Nuclear Physics Mid Term Plan in Italy

LNL – Session

Legnaro, April 11th-12th 2022

Nucleosynthesis of trans-iron elements

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Neutron Pathways to Nucleosynthesis

- ✓ The r process
  (neutrino-wind, NS mergers, jet-SNe, etc)
  Nn 10^{20} n cm^{-3};

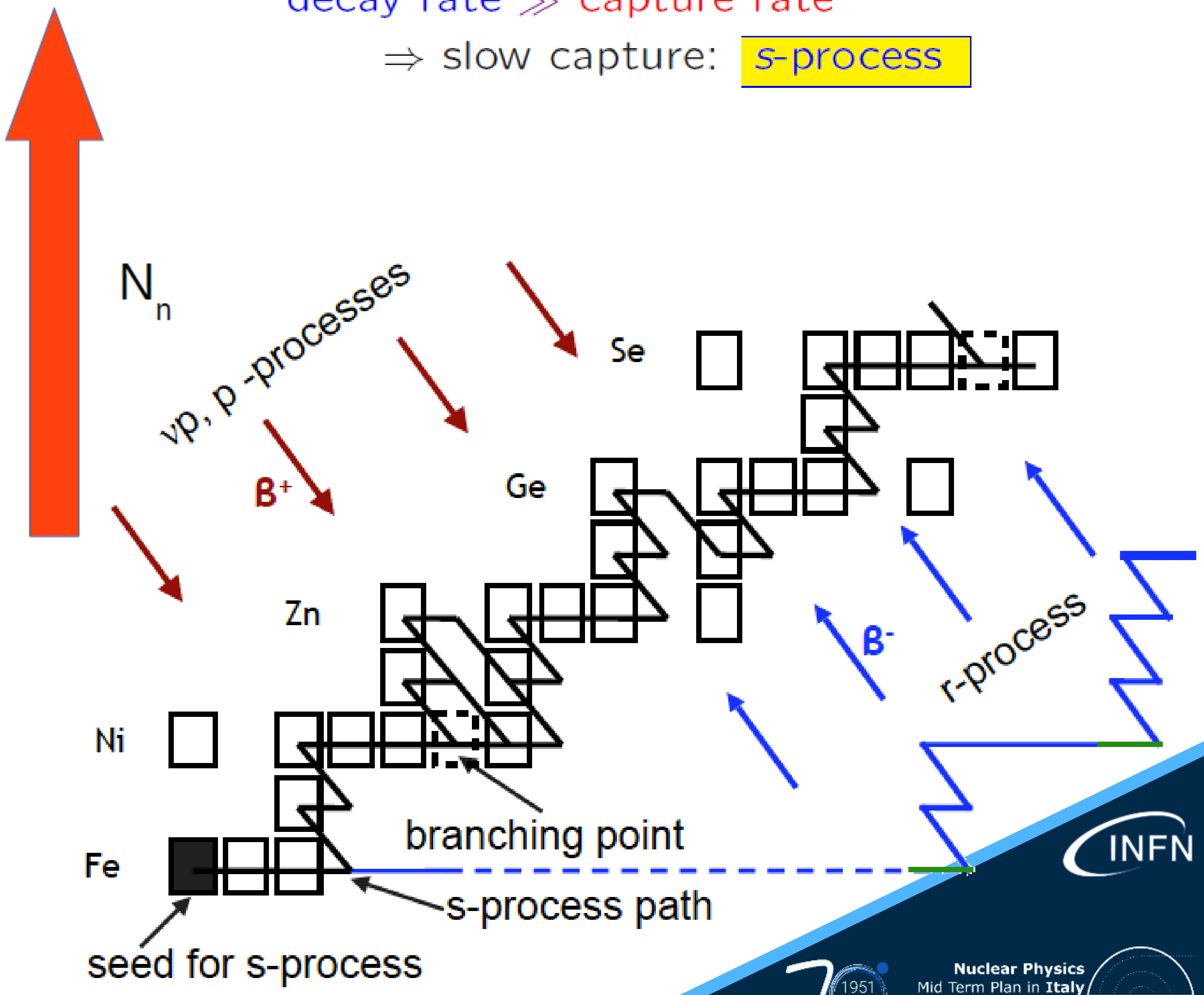
- ✓ The n process
  (explosive He-burning in CCSN)
  10^{18} n cm^{-3} < Nn < 10^{20} n cm-^{3};

- ✓ The i process
  (H ingestion in convective He burning conditions)
  10^{14} n cm^{-3} < Nn < 10^{16} n cm^{-3};

- ✓ Neutron capture triggered by the $^{22}Ne(\alpha,n)^{25}Mg$
  in massive AGB stars and super-AGB stars
  Nn < 10^{14} n cm^{-3};

- ✓ The s process
  (s process in AGB stars, s process in massive stars and fast rotators)
  Nn < few 10^{12} n cm^{-3} .

capture rate $\gg$ decay rate
$\Rightarrow$ rapid capture: *r*-process
decay rate $\gg$ capture rate
$\Rightarrow$ slow capture: *s*-process



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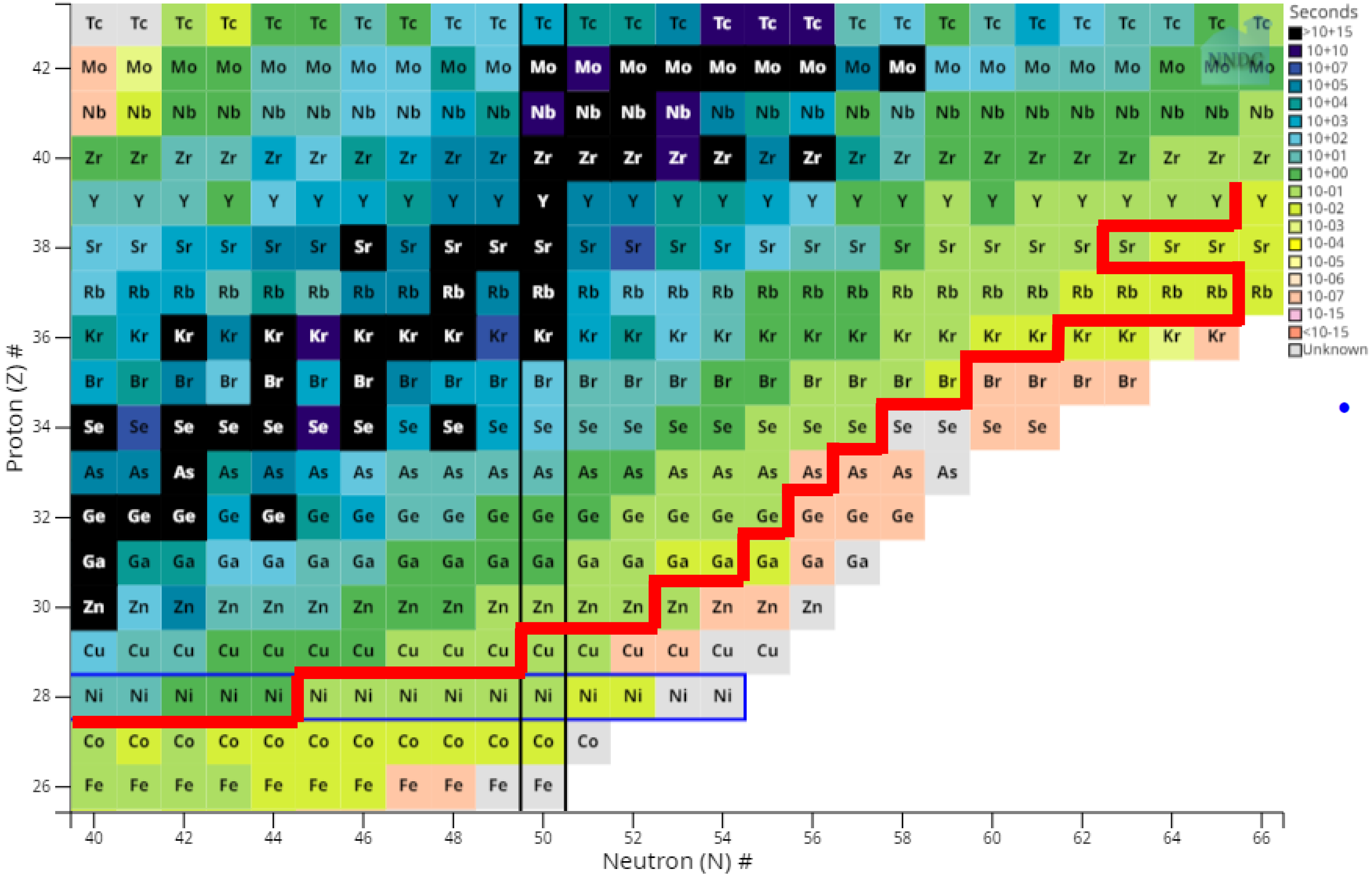
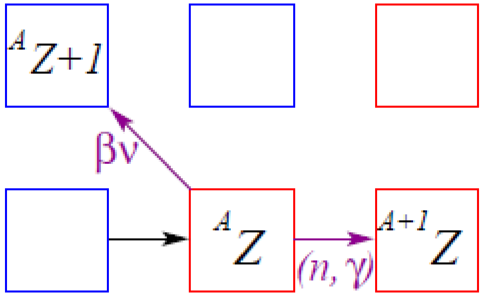
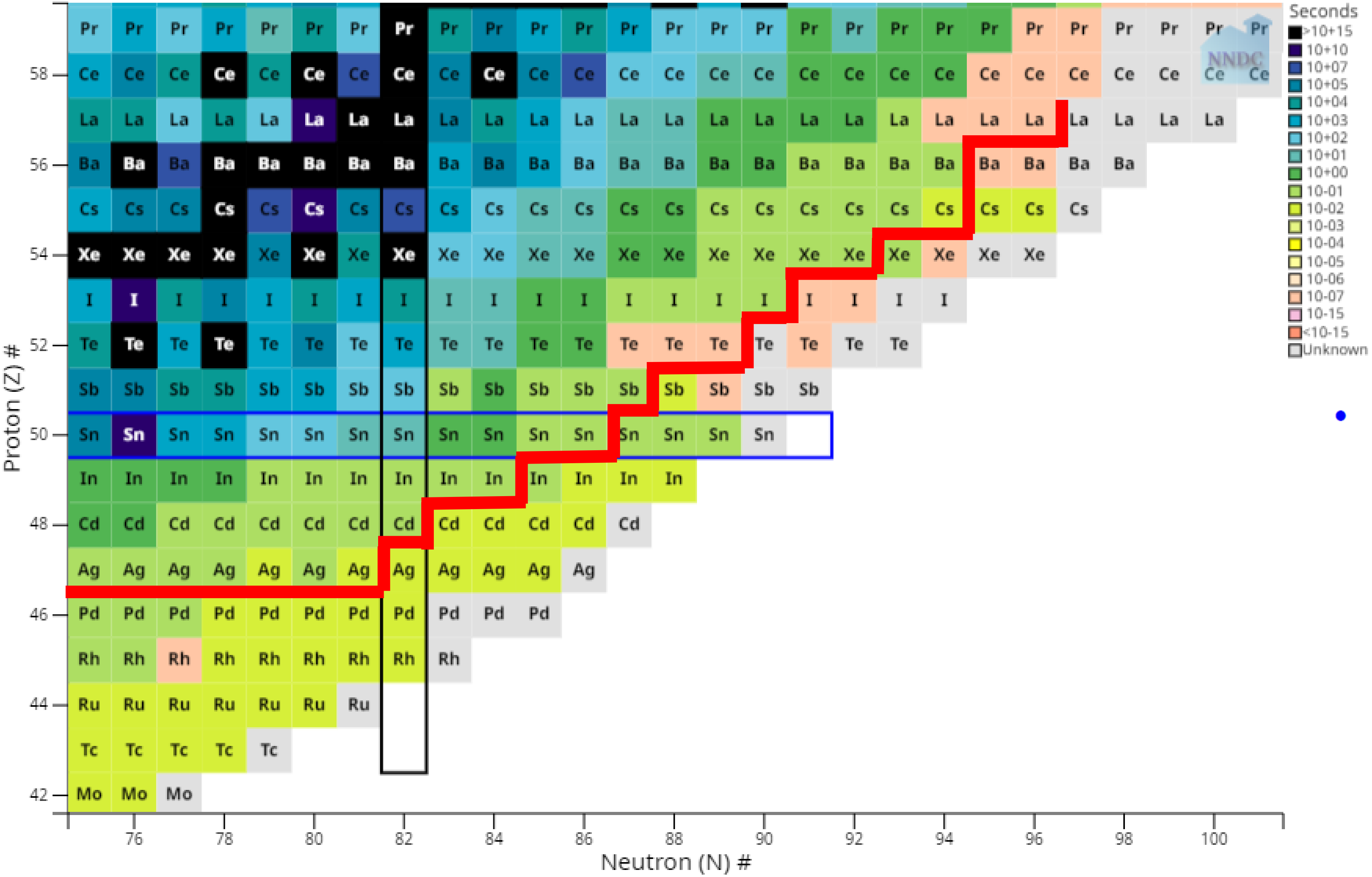
Experimental nuclear data at 1rst peak

