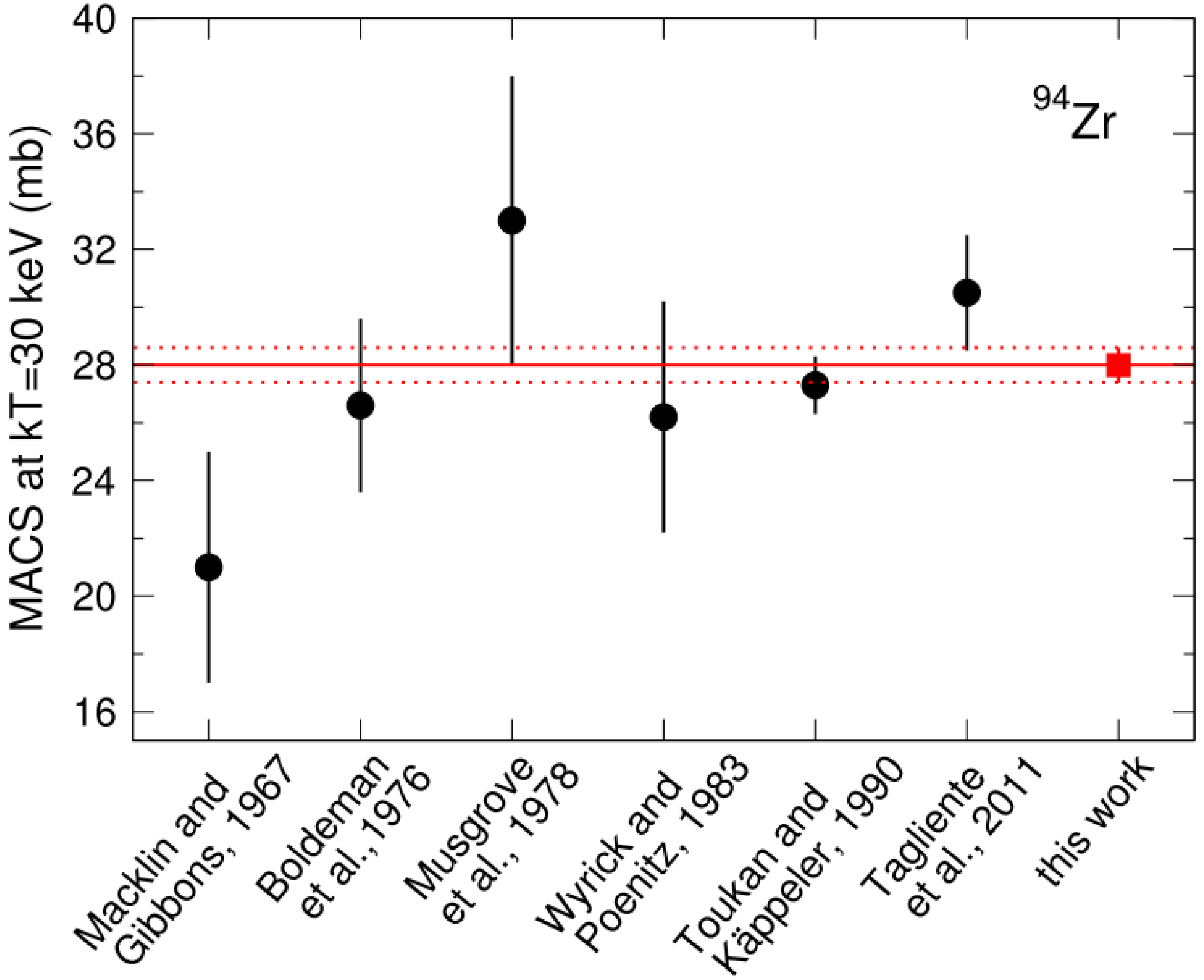
M. Tessler *et al.*, PRL **121**, (2018)

atom trap trace analysis



M. Tessler *et al.*, PRC **104**, (2021)

Commissioning experiment – $^{94,96}Zr(n,\gamma)$



M. Tessler *et al.*, PLB **751**, (2015)

Phase-I experiments

Reaction	Detection tech.	Hebrew U, SARAF and collaborations below
$^{94,96}Zr(n,\gamma)$	γ spect.	–
$^{90}Zr(\gamma,n)$	γ spect.	–
$^{7}Be(n,\alpha)$	CR39	UConn, PSI, ILL WIS, CERN, TUNL
^{23}Na, $^{35,37}Cl(n,\gamma)$	γ spect., AMS	ANU, Goethe U, Rossendorf
$^{36,38}Ar(n,\gamma)$	AMS, LLC	ANL, Goethe U, U Bern
$^{53}Mn(n,\gamma)$	γ spect.	PSI
$^{69,71}Ga(n,\gamma)$	γ spect.	–
$^{74,78,80,82}Se(n,\gamma)$	γ spect.	–
$^{78,80,84,86}Kr(n,\gamma)$	γ spect., ATTA, LLC	ANL, Goethe U, U Bern
$^{80,82,86}Kr(\gamma,n)$	γ spect., ATTA	ANL, Goethe U
$^{92}Zr(n,\gamma)$	AMS	ANL, ANU
$^{124,126,132,134}Xe(n,\gamma)$	γ spect.	Goethe U
$^{136,138,140,142}Ce(n,\gamma)$	γ spect.	–
$^{147}Pm(n,\gamma)$	γ spect.	U Seville, ILL, PSI
$^{169,171}Tm(n,\gamma)$	γ spect.	U Seville, nTOF, ILL, PSI
$^{208}Pb(n,\gamma)$	β, γ spect.	U Seville
$^{209}Bi(n,\gamma)$	α, β, γ spect.	JRC, Geel