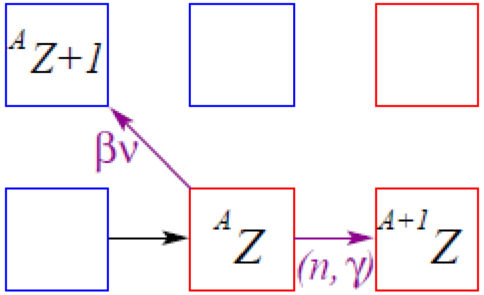




- beta decay rates ^{89}As

Experimental nuclear data at 2nd peak

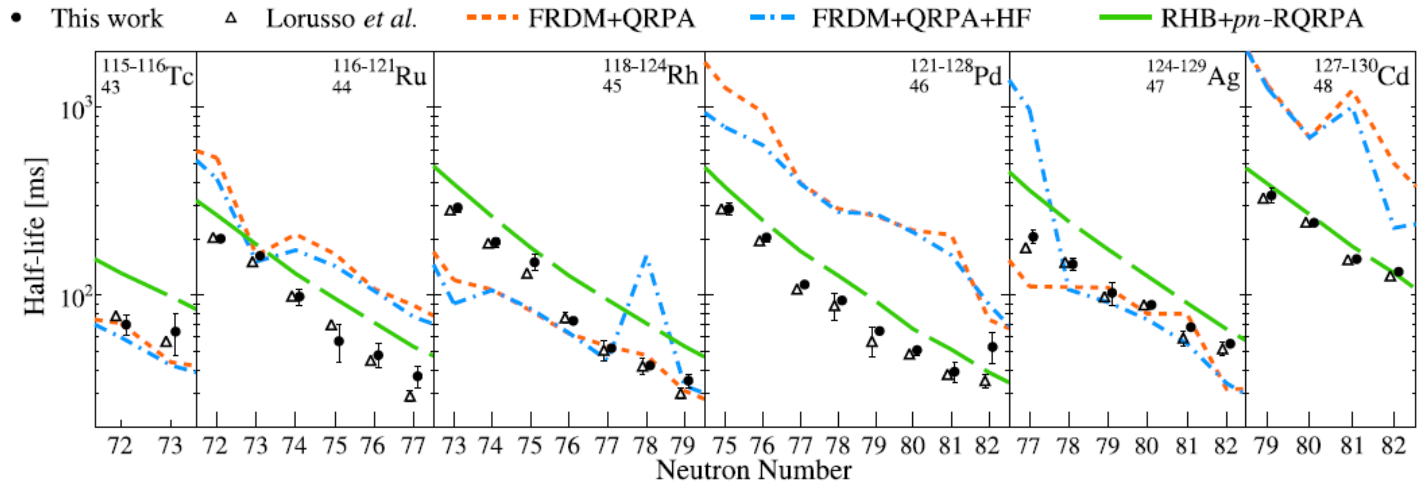


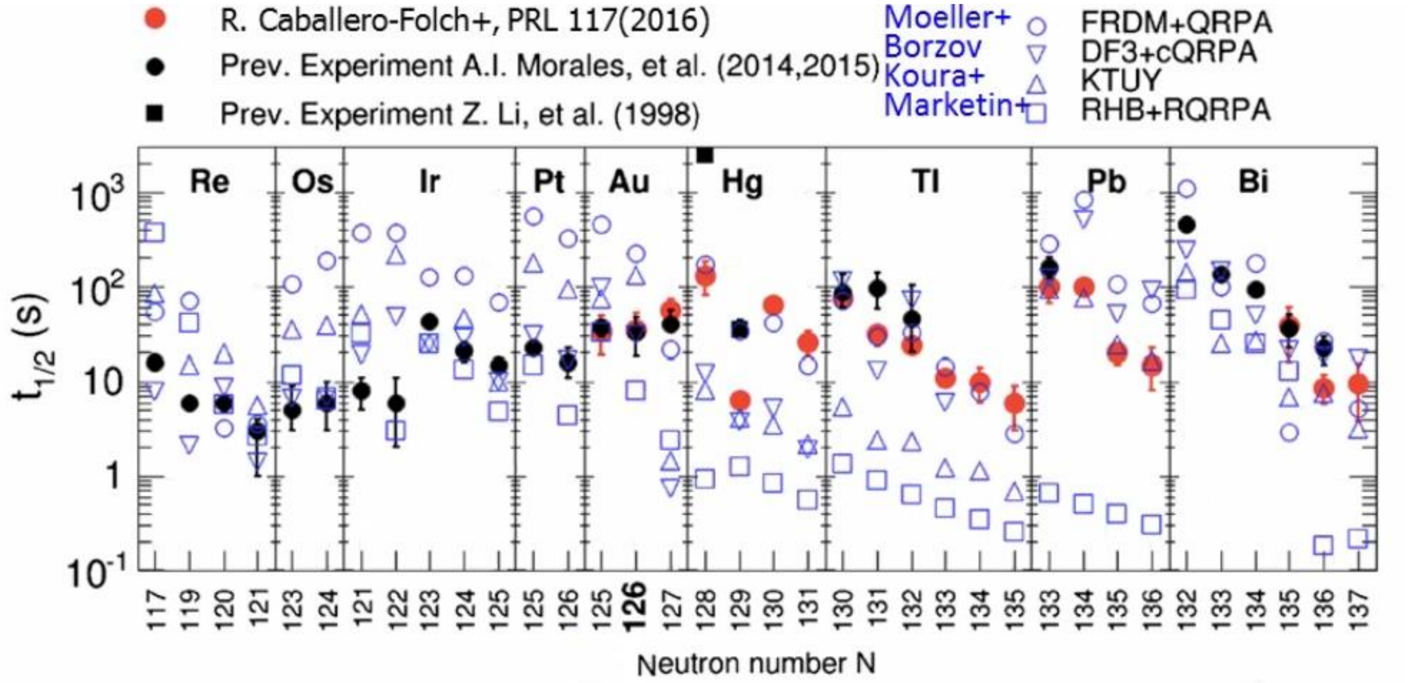


- beta decay rates $^{151\text{-}153}$La $^{139\text{-}141}$Te

How good are models?

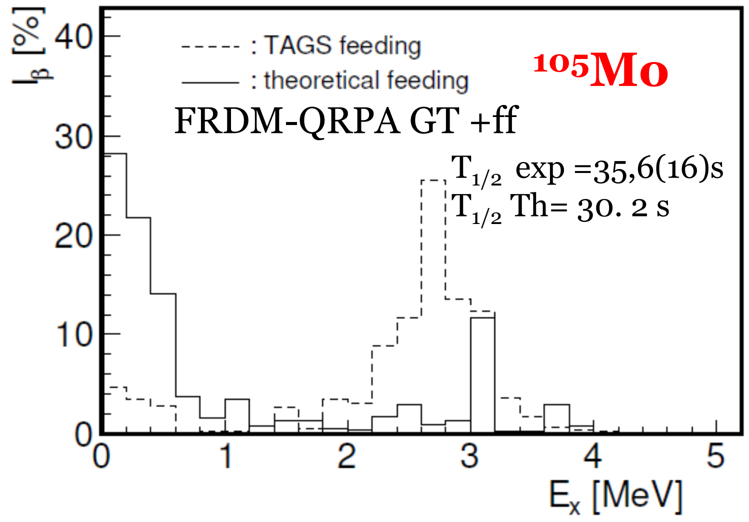
O. Hall et al., Physics Letters B,816, 136266 (2021)





$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} S_\beta(E) f(Q_\beta - E) dE$$

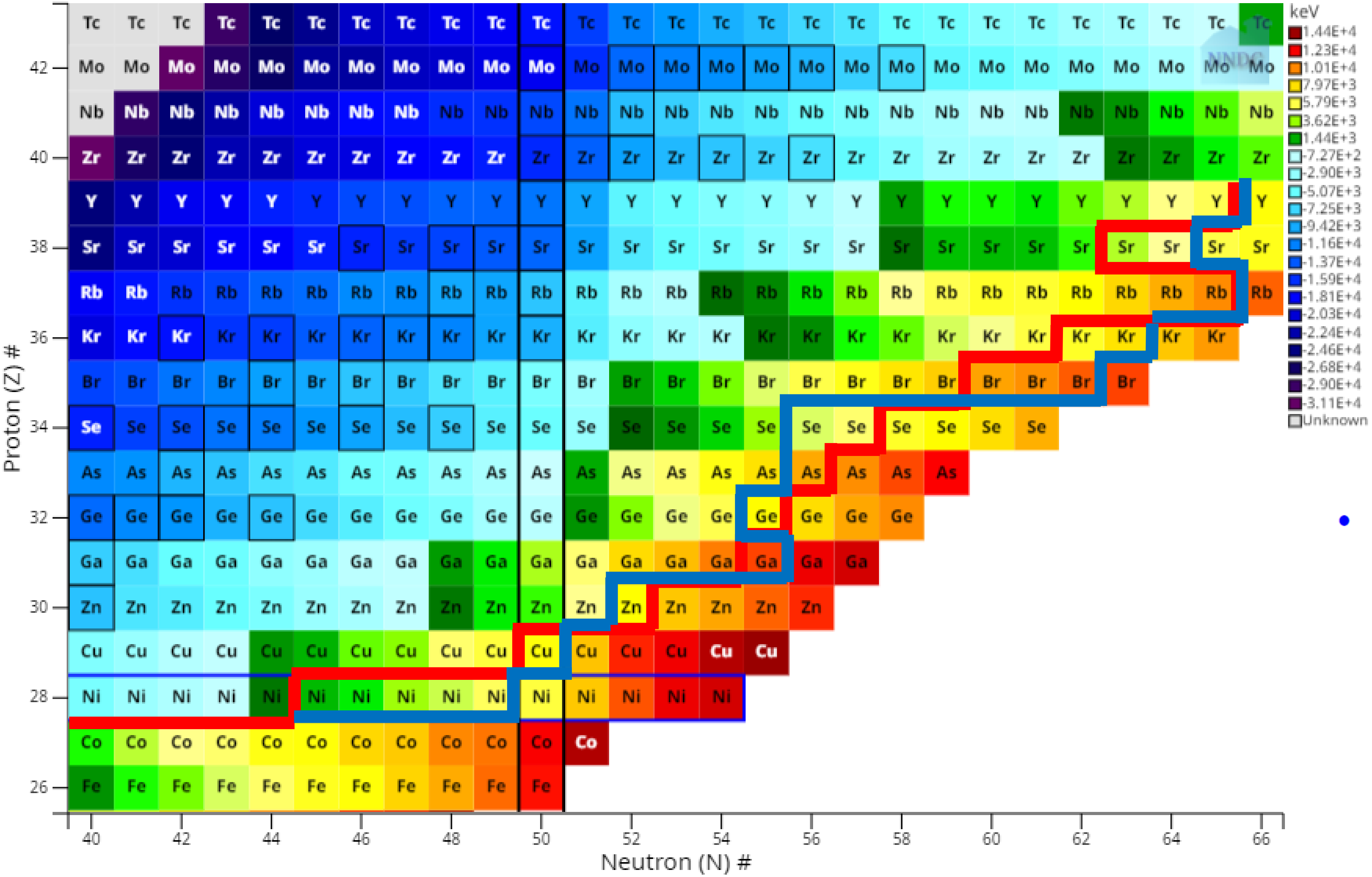
$$S_\beta(E) = \frac{I_\beta(E)}{f(Q_\beta - E) T_{1/2}}$$

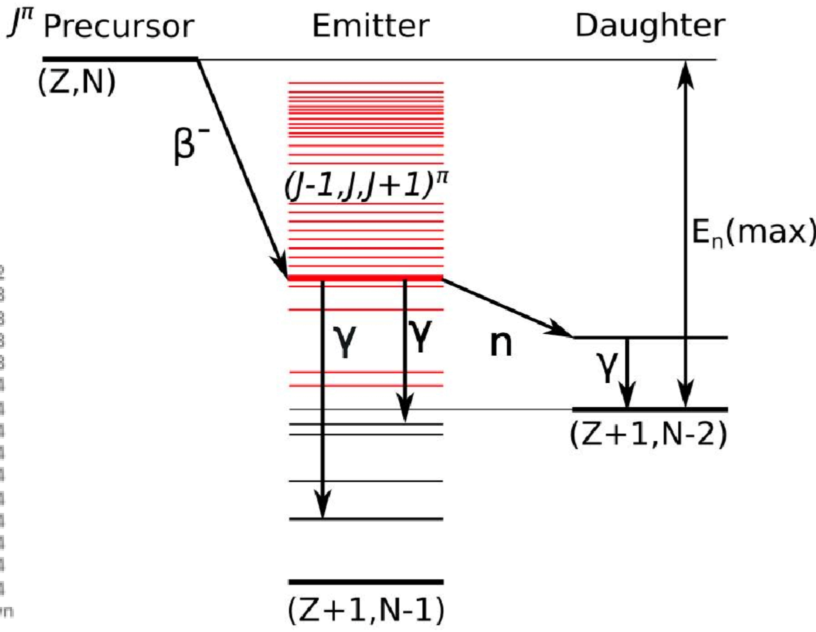


A. Algora et al.,

$$P_n = T_{1/2} \int_{S_n}^{Q_\beta} \frac{\Gamma_n}{\Gamma_n + \Gamma_\gamma} S_\beta(E) f(Q_\beta - E) dE$$