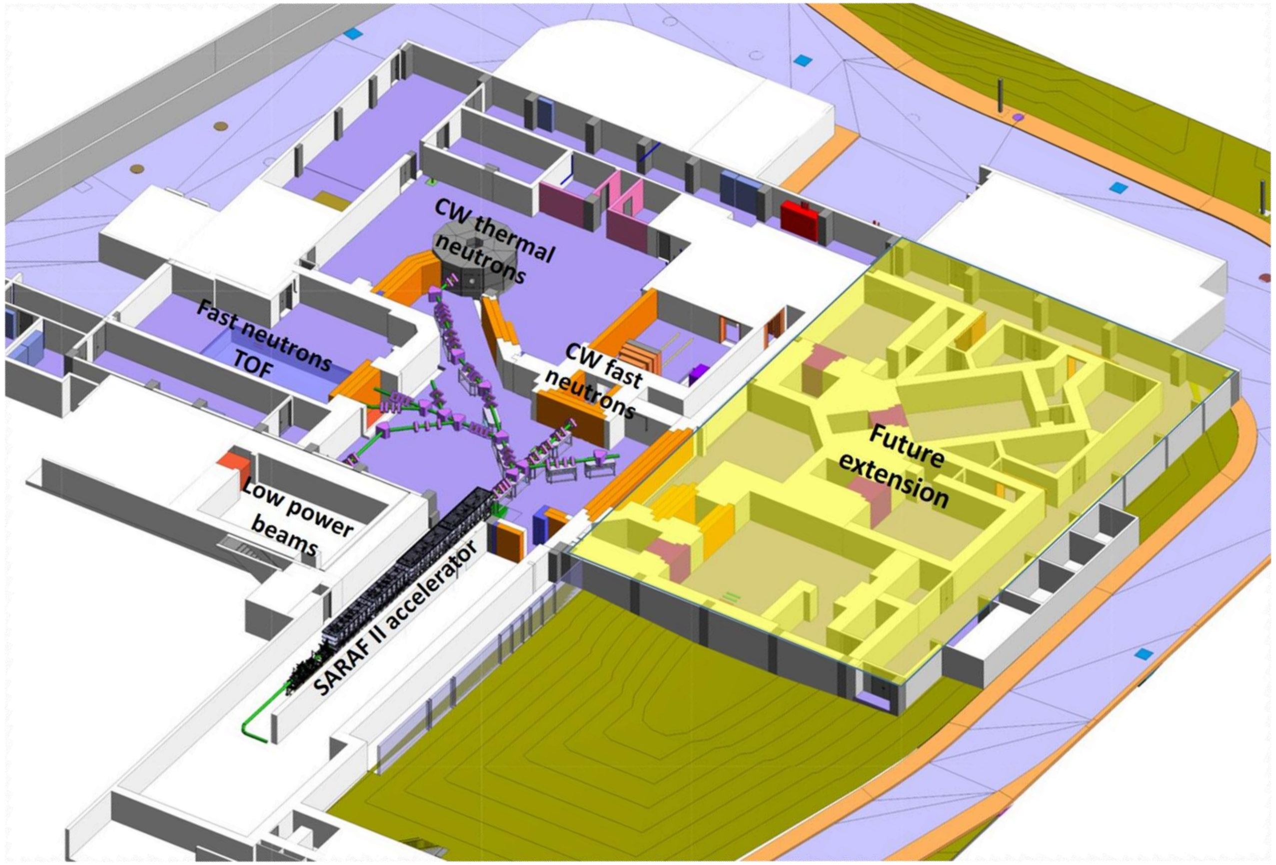
Work led by Michael Paul (HUJI) and Moshe Tessler (SARAF)

SARAF Phase II

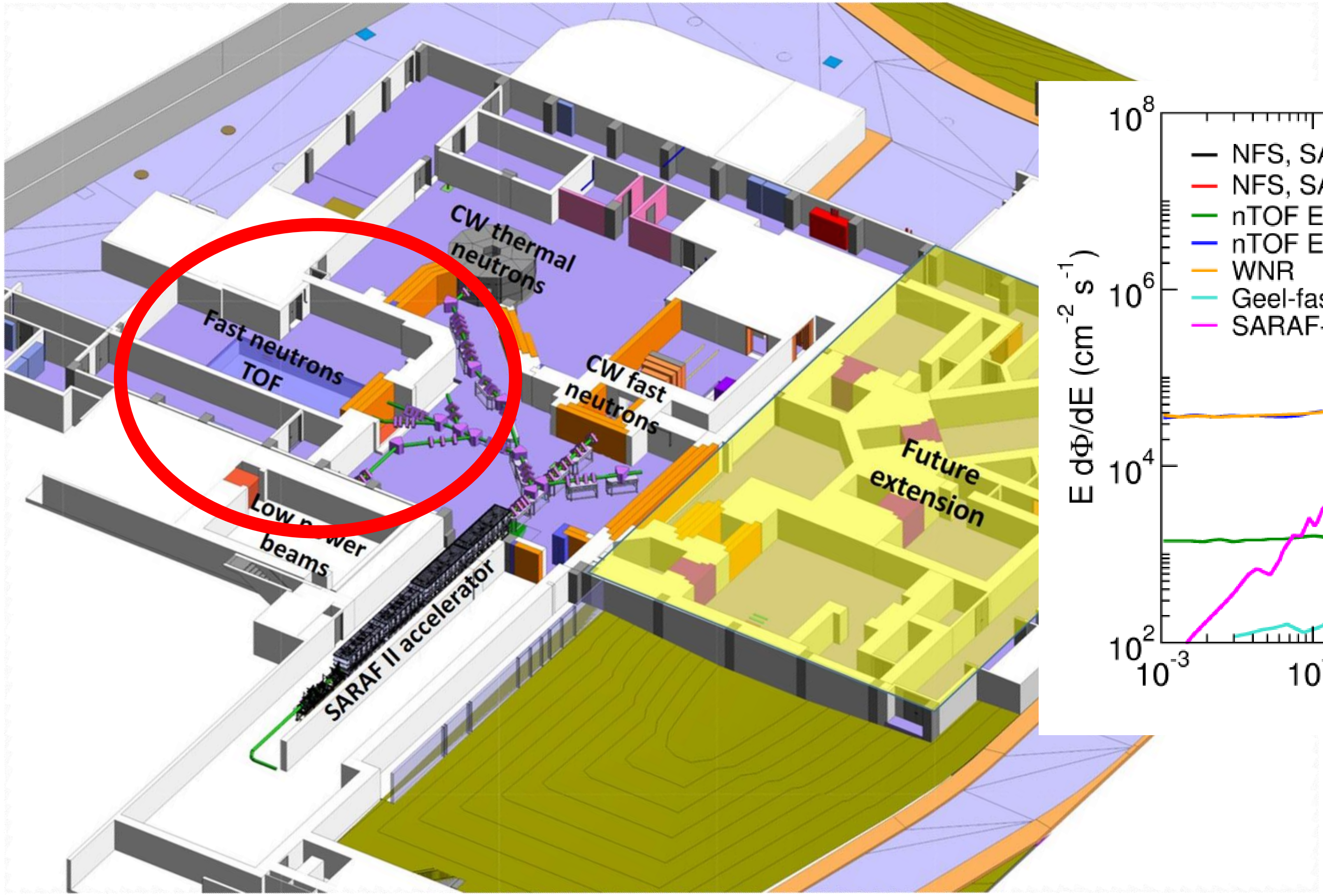
Table 1. SARAF-II beam top-level requirements.

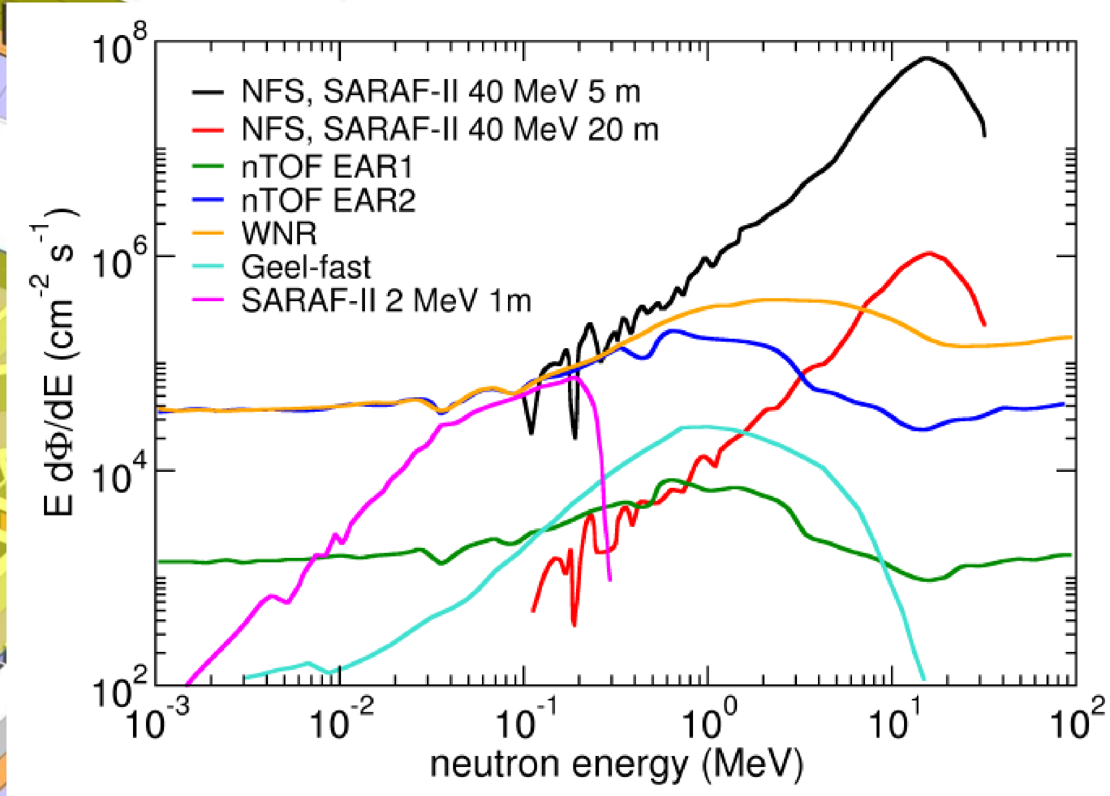
Parameter	Value	Comment
Ion species	protons/deuterons	$M/q \leq 2$
Energy range	5–40 MeV deuterons 5–35 MeV protons	variable energy
Current range	0.04–5 mA	CW (and pulsed)
Operation	6000 hours/year	
Maintenance	hands-on	low beam loss