Experimental nuclear data at 1rst peak

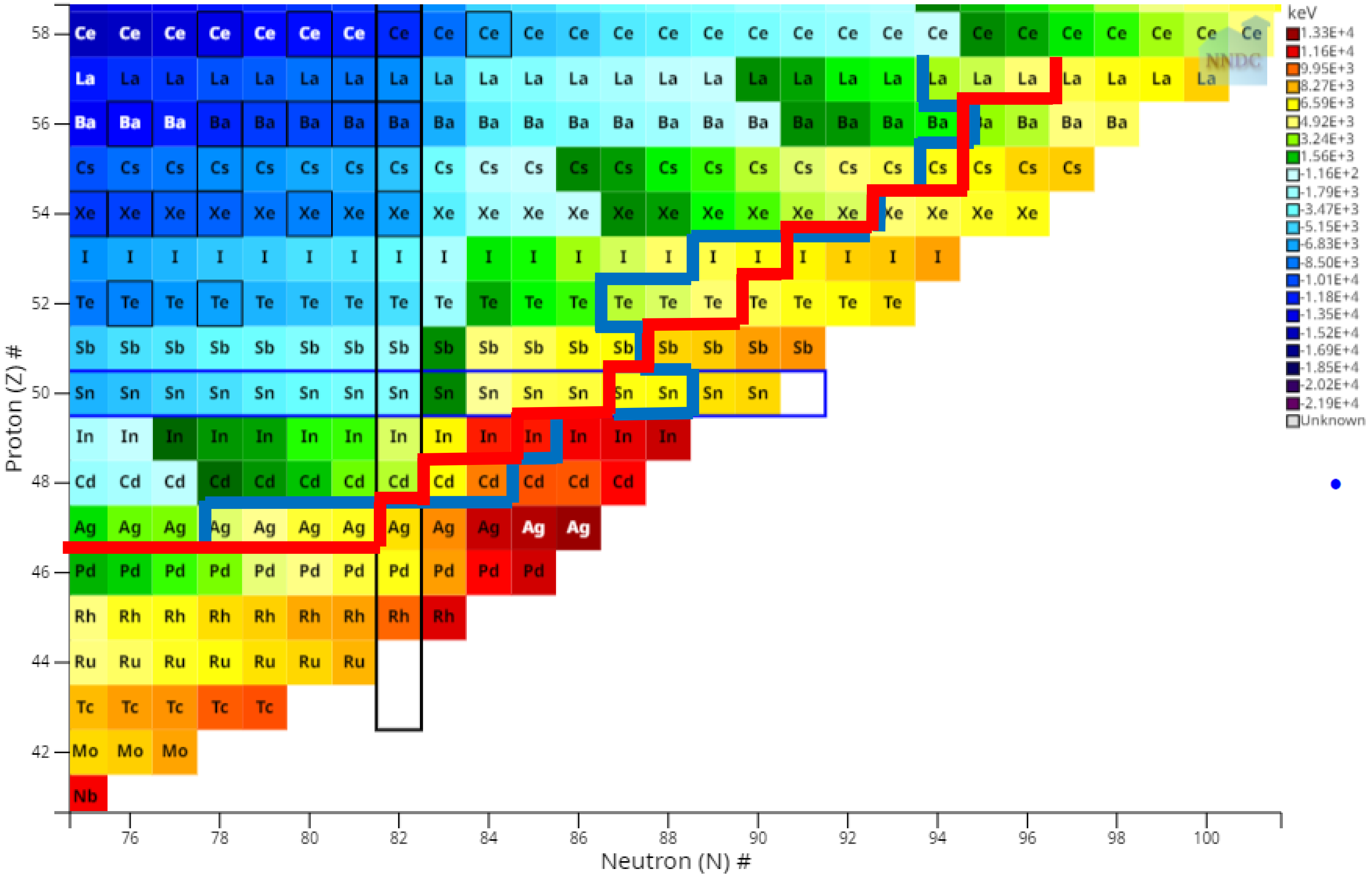


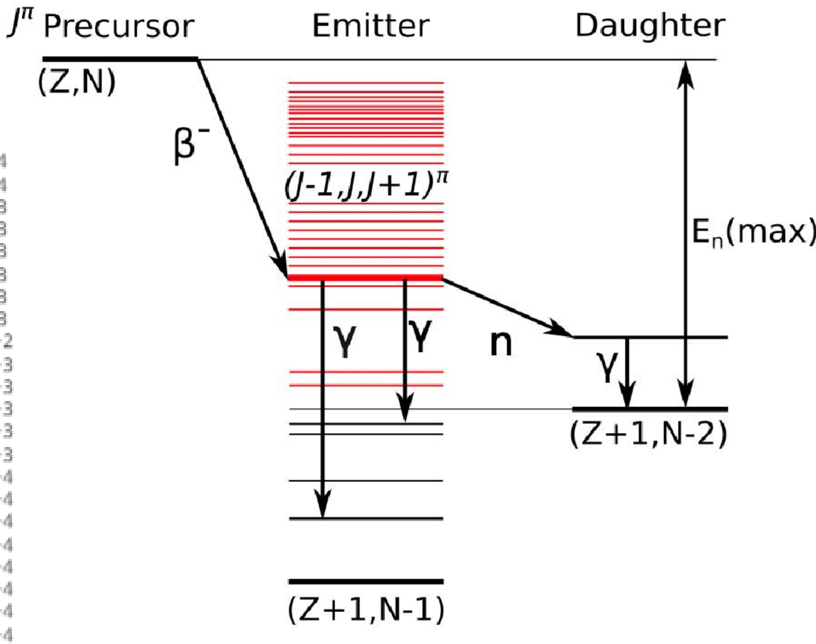


- Beta-delayed neutron emission

^{82}Zn, ^{87}Ge, ^{89}As, ^{90}Se

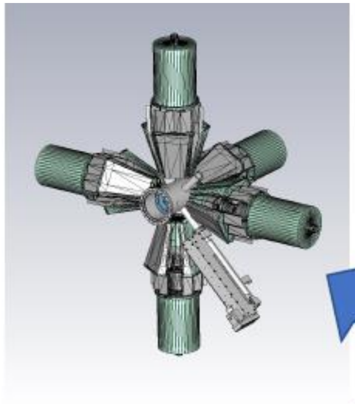
Experimental nuclear data at 2nd peak





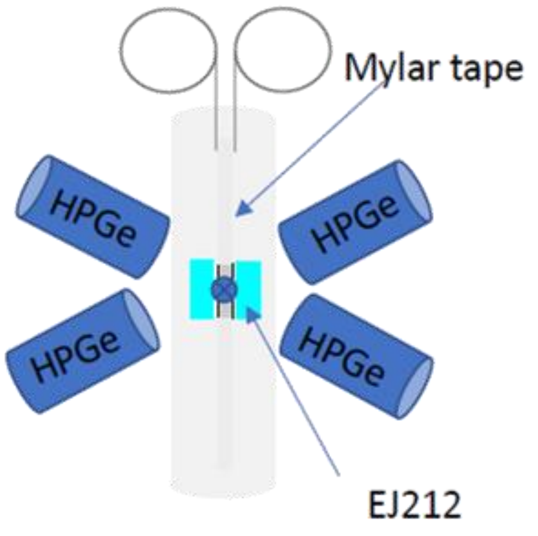
- Beta-delayed neutron emission

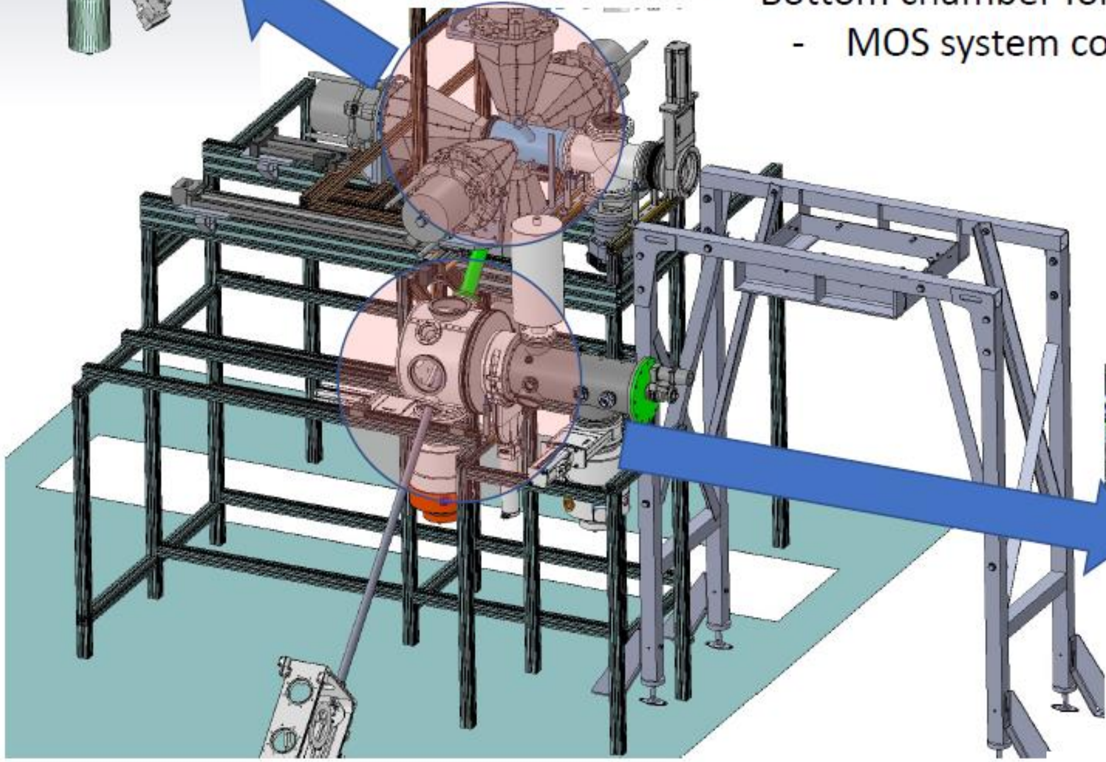
$^{151-153}$La
^{148}Cs
$^{142-143}$I
$^{139-141}$Te
$^{125-128}$Ag

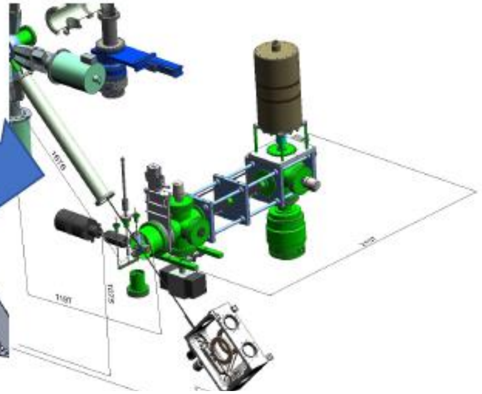


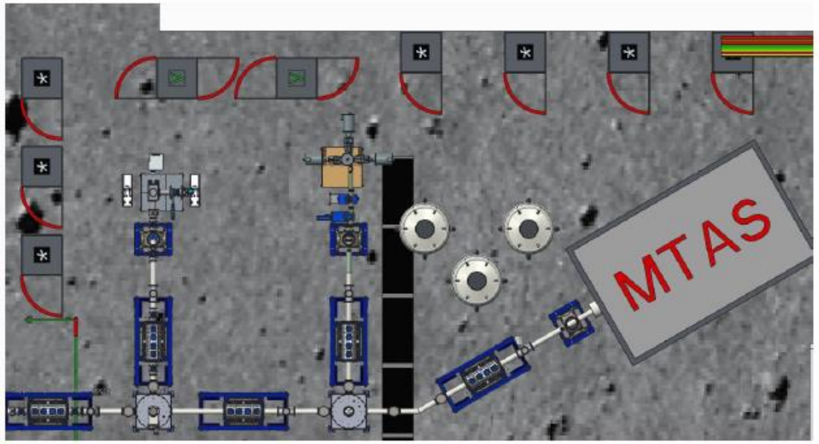
Decay Station

3D rendering of the structure:
- 2 chambers connected via same tape system
- Top chamber dedicated to decay studies:
  - Plastic det. For betas and HPGe for gammas
- Bottom chamber for E0 and EC measurements:
  - MOS system coupled to cooled Si(Li) ^{134}Cs





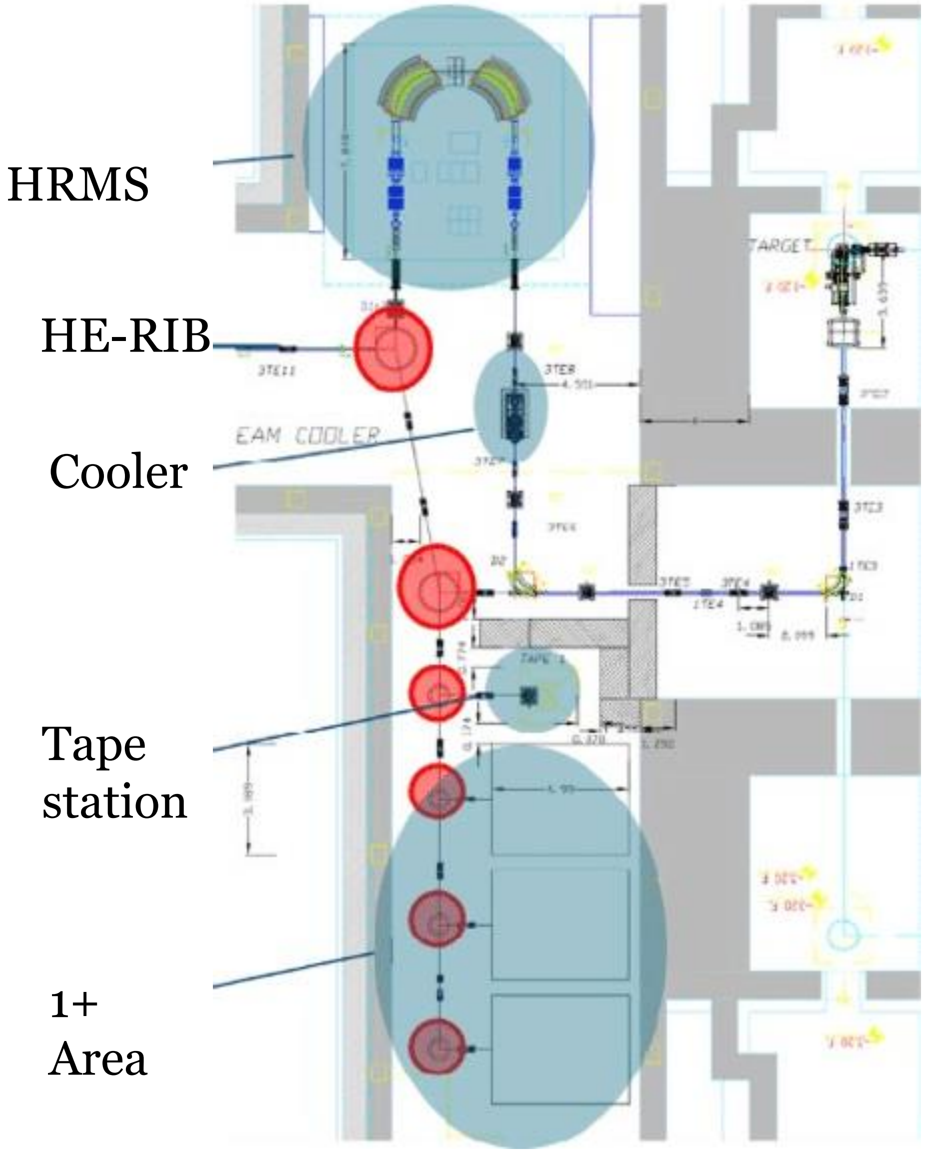


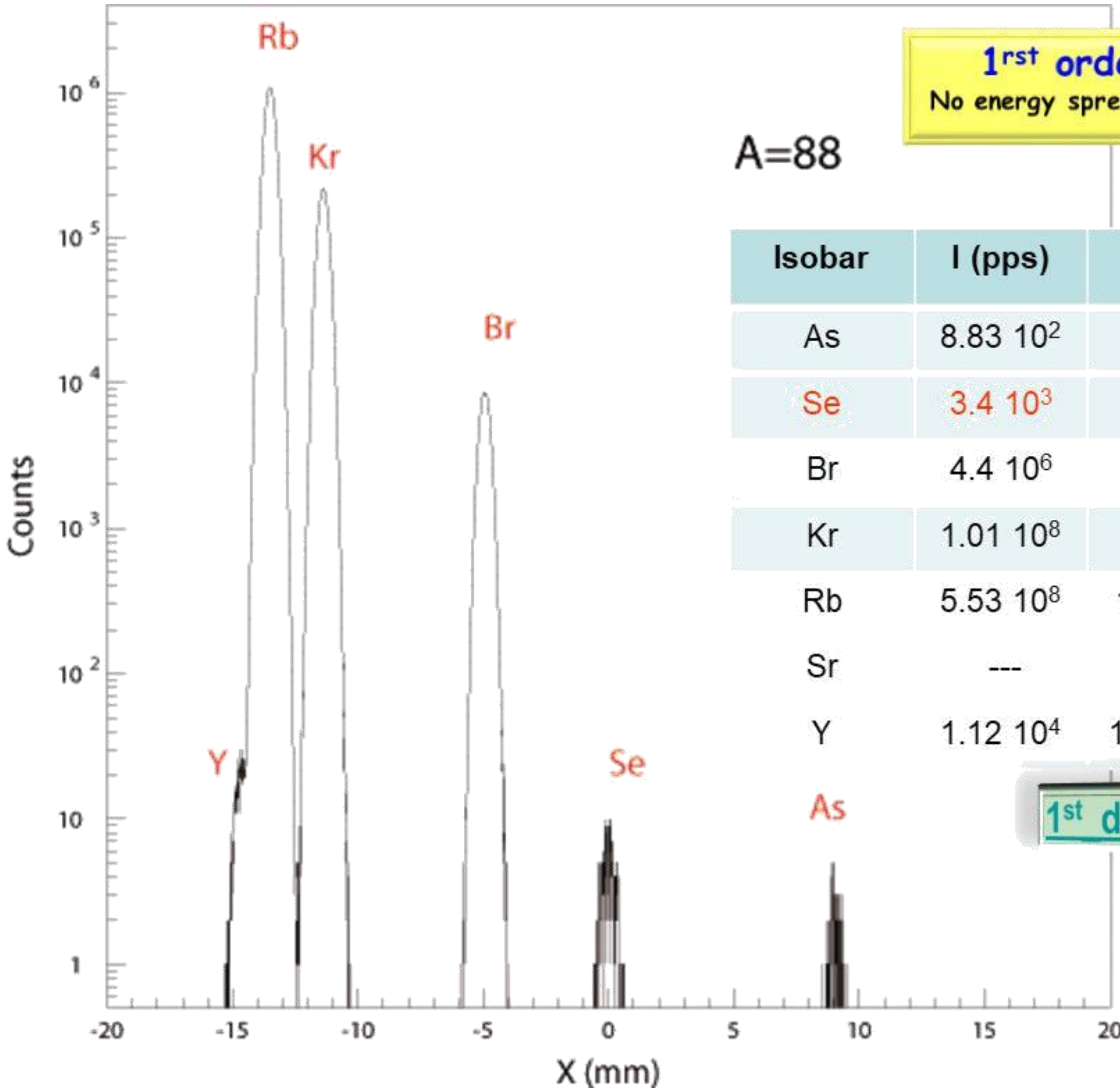


- Implantation and decay in the same measuring point
- Equipped with HPGe for γ and Plastic (or Si) for β particles
- Trigger given by proton arrival and β signal
- Long-living activity is removed by moving away the tape