I. Mardor *et al.*, EPJA **54** (2018)

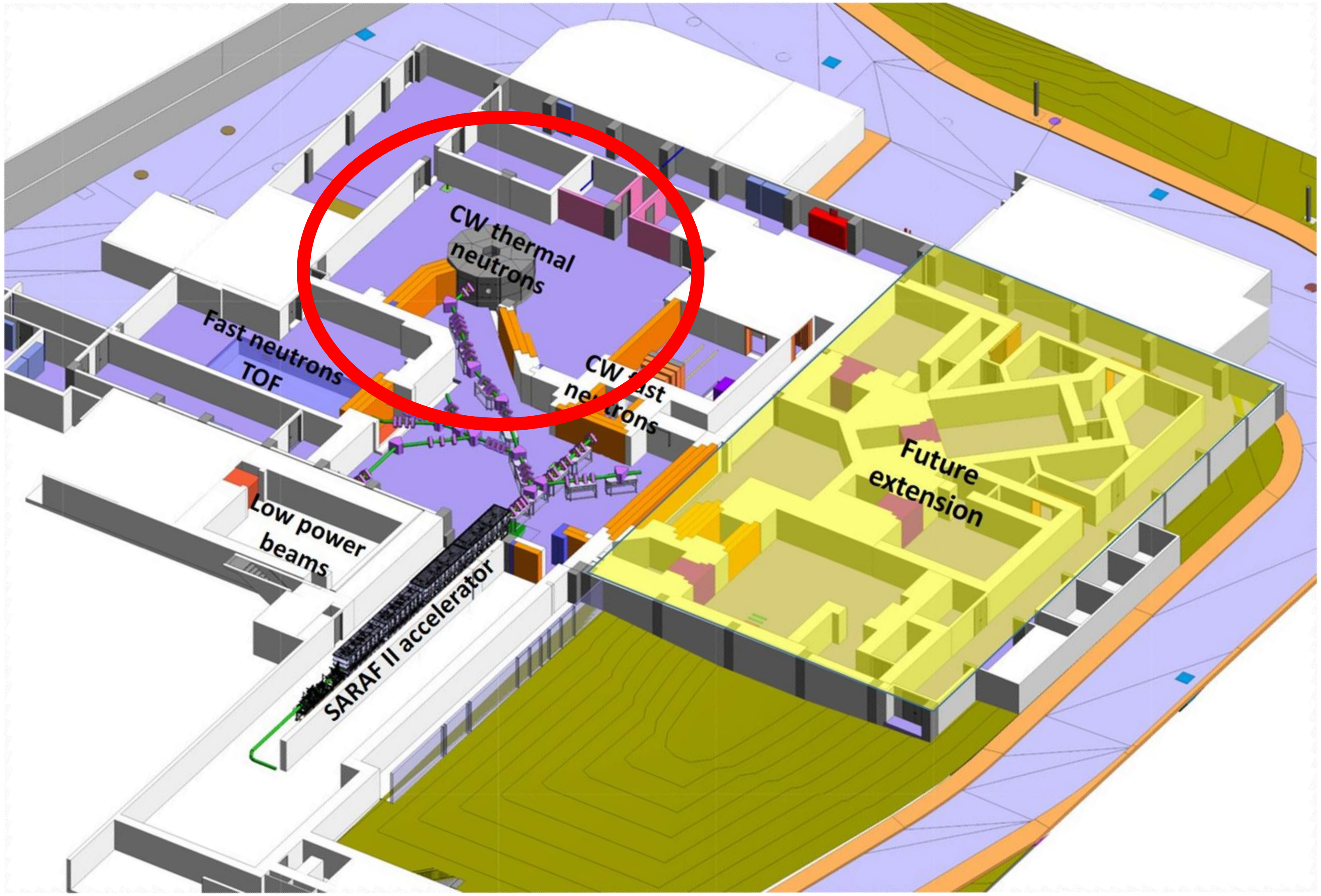


SARAF Phase II – neutron TOF area

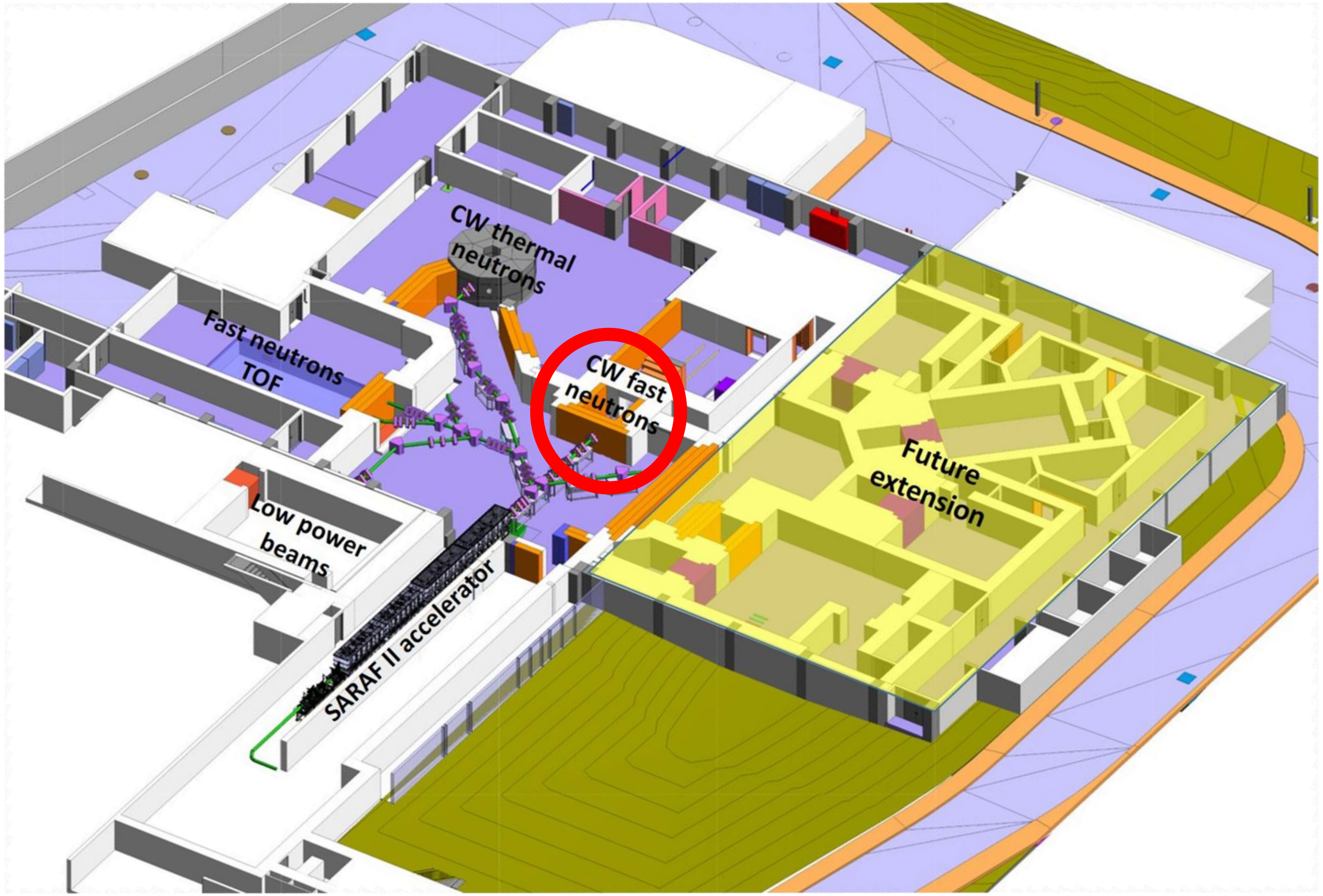




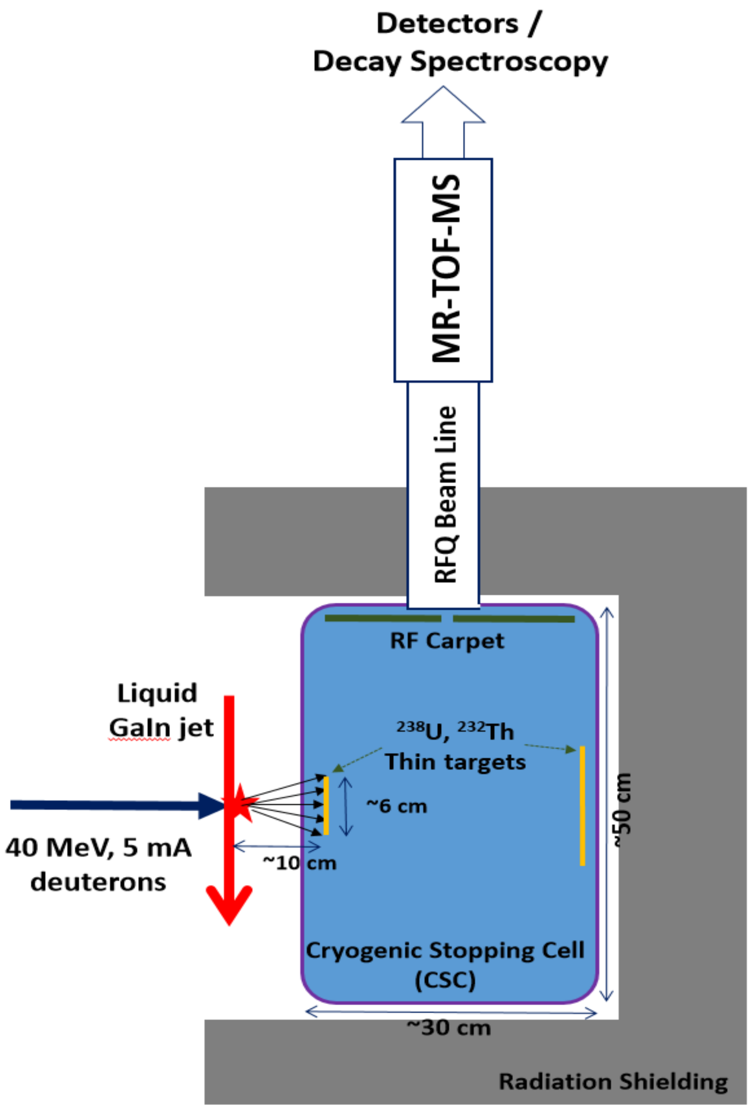
SARAF Phase II – neutron camera

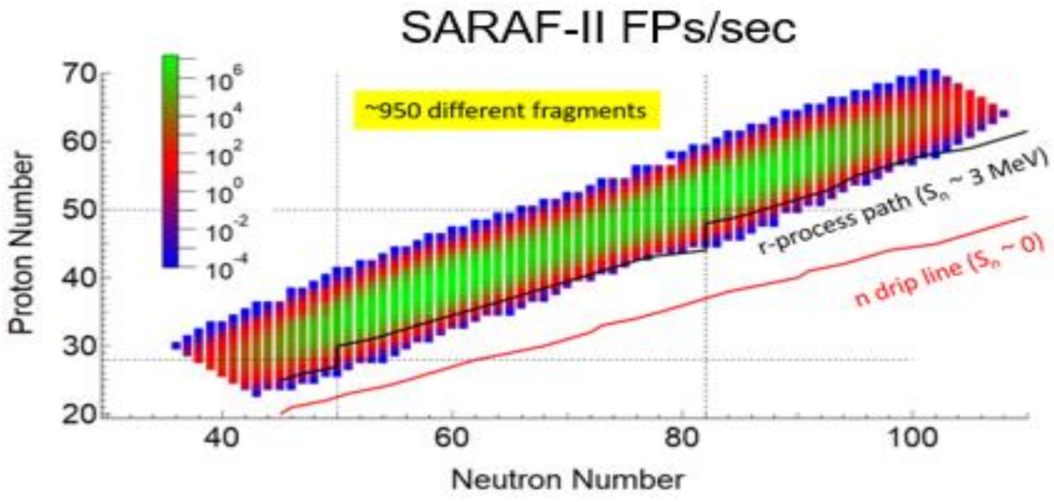


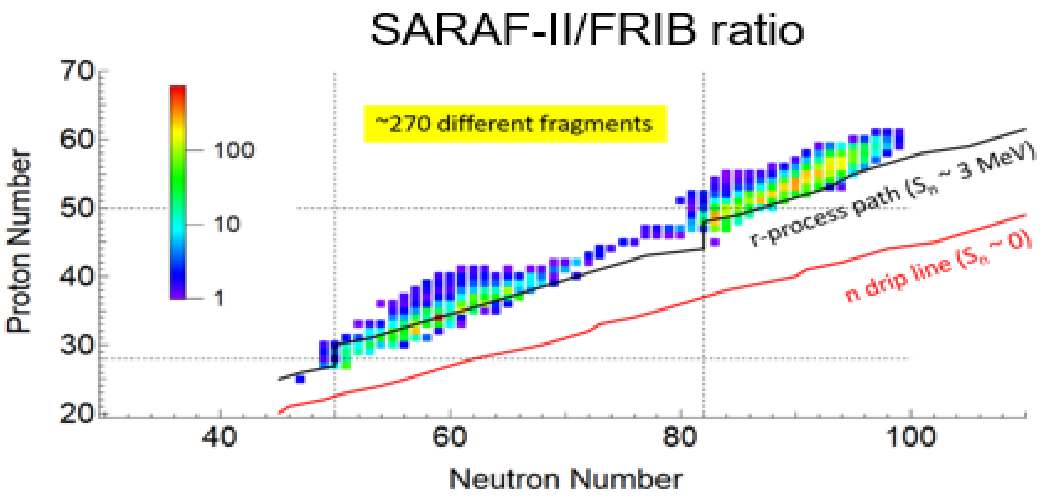
SARAF Phase II – exotic nuclide facility