PHASE A

Use of SPES HRMS for isobar purification



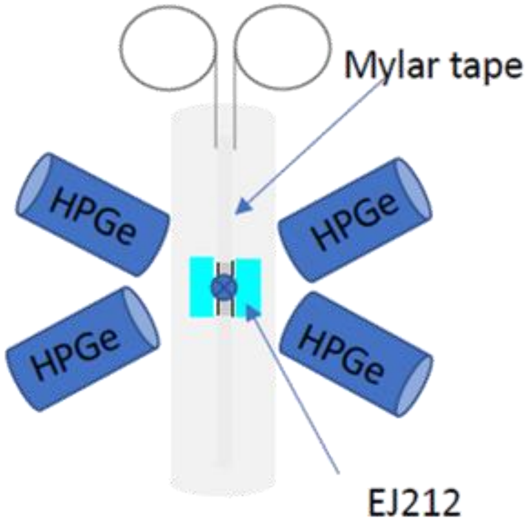


1^{rst} order calculation:
No energy spread/misalignment included

Isobar	I (pps)	$T_{1/2}$	m/Δm
As	8.83 10^2		-6 511
Se	3.4 10^3	1.53 (6) s	0
Br	4.4 10^6	16.29(6) s	+11 960
Kr	1.01 10^8	2.84 (3) h	+5 184
Rb	5.53 10^8	17.773(11) m	+4 376
Sr	---	stable	+3409
Y	1.12 10^4	106.626(21) d	+4 014

1^{st} day UCx 5μA

Measurement of the decay characteristics

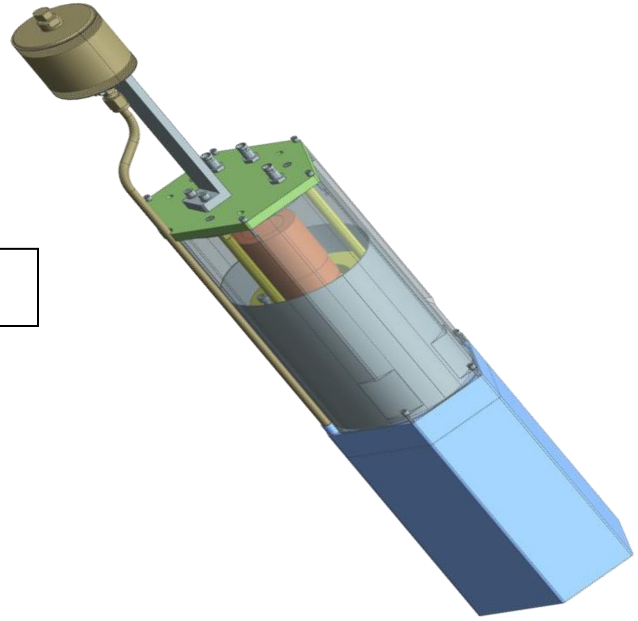


Tape transport system
Beam-on/off time sequence
β-γ, γ-γ coincidence for β decay studies

detection
- **β plastic scintillator**
- **γ germanium**

Can be coupled with a neutron-detector (NEDA)

✓ Pn of the nuclei of interest.
✓ neutron-gated γ-ray spectra

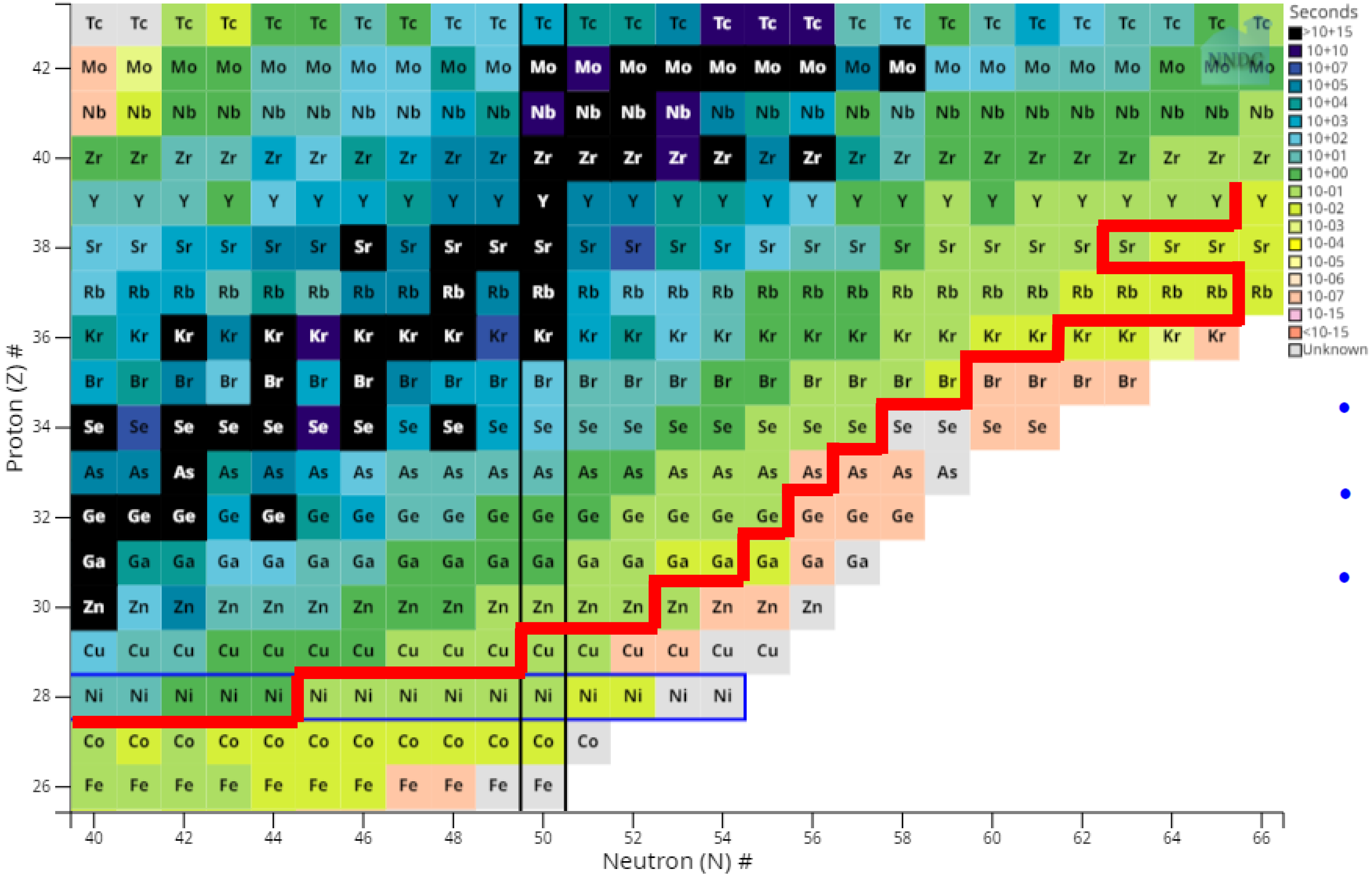


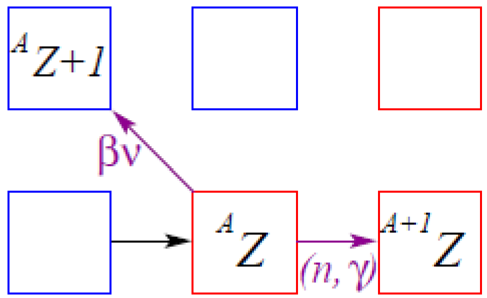
Accumulation → **Measuring time** → **Transport**

- **cycle length:**
  - **Half-lives**
  - **BR**

$$1T_{1/2} + 5\,T_{1/2} + T_t$$
$$1T_{1/2} + 3T_{1/2} + T_t$$

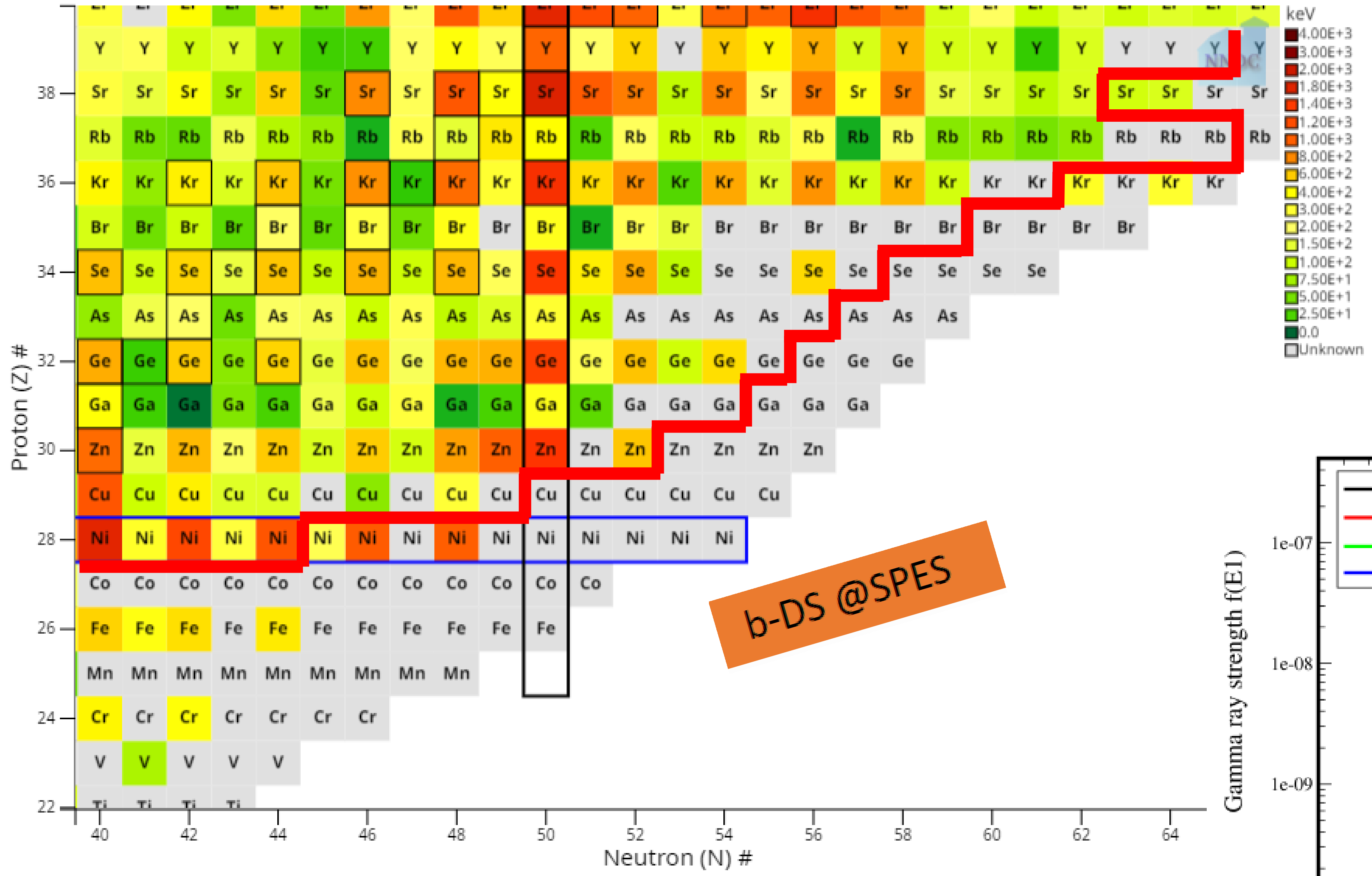
Experimental nuclear data





- beta decay rates
- Beta-delayed neutron emission
- neutron capture rates

Decay schemes for (n,γ) cross-sections

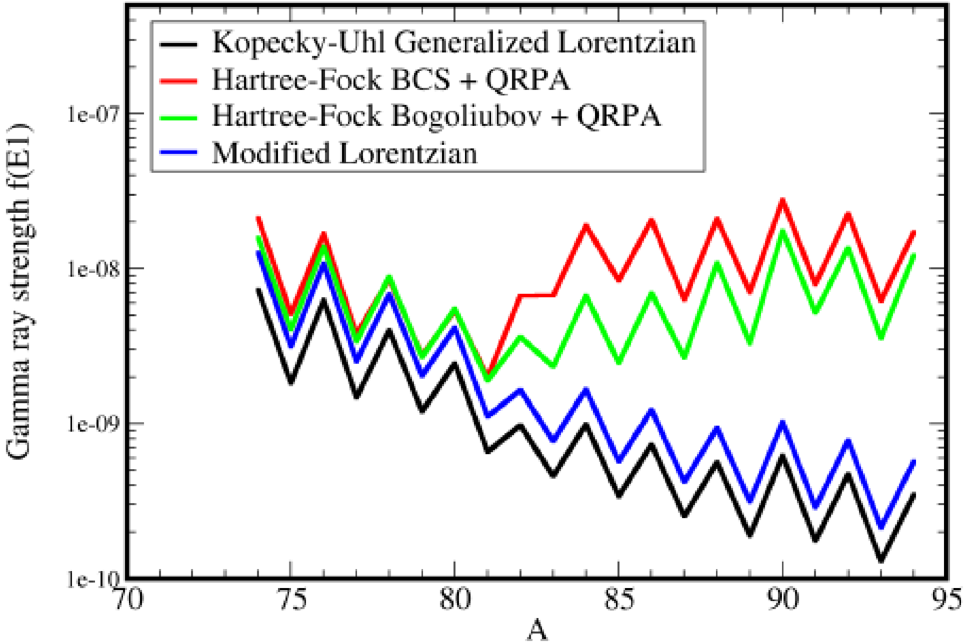


Gamma ray emission in the Hauser-Feshbach model is described by the gamma-ray transmission coeficient.