SARONA - The SARaf exotic Nuclide fAcility

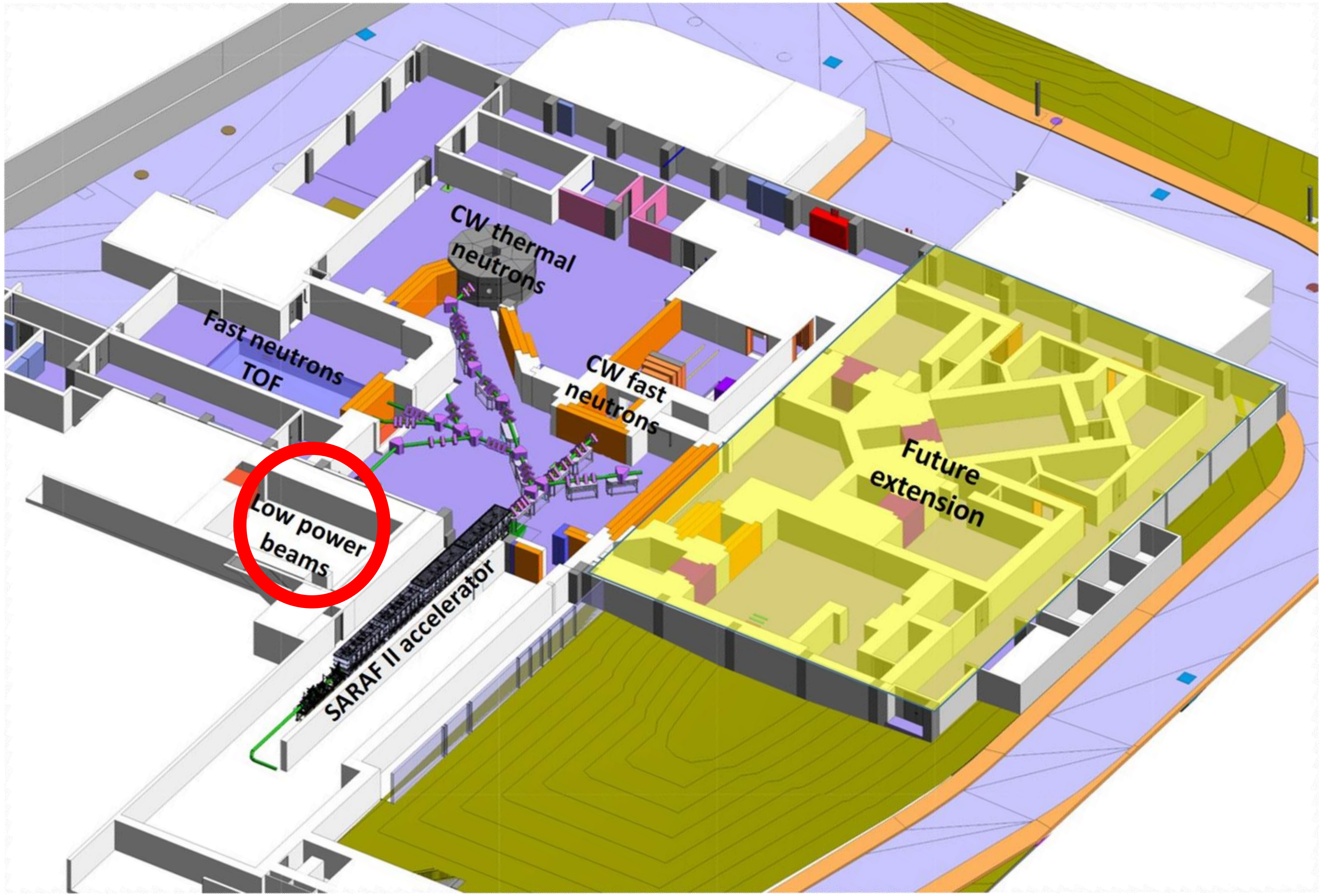






I. Mardor *et al.*, EPJA **54** (2018)

SARAF Phase II – neutron induced cross-sections



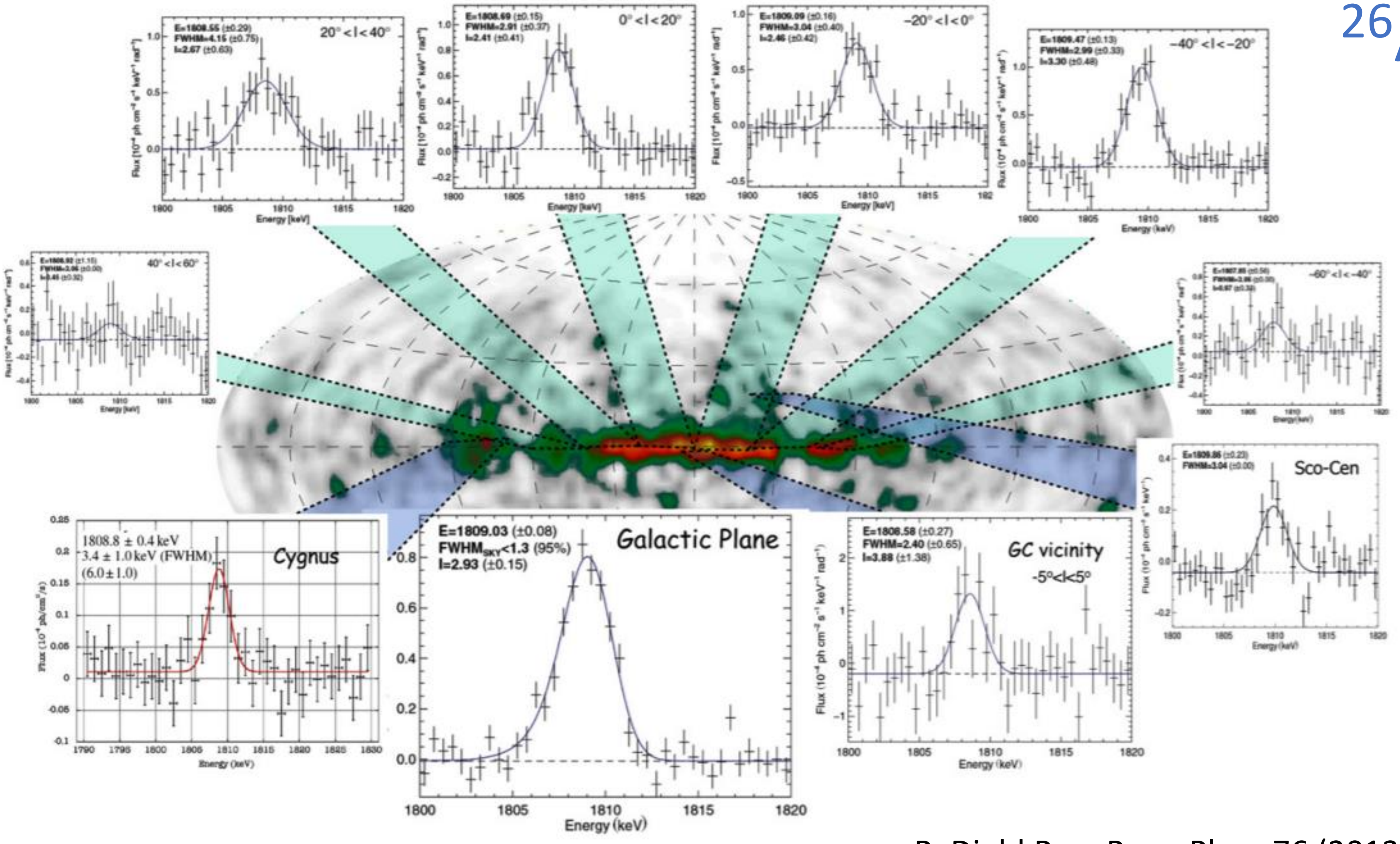
Why (n,p) and (n,α)?

- Supernovae and other explosive scenarios are fast.
- Nucleosynthesis follows sequences of capture-decay processes.
- Waiting points: Long-lived (>minutes) nuclei tend to create bottlenecks. High impact on nucleosynthesis. High abundancies.
- For proton-rich nuclei, (n,p) and (n,α) enhance destruction of waiting-point nuclei.

Gamma emitting ashes

- ^{56}Ni
- ^{44}Ti
- ^{26}Al

^{26}Al



R. Diehl Rep. Prog. Phys. 76 (2013) 026301

Data status

THE ASTROPHYSICAL JOURNAL, 653:474–489, 2006 December 10

SENSITIVITY OF *p*-PROCESS NUCLEOSYNTHESIS TO NUCLEAR REACTION RATES IN A 25 $M_\odot$ SUPERNOVA MODEL

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Received 2005 August 5; accepted 2006 August 14

TABLE 2

SELECTED (γ, p) OR (n, p) REACTIONS

Reactions		
^{126}Ba$(\gamma,p)^{125}$Cs*	^{92}Mo$(\gamma,p)^{91}$Nb*	^{75}Se$(n,p)^{75}$As*
^{110}Sn$(\gamma,p)^{109}$In*	^{86}Rb$(n,p)^{86}$Kr*	^{74}Se$(\gamma,p)^{73}$As*
^{106}Cd$(\gamma,p)^{105}$Ag	^{85}Sr$(n,p)^{85}$Rb*	^{76}As$(n,p)^{76}$Ge*
^{104}Cd$(\gamma,p)^{103}$Ag	^{84}Sr$(\gamma,p)^{83}$Rb*	^{75}As$(\gamma,p)^{74}$Ge*
^{100}Pd$(\gamma,p)^{99}$Rh	^{78}Kr$(\gamma,p)^{77}$Br*	^{73}As$(\gamma,p)^{72}$Ge
^{96}Ru$(\gamma,p)^{95}$Tc*	^{77}Se$(n,p)^{77}$As	^{71}Ge$(n,p)^{71}$Ga

NOTES.—These are reactions that, together with their respective inverse reactions, were found to exhibit the strongest influence on the final *p*-abundances. Their impact is illustrated in Fig. 15*a*. Particularly important rates are marked with an asterisk (*).

-NO DATA FOUND-

Data status

THE ASTROPHYSICAL JOURNAL, 729:46 (18pp), 2011 March 1 doi:10.1088/0004-637X/729/1/4(

UNCERTAINTIES IN THE νp-PROCESS: SUPERNOVA DYNAMICS VERSUS NUCLEAR PHYSICS

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ABSTRACT

We examine how the uncertainties involved in supernova dynamics, as well as in nuclear data inputs, affect the νp-process in the neutrino-driven winds. For the supernova dynamics, we find that the wind termination by the preceding dense ejecta shell, as well as the electron fraction ($Y_{e,3}$; at 3×10^9 K), plays a crucial role. A wind termination within the temperature range of $(1.5–3) \times 10^9$ K greatly enhances the efficiency of the νp-process. This implies that the early wind phase, when the innermost layer of the preceding supernova ejecta is still $\sim$ 200–1000 km from the center, is most relevant to the νp-process. The outflows with $Y_{e,3} = 0.52–0.60$ result in the production of the p-nuclei up to $A = 108$ with interesting amounts. Furthermore, the p-nuclei up to $A = 152$ can be produced if $Y_{e,3} = 0.65$ is achieved. For the nuclear data inputs, we test the sensitivity to the rates relevant to the breakout from the p–p chain region ($A < 12$), to the (n, p) rates on heavy nuclei, and to the nuclear masses along the νp-process pathway. We find that a small variation of the rates of triple-α and of the (n, p) reaction on ^{56}Ni leads to a substantial change in the p-nuclei production. We also find that ^{96}Pd ($N = 50$) on the νp-process path plays a role as a second seed nucleus for the production of heavier p-nuclei. The uncertainty in the nuclear mass of ^{82}Zr can lead to a factor of two reduction in the abundance of the p-isotope ^{84}Sr.

-NO DATA FOUND-

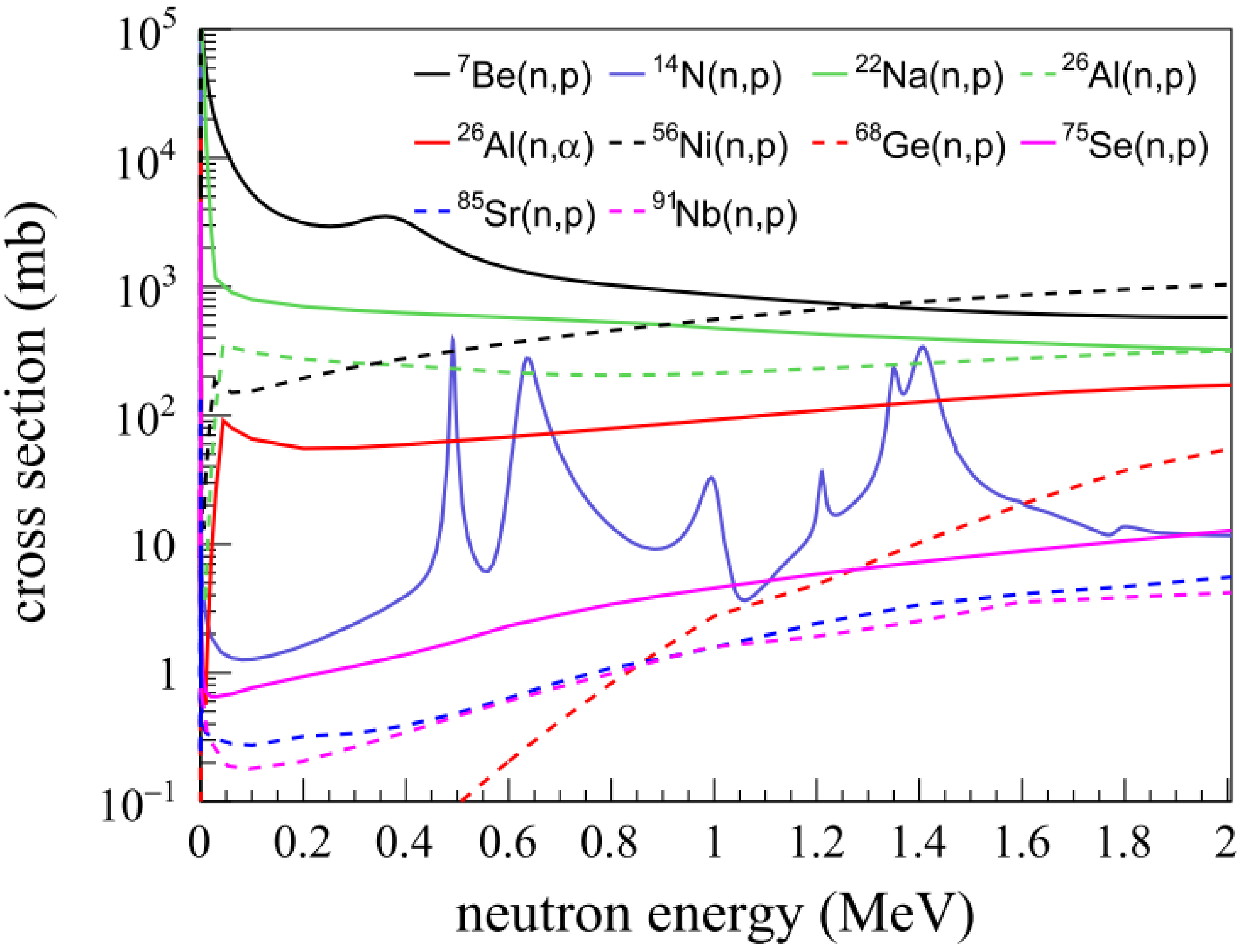
Data status

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 19

THE EFFECTS OF THERMONU
MAS

CHRISTIAN ILIADIS[1,2], A

proximate order of
Tables 2, 4, and 6
five reactions, ^{26}Al(n
^{23}Na(α,p)^{26}Mg, and
future measurements
which the rate needs
Ne/C burning, ≈1.4



/ C **104**, L022803 (2021)

massive stars: Study of the key ^{26}Al(n, p) reaction

W C **104**, L032803 (2021)

massive stars: Study of the key ^{26}Al(n, α) reaction

nd ^{26}Al(n,α)
to ~150 keV

21). PRC 104 L022803
C. Lederer et al. (2021). PRC 104 L032803

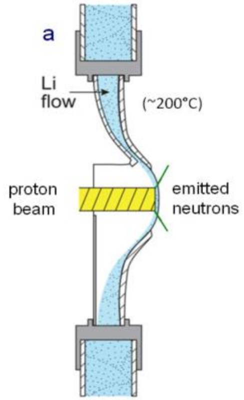
Motivation: *(n,p)* and *(n,α)* data scarce, especially for unstable proton-rich isotopes. (^{26}Al*(n,p)*, ^{56}Ni*(n,p)* and more).

Goal: Establish an apparatus for *(n,p)* and *(n,α)* measurements on stable <u>and unstable</u> isotopes at explosive stellar temperatures (~1.5-3.5 GK, ~10-2000 keV).

Protons - SARAF

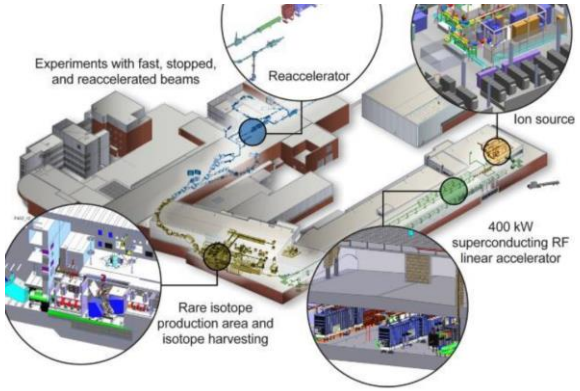
2-5 MeV protons
Beam current > 1 mA.

Neutrons - LiLiT



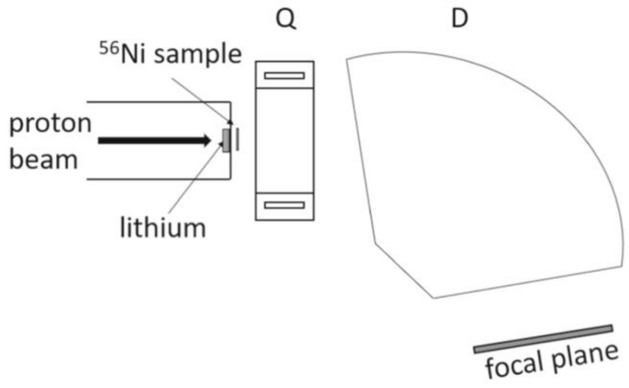
keV neutrons via ^{7}Li(p,n)
Operational

Targets - FRIB



Isotope Harvesting project
E. Abel *et al.* J. Phys. G 46 (2019)