$$T_l = 2\pi f_l(E_\gamma) E_\gamma^{2l+1}$$

S. Nikas et al., https://arxiv.org/abs/2010.01698}

f(E1) strength for (n,γ) on Ga isotopes @ 1GK



Activation measurements of isotopes of interest for the s-process

Maxwellian Averaged Cross Section (MACS)

$$\mathrm{MACS} = \langle\sigma\rangle = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^2}\int_0^\infty \sigma(E)\, E\, \exp\left(-\frac{E}{kT}\right)\, dE$$

↓

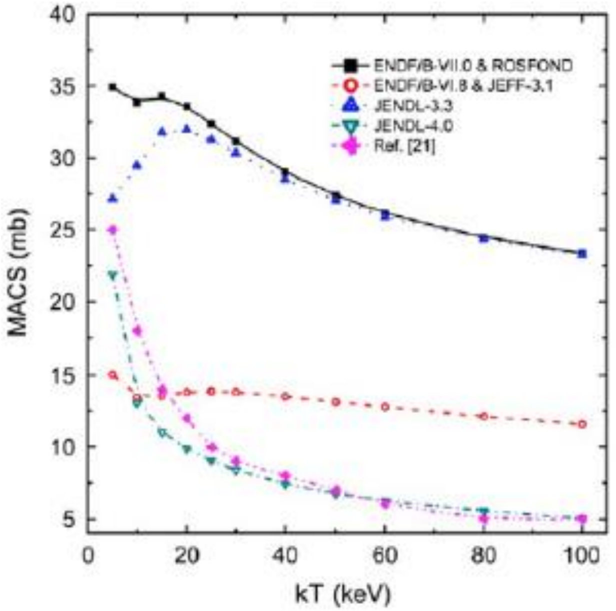
s-process reaction rate

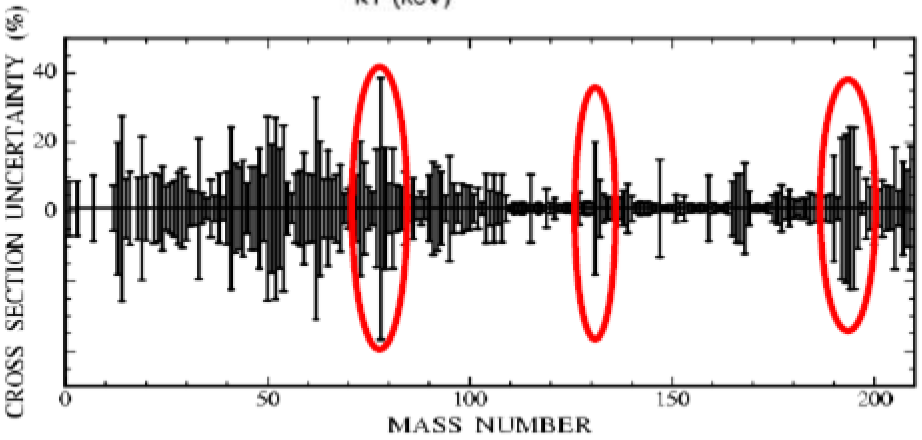
$$\langle\sigma v\rangle = \int_0^\infty \Phi(v)\sigma(v) v dv = 4\pi\left(\frac{\mu}{2\pi kT}\right)^{3/2}\int_0^\infty \sigma(v) v^3 \exp\left(-\frac{\mu v^2}{kT}\right) dv$$

↓

Predicted Abundance

Comparison with experimental observed abundances

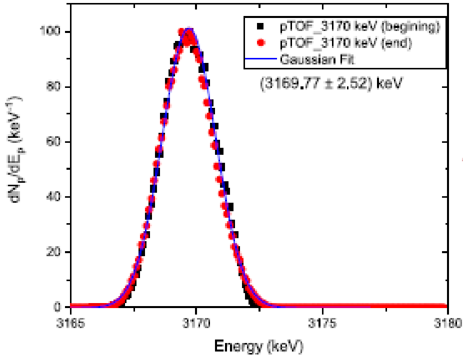




MACS calculated uncertainties of several stable and most of the unstable isotopes are higher than the requested accuracy (for s-process: 3-5%).

Activation measurements of isotopes of interest for the s-process

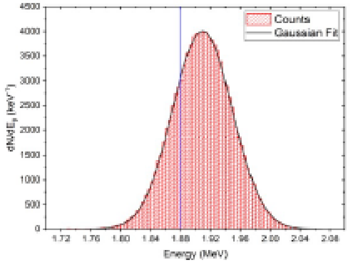
PROTON BEAM



E_p = 3.17 MeV

51 μm Al foil

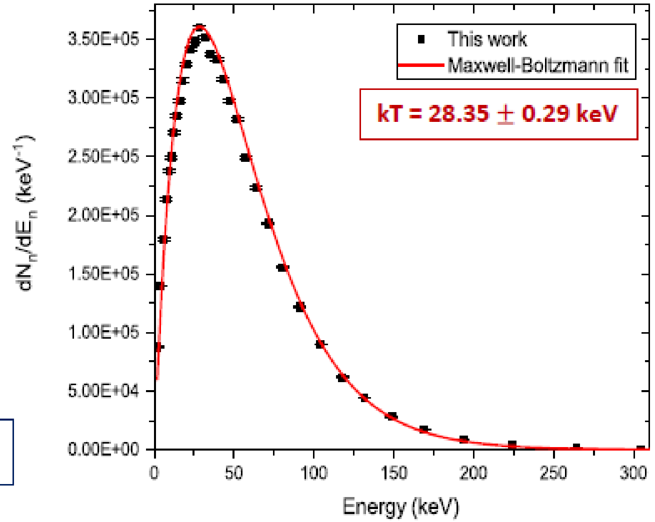
Shaped proton distribution



Li target

Neutron Time-of-Flight

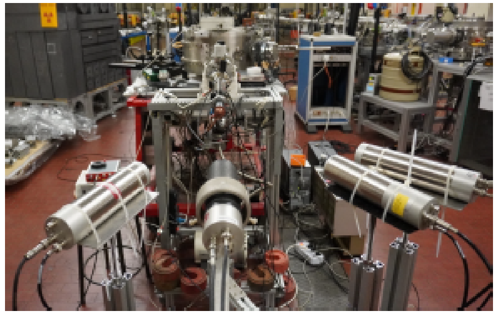
0°-90° INTEGRAL NEUTRON SPECTRUM

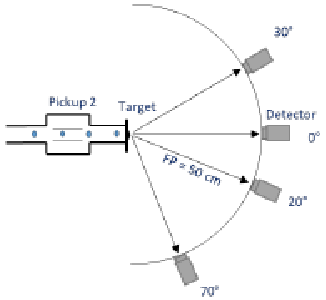


$R^2 = 0.992$

Well reproduce Maxwell-Boltzmann spectrum

CN accelerator.BELINA beam line

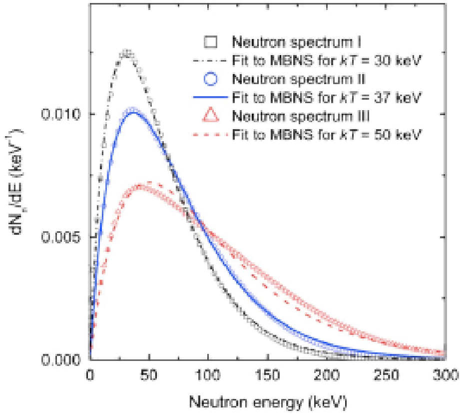




Mastinu, P.F.,Martín-Hernández, G.,Praena, J., 2009.Nucl.Instrum.Methods.A 601, 333.

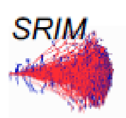
Activation measurements of isotopes of interest for the s-process

Produce and measure Maxwell-Boltzmann-like neutron spectrum at different kT



Proton energy shaper

Proton energy



PYSim CODE

Theoretical neutron energy spectrum

Fit to MB distribution

Experimental neutron spectrum measurement validation @ CN accelerator

PHASE A — Case of study: ^{88}Sr

PHASE B — irradiation of radioactive targets produced at SPES

Activation measurements to determine the MACS of isotopes of interest at different thermal temperatures.

Gold activation measurement

Irradiating a sample (sandwiched between two Au foils) to measure the MACS respect to the Au

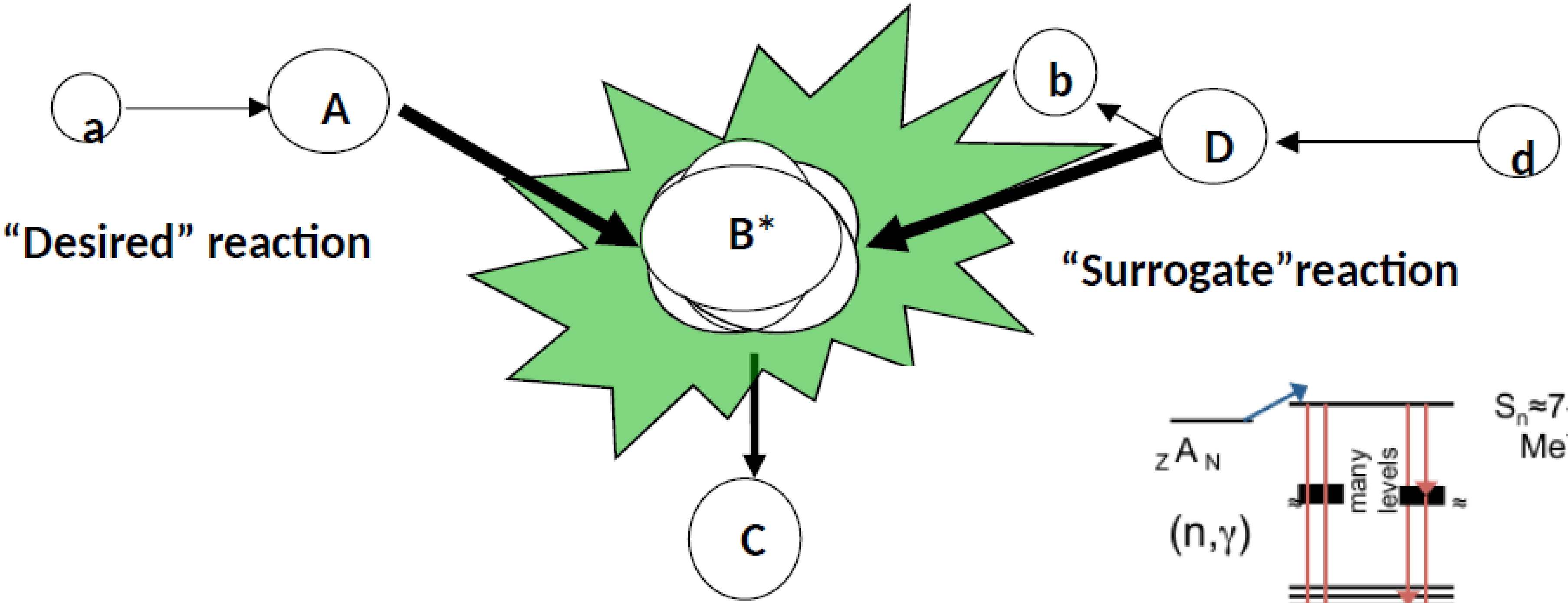
Reference measurement
MACS of gold (Au-197)

(absolute measurement committed by IAEA)

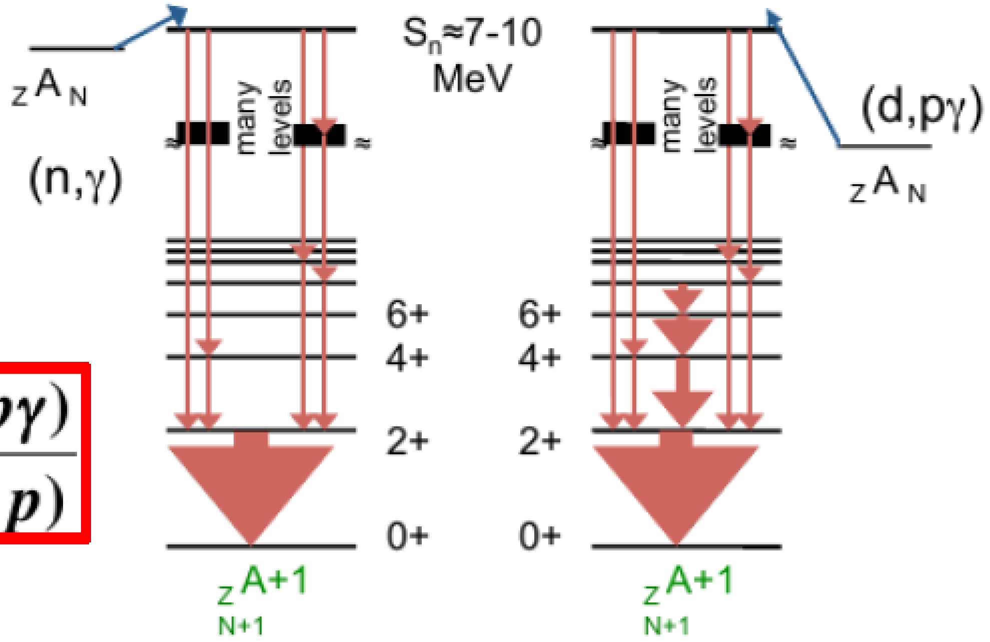
Benchmark measurement
MACS of yttrium (Y-89) or zirconium (Zr-94)

Well measured MACS
Moreover, the same reaction will be done at **CERN n_TOF irradiation facility** for comparison

Neutron capture cross sections via surrogate reaction approach



Also ^{3}He,^{4}He



$$\sigma_{n\gamma}^{WE}(E_n) = \sigma_n^{CN}(E_n) G_\gamma^{CN}(E_n) = \sigma_n^{CN}(E_n)\frac{N(d,p\gamma)}{\varepsilon N(d,p)}$$

Neutron capture cross sections via surrogate reaction approach

What we measure:

$$P(d,p\gamma) = \sum_{J,\pi} \sigma_{(d,p)}(E,J,\pi) * G(E,J,\pi,\gamma)$$

Entry state correction: spin-parity distribution needed!!

Decay of the formed compound nucleus (can be calculated)

What we want:

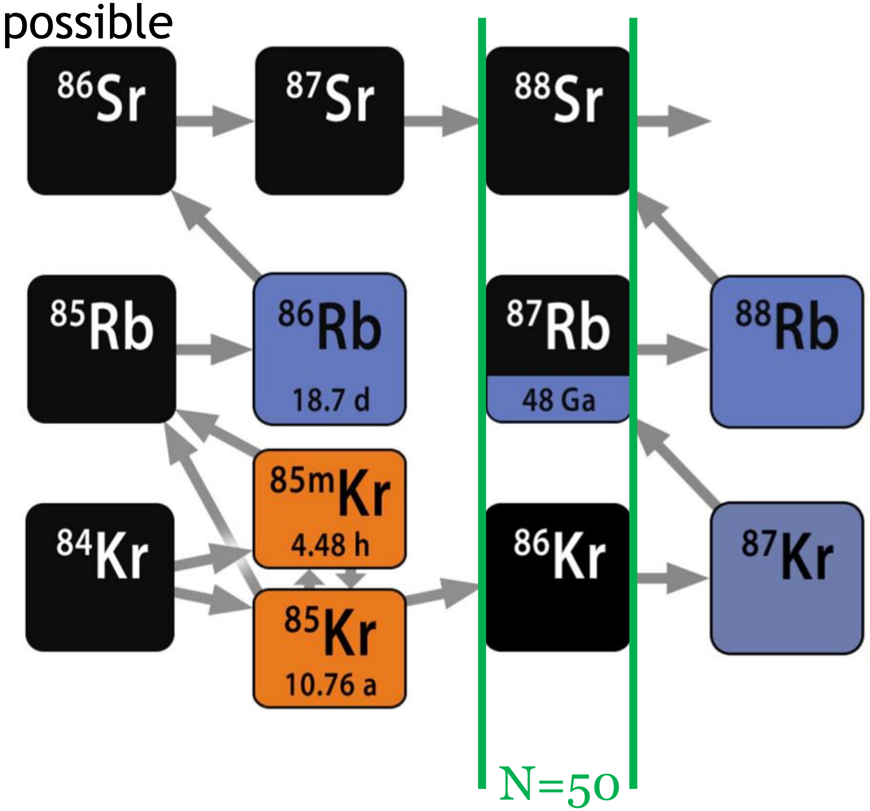
$$P(n,\gamma) = \sum_{J,\pi} \sigma_{(n,\gamma)}(E,J,\pi) * G(E,J,\pi,\gamma)$$

^{85}Kr(d,p) w/ Ex=10 MeV, just above S_n

^{85}Kr branching

$\sigma(^{85}Kr) = (55 \pm 45)$ mb

When $\tau_\beta \sim \tau_n$ → several paths are possible



- ✓ The branching is important for Rb and Sr abundances
- ✓ It offers an estimation of the neutron density
- ✓ Crucial for both main and weak component
- ✓ **Challenge present understanding!**

When ^{22}Ne neutron source is active

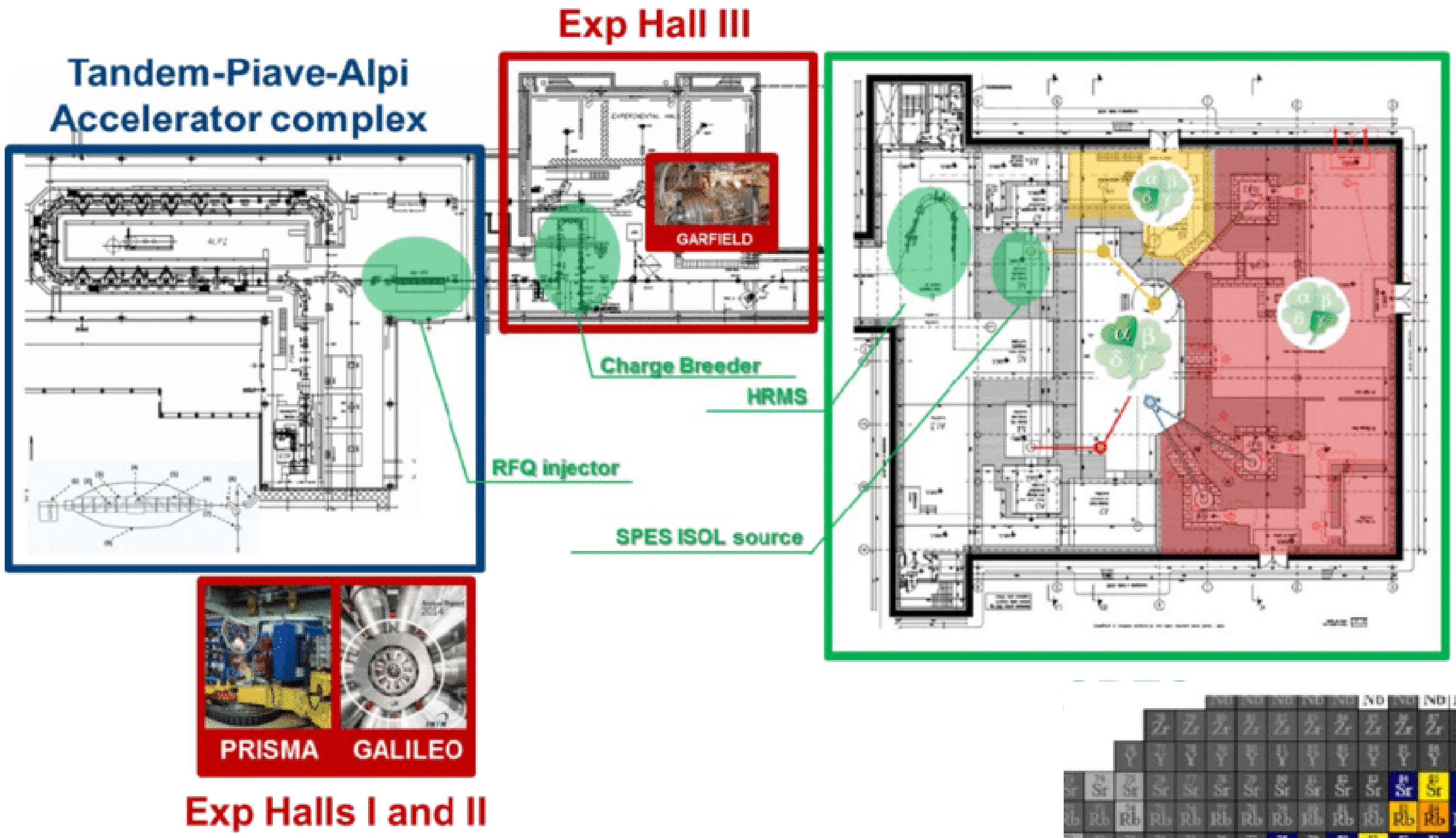
At high neutron densities (5 x 10^8 n/cm^3), about the 80% of the flux goes through ^{85}Kr, allowing the production of ^{86}Kr and ^{87}Rb:

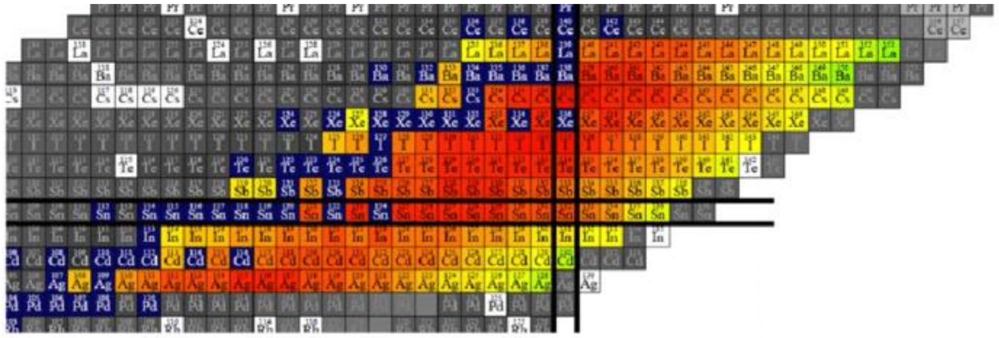
--> ^{87}Rb in AGB stars in an indicator of the neutron density!

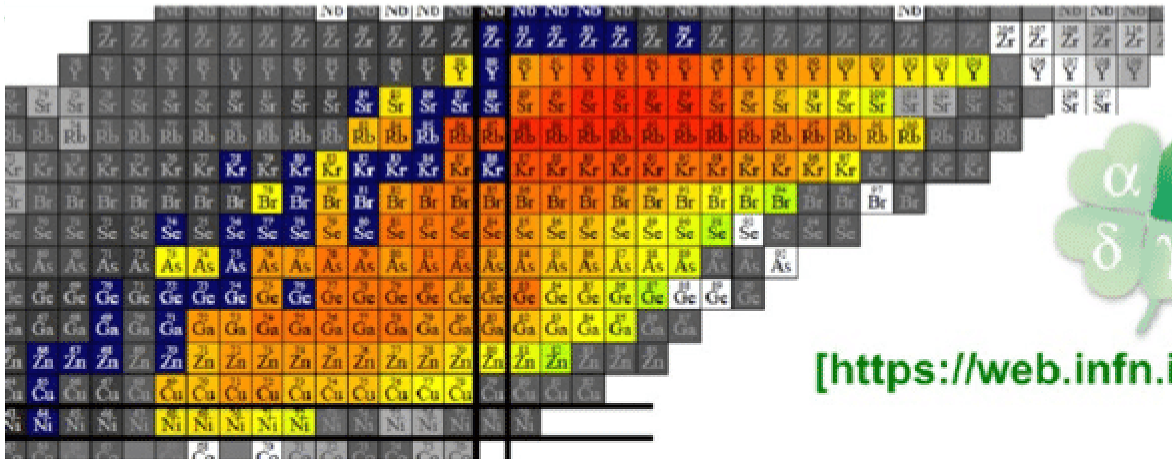
^{86}Kr, ^{87}Rb, and ^{88}Sr are all magic, with low neutron capture cross sections

- ✓ In low-mass stars: ^{88}Sr produced
- ✓ In massive AGB: ^{87}Rb

SPES reaccelerated beams

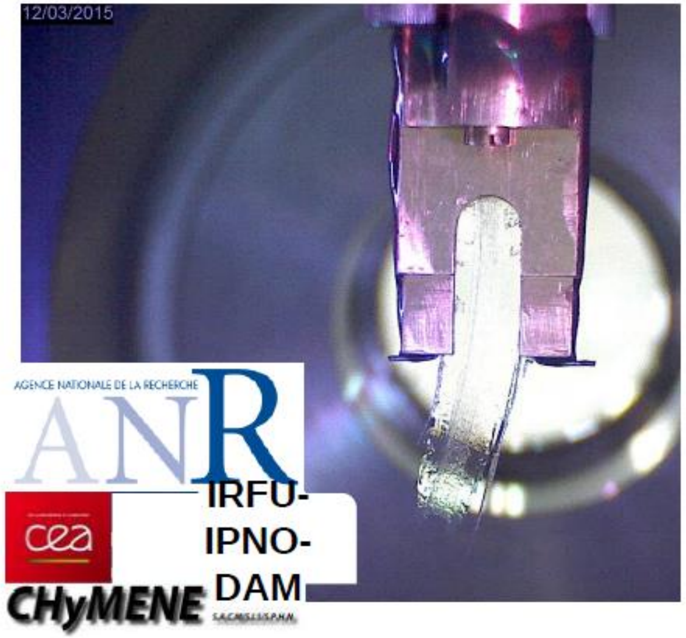






[https://web.infn.it/spes/]

Targets



- Hydrogen (h,d) target in a solid phase near triple point (~17K)
- Thickness 50 – 200 µm
- No window - C free
- Continuous flow in vacuum 2-10mm/sec
- Compatible with particle detection

- H, D, ^{3,4}He
- Dense: up to ~**10^{21} nuclei/cm^{2}**
- Havar window
- Compativle with particle det.

CTADIR
PRIN Giovani
A.Gottardo et al.

Neutron capture cross sections via surrogate reaction approach

s process

- (n,γ):
  - ^{79}Se, ^{81,85}Kr, ^{86}Rb, ^{65}Zn, ^{121}Sn,
  - ^{64}Cu, ^{108}Ag, ^{109}Pd, and ^{123}Sn and many more

➔ collaboration with INFN Pg and INAF Teramo

➔ 2 LoIs presented at the 3rd SPES workshop in 2016

➔ Tests proposed at LNL

r process

- $^{123,131\text{-}134,131}$In, ^{133}Sb
- Ni, Cu, Zn, Ga, Ge, As

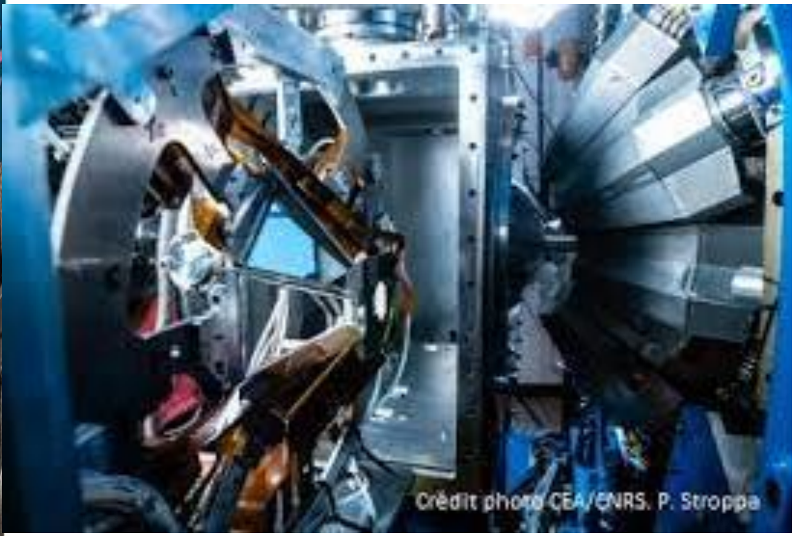
➔ Collaboration with ORNL/Rutgers Univ. (exp) and NSCL (theory)

➔ 2 LoIs presented at the 3rd SPES workshop in 2016

➔ Commissioning tests needed with stable beam

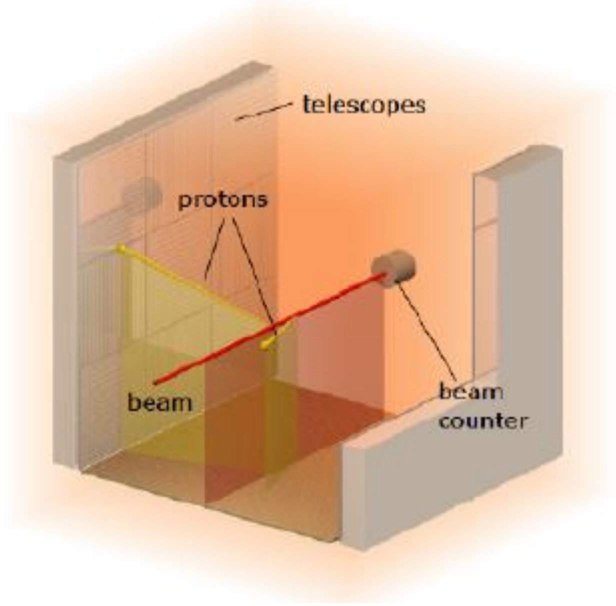
Instrumentation

Traditional gamma/particle spectroscopy but state-of-the-art tech.