Detection

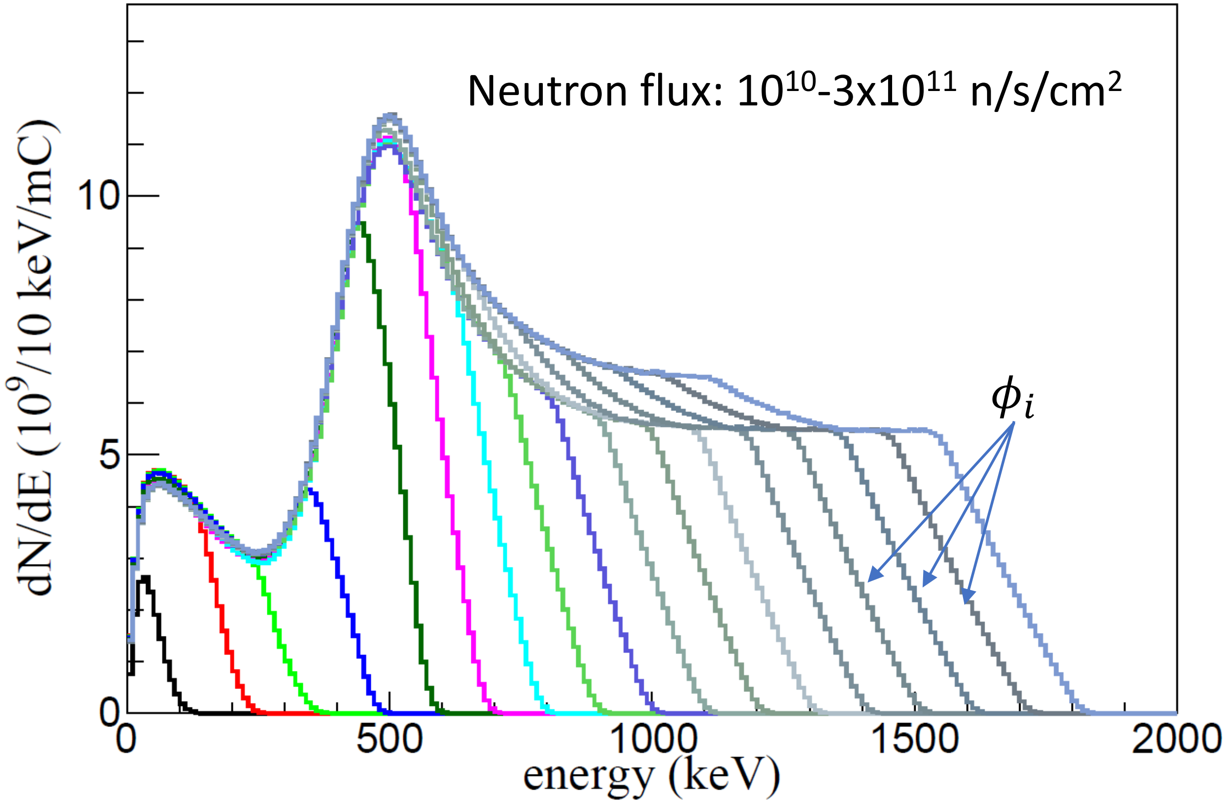


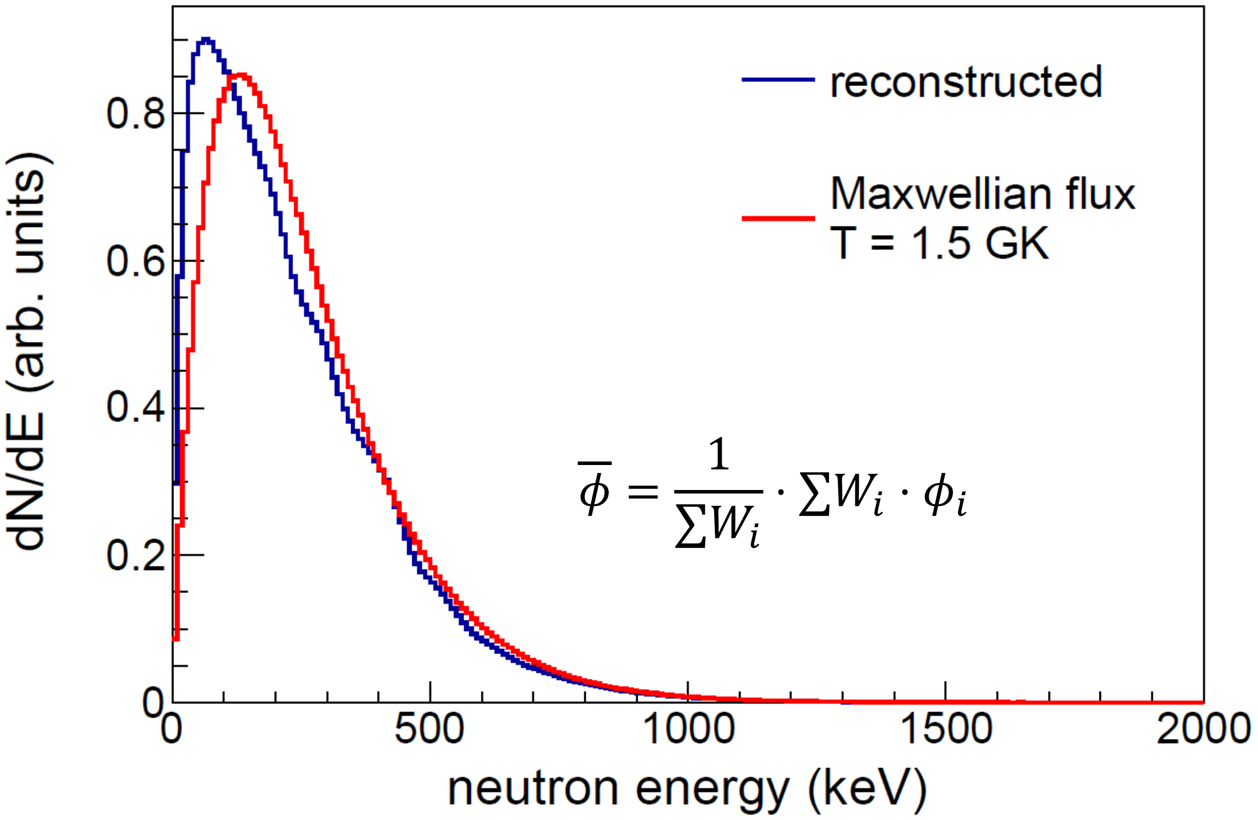
Design stages
efficiency ~0.5%

->See also a talk by Pelagia Tsintari about (n,p) studies with SECAR!

Neutrons for studies of explosive nucleosynthesis

neutron energy spectra for different proton energies
E_p = 1900-3600 keV





^{56}Ni*(n,p)* ($t_{1/2}$ = 6 d)
Sample size: 1 mCi ($3x10^{13}$ atoms)
Detection rate: 1-150 counts/hour (TENDL2019)

M. Friedman, EPJA **56** (2020)

Effect of differences in the neutron spectrum

	calculated cross section (mb)					
	T = 1.5 GK			T = 3.5 GK		
reaction	Maxwell.	reconst.	corr.	Maxwell.	reconst.	corr.
$^{14}N(n,p)$	9.10	9.08	1.00	27.1	27.9	0.97
$^{26}Al(n,p)$	266	261	1.02	242	241	1.00
$^{26}Al(n,\alpha)$	61.2	60.6	1.01	73.3	72.9	1.01
$^{40}K(n,p)$	8.21	9.17	0.90	11.47	11.89	0.96
$^{40}K(n,\alpha)$	22.63	26.49	0.85	25.34	27.59	0.92

Summary

- LiLiT @ SARAF is a high-intensity neutron source for s-process measurements, with a neutron flux on the order of 10^{10} n/s on the sample.
- During the operation of SRARAF Phase-I, LiLiT produced many MACS values of relevance for the s-process, and is expected to continue conducting similar measurement in the future.
- SARAF Phase-II will provide new opportunities for nuclear nucleosynthesis studies.
- LiLiT will also be used to produce higher energy neutrons, which will allow direct (n,p) and (n,α) cross section at explosive stellar temperatures.

Thanks for listening!