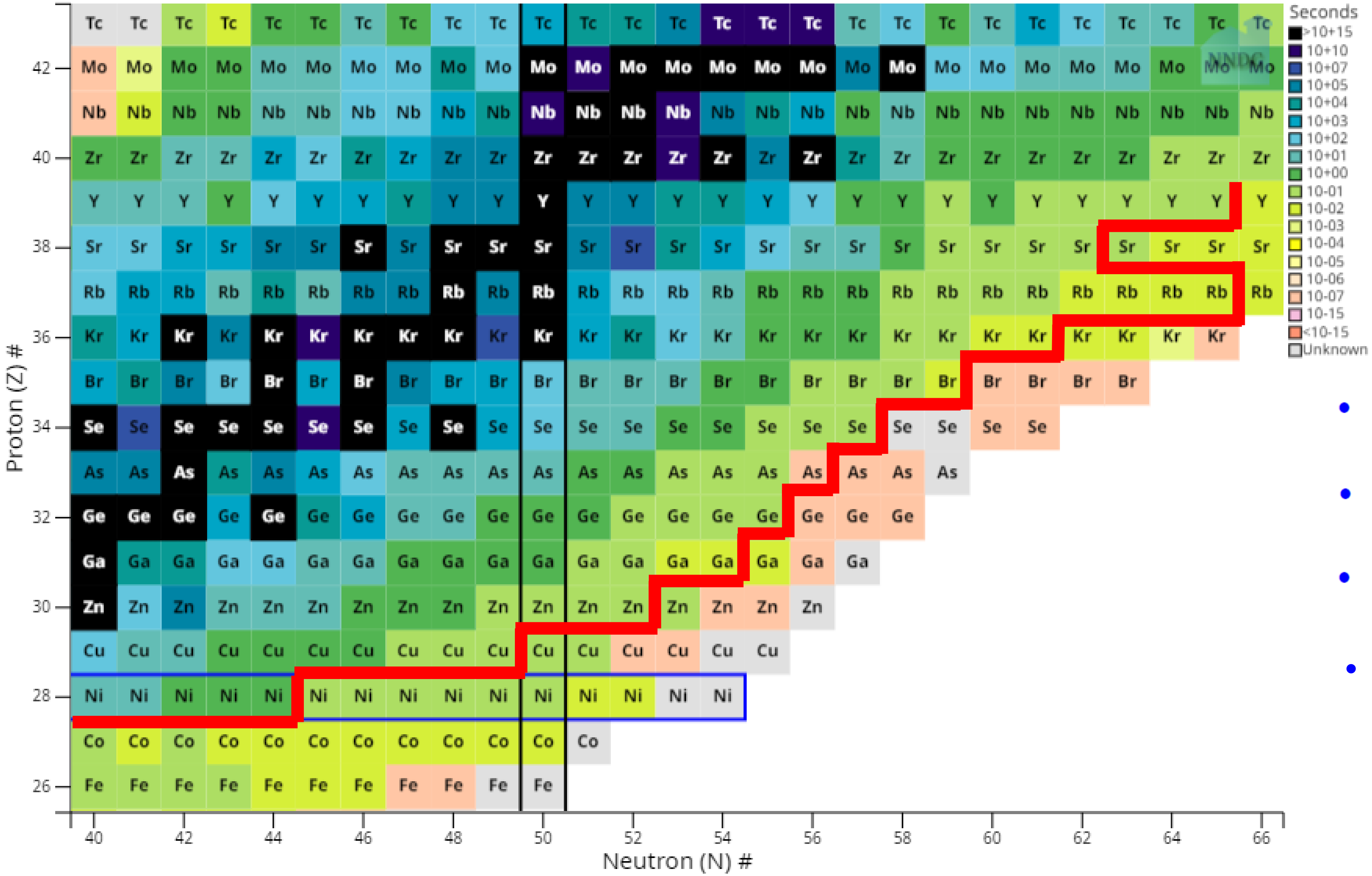
ACTAR-TPC + ANCILLARY DETECTORS

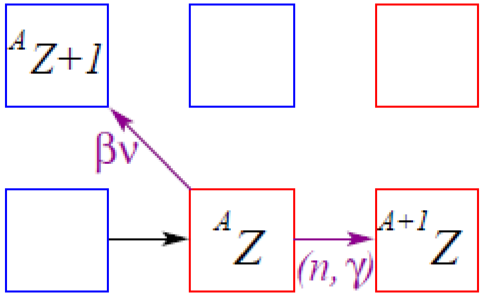
- Si-CsI telescope
- LaBr3/CeBr3 for γ-tagging



PHASE B/C

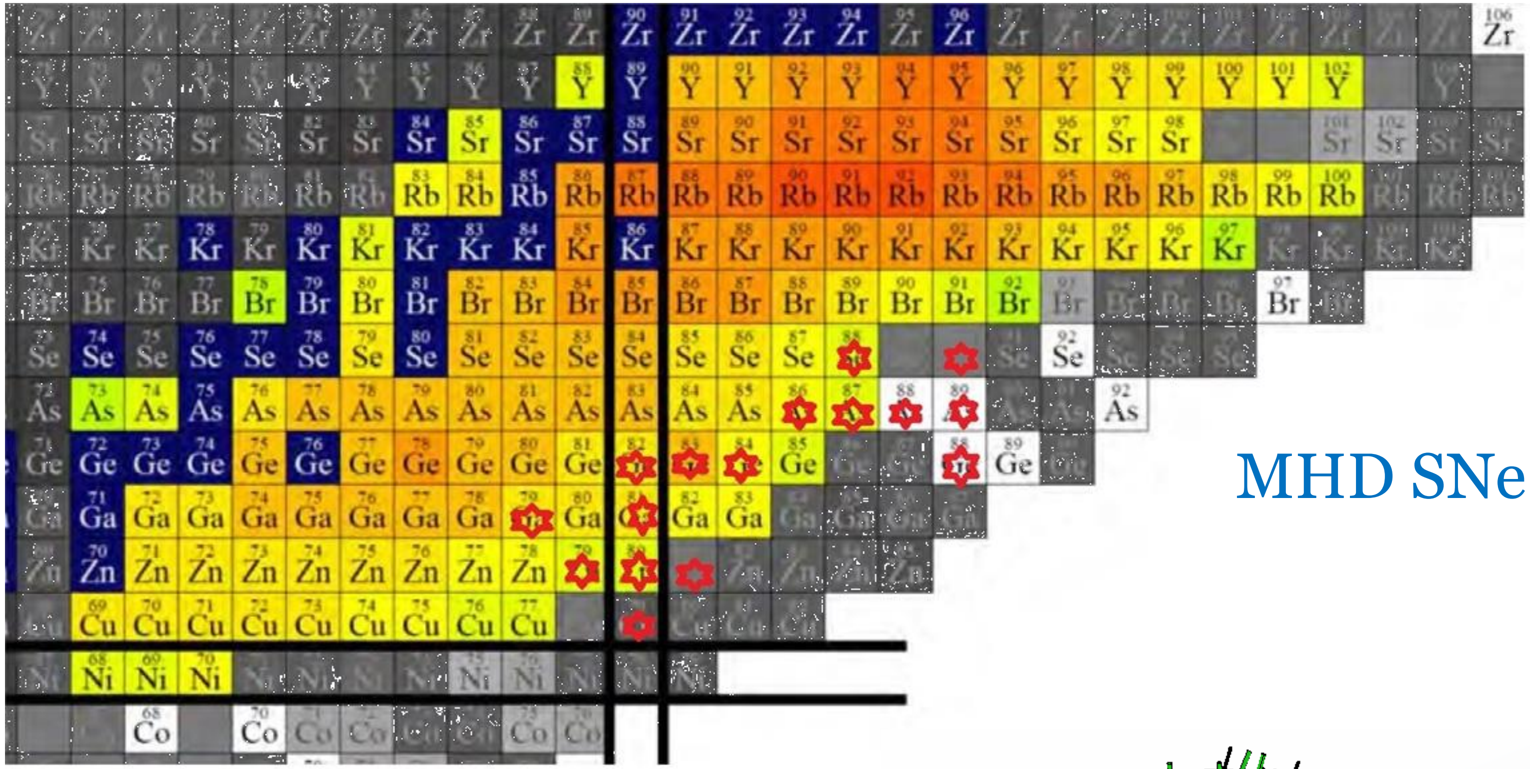
Experimental nuclear data





- beta decay rates
- Beta-delayed neutron emission
- neutron capture rates
- **(α, n)** $n-1 \underset{\beta n}{\overset{\alpha n}{\rightleftarrows}} n$

(α, n) reactions with reaccelerated SPES beams and SUGAR

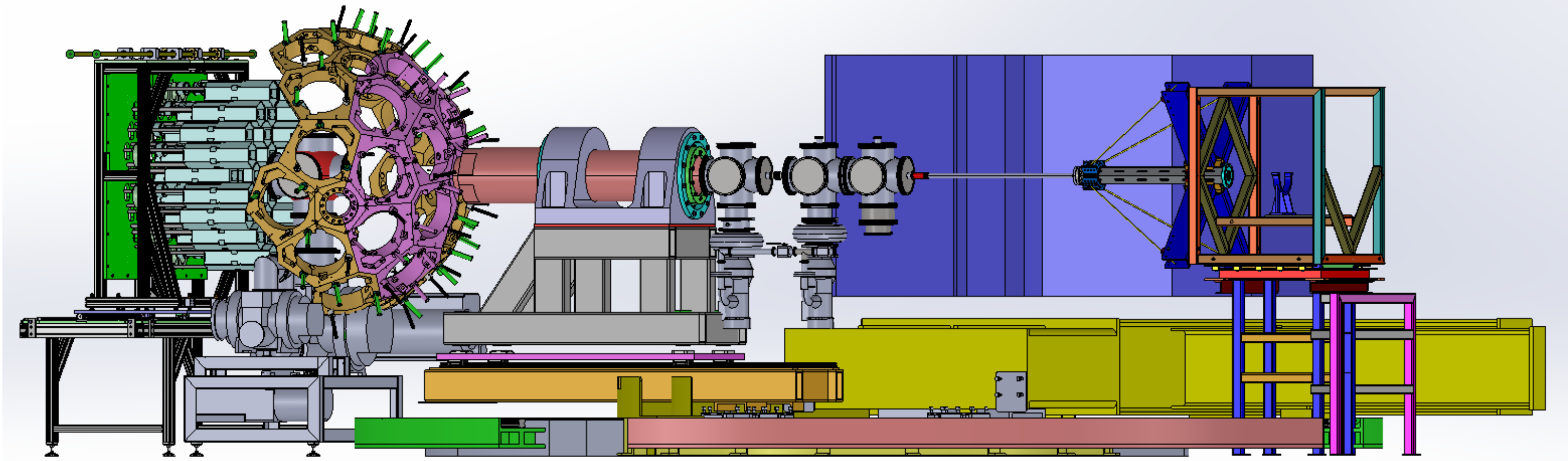


MHD SNe

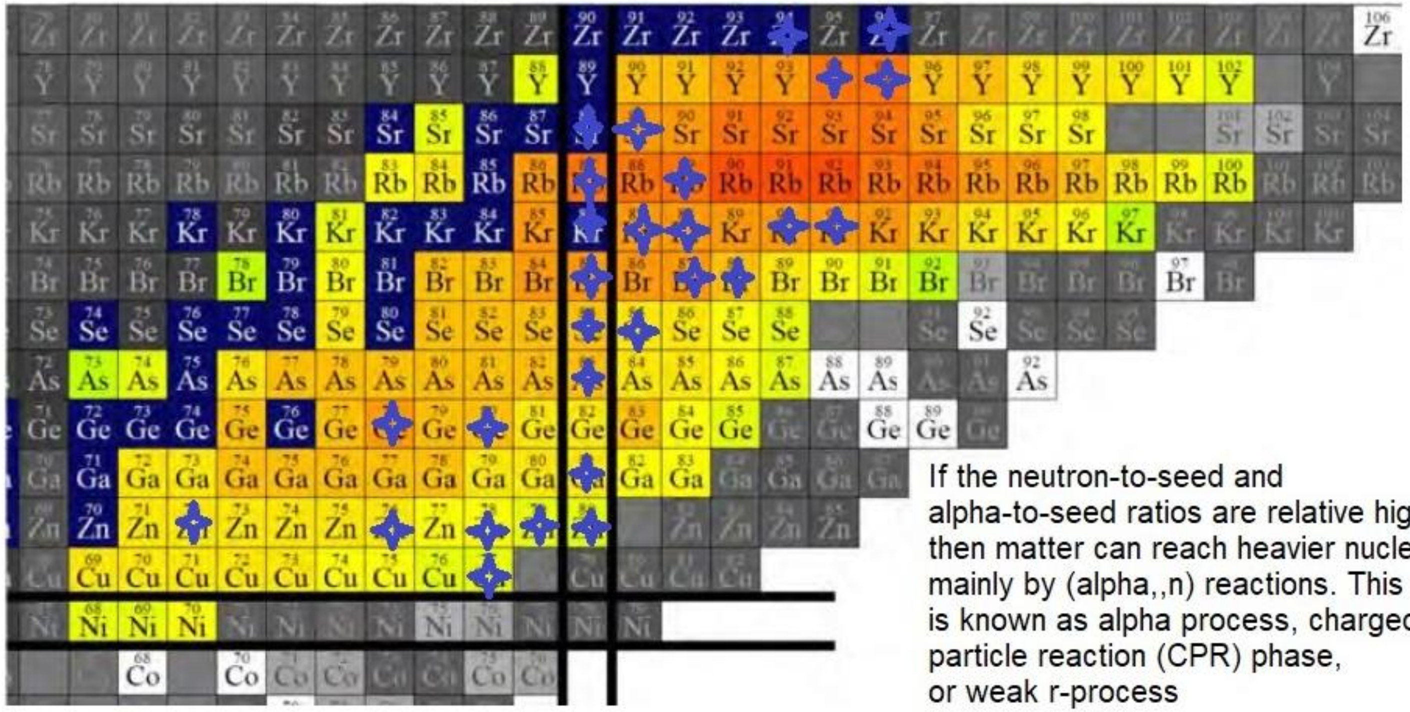
The Astrophysical Journal, 927:116 (8pp), 2022 March 1

Table 1
Reaction Rate Variations That Affect Most Elements

Reaction	Z of Element	Tracer
^{80}Zn(α,n)	25–28, 33–52	1, 2, 3, 6
^{79}Zn(α,n)	25–27, 34–52	1, 2, 3, 6
^{81}Zn(α,n)	25–28, 34–46, 48–52	2, 3
^{81}Ga(α,n)	25–28, 34–45, 47, 48, 50–52	2, 8
^{79}Cu(α,n)	25–29, 52–66	2, 4
^{82}Ge(α,n)	25–27, 42–52	2, 8
^{83}Ge(α,n)	25–28, 44–52	2, 8
^{88}As(α,n)	25–29, 33–39	2
^{87}As(α,n)	25–29, 33–38	2
^{84}Ge(α,n)	26–29, 32, 33, 50–52	2, 8
^{79}Ga(α,n)	44–52	8
^{88}Se(α,n)	25–27, 34–39	2
^{90}Se(α,n)	25–27, 34, 36–39	2
^{86}As(α,n)	25–28, 35, 36, 38	2
^{78}Ni(α,n)	25–29	2, 3
^{86}Ge(α,n)	25–29, 32	2
^{89}As(α,n)	25–28, 33, 35	2



(α, n) reactions with reaccelerated SPES beams and SUGAR



If the neutron-to-seed and alpha-to-seed ratios are relative high then matter can reach heavier nuclei mainly by (alpha,,n) reactions. This is known as alpha process, charged-particle reaction (CPR) phase, or weak r-process

$^{77}Cu(\alpha,n)^{80}Ga$
$^{72}Zn(\alpha,n)^{75}Ge$
$^{76}Zn(\alpha,n)^{79}Ge$
$^{78}Zn(\alpha,n)^{81}Ge$
$^{79}Zn(\alpha,n)^{82}Ge$
$^{80}Zn(\alpha,n)^{83}Ge$
$^{81}Ga(\alpha,n)^{84}As$
$^{78}Ge(\alpha,n)^{81}Se$
$^{80}Ge(\alpha,n)^{83}Se$
$^{82}Ge(\alpha,n)^{85}Se$
$^{83}As(\alpha,n)^{86}Br$
$^{84}Se(\alpha,n)^{87}Kr$
$^{85}Se(\alpha,n)^{88}Kr$
$^{85}Br(\alpha,n)^{88}Rb$
$^{87}Br(\alpha,n)^{90}Rb$
$^{88}Br(\alpha,n)^{91}Rb$

$^{86}Kr(\alpha,n)^{89}Sr$
$^{87}Kr(\alpha,n)^{90}Sr$
$^{88}Kr(\alpha,n)^{91}Sr$
$^{89}Kr(\alpha,n)^{92}Sr$
$^{90}Kr(\alpha,n)^{93}Sr$
$^{87}Rb(\alpha,n)^{90}Y$
$^{89}Rb(\alpha,n)^{92}Y$
$^{88}Sr(\alpha,n)^{91}Zr$
$^{89}Sr(\alpha,n)^{92}Zr$
$^{90}Sr(\alpha,n)^{93}Zr$
$^{91}Sr(\alpha,n)^{94}Zr$
$^{92}Sr(\alpha,n)^{95}Zr$
$^{93}Sr(\alpha,n)^{96}Zr$
$^{94}Sr(\alpha,n)^{97}Zr$
$^{94}Y(\alpha,n)^{97}Nb$
$^{95}Y(\alpha,n)^{98}Nb$

$^{94}Zr(\alpha,n)^{97}Mo$
$^{96}Zr(\alpha,n)^{99}Mo$

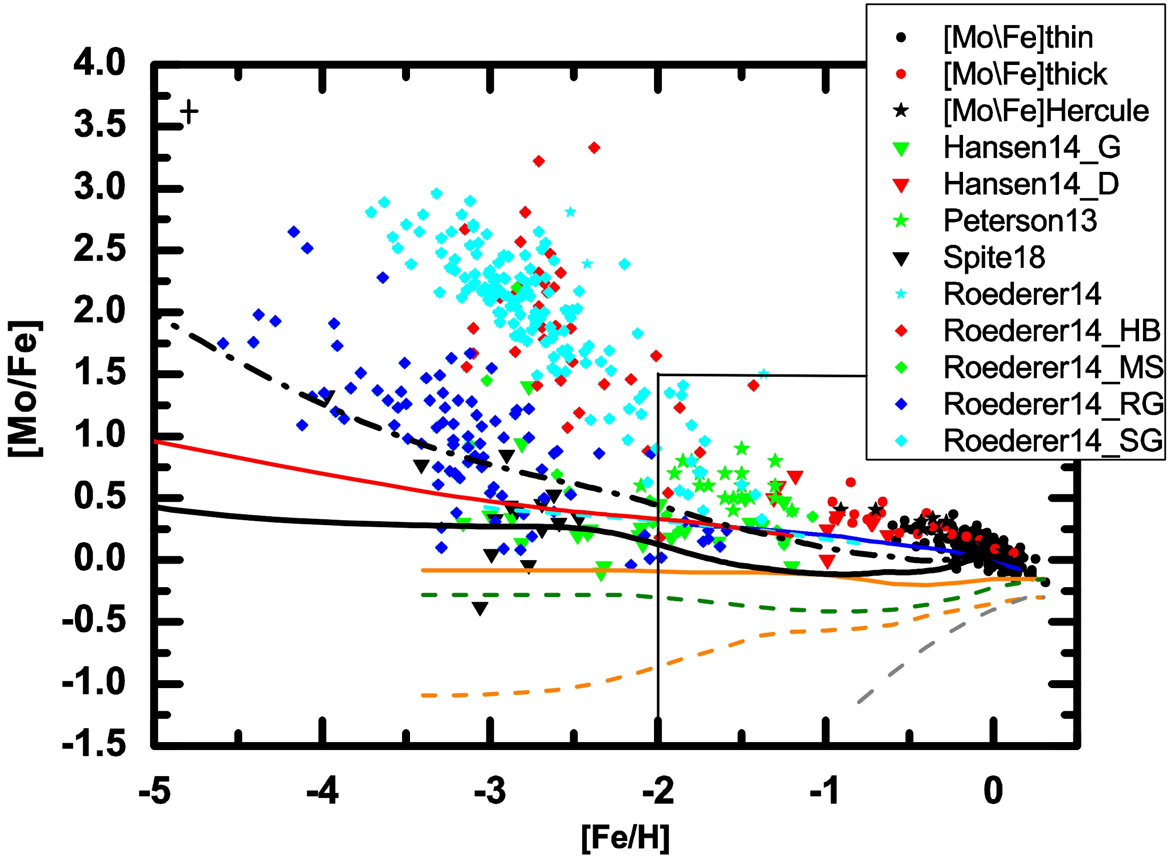
J. Bliss et al., Journal of Physics G: Nuclear and Particle Physics ***44****, 054003 (2017)*

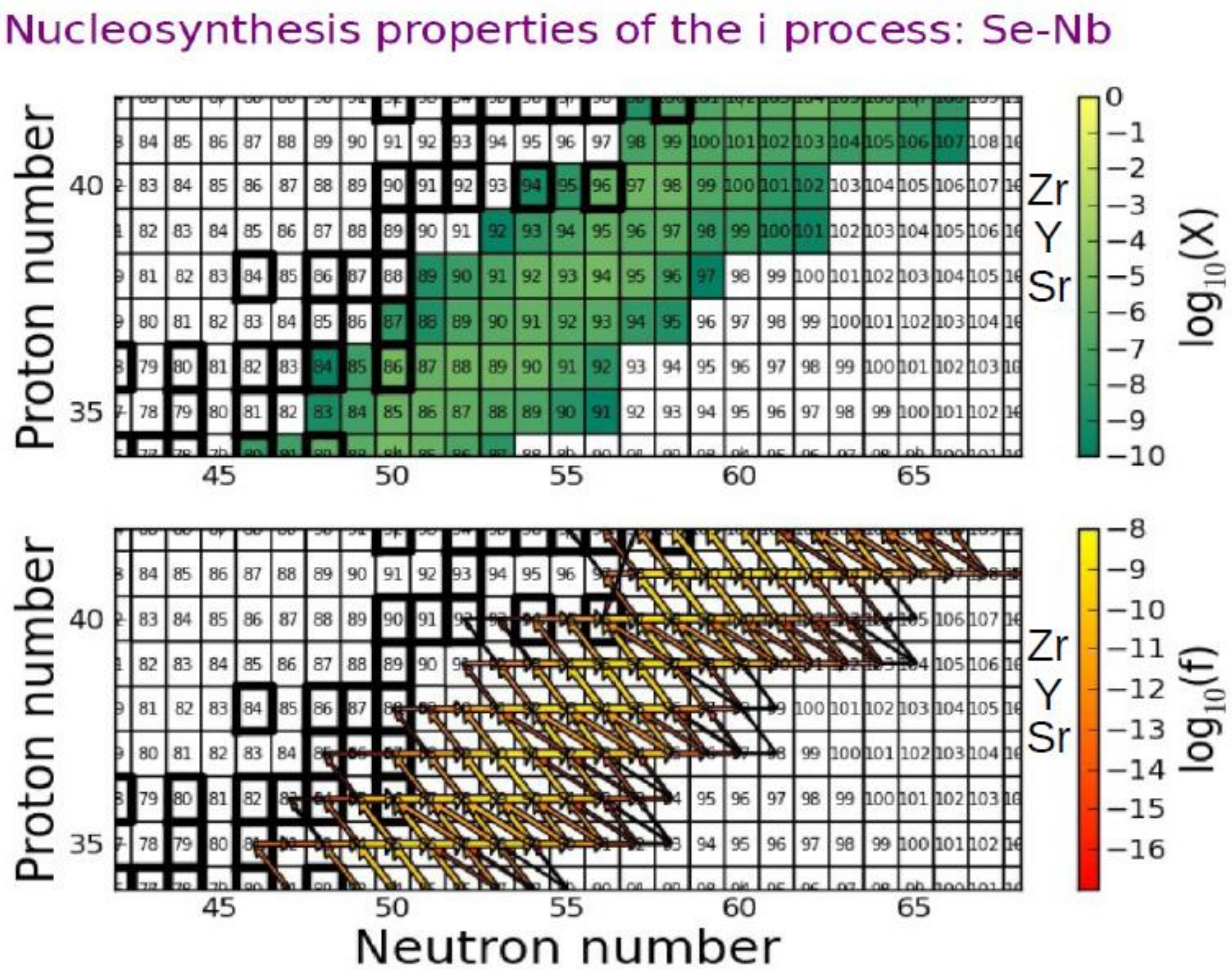
TALYS 1.6 considered 909 (alpha,n) reactions on stable andneutron-rich nuclei between Fe (Z=26) and Rh (Z=45).

masses, which were taken from data table if available, or from the FRDM otherwise.

$1\ \mathrm{GK} \lesssim T \lesssim 5\ \mathrm{GK}$

The production of molybdenum in stars: a nuclear astrophysics challenge

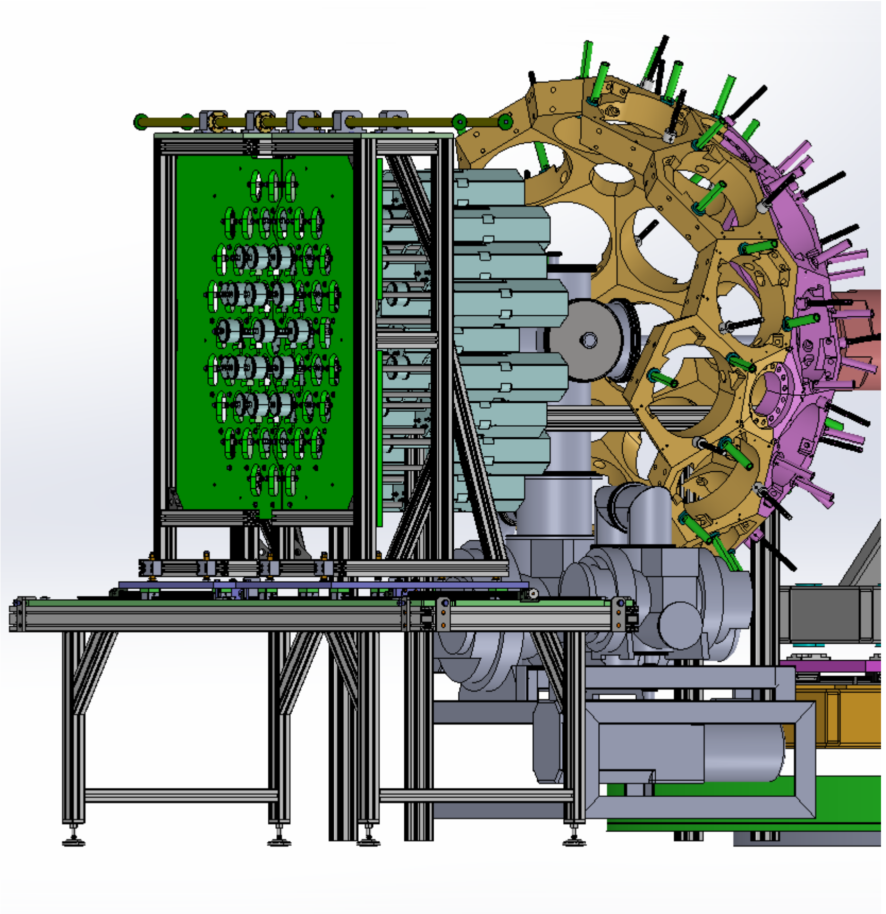




The production of molybdenum in MHD SNe

Element	Reaction	Rate varied	$R(i)$	Tracer
Mo ($Z=42$)	^{80}Zn(α,n)	100	0.326, 0.224, 0.099	3, 6, 1
	^{81}Ga(α,n)	100	0.234, 0.034	8, 3
	^{82}Ge(α,n)	100, 0.01	0.108, 0.110	8
	^{79}Zn(α,n)	100	0.195, 0.149, 0.066	3, 6, 1
	^{78}Zn(α,n)	100	0.173, 124	3, 6
	^{81}Zn(α,n)	100	0.119, 106, 0, 063	3, 6, 1
	^{83}Ge(α,n)	100	0.094	8
	^{79}Ga(α,n)	100	0.086	8
	^{80}Ga(α,n)	100	0.072	8
	^{81}Ge(α,n)	100	0.059	8
	^{90}Se(α,n)	100	0.049	2
	^{87}As(α,n)	100	0.045	2
	^{88}Se(α,n)	100	0.028	2
	^{121}Tc(α,n)	100	0.020	6
	^{119}Tc(α,n)	100	0.018	6
	^{89}Nb(α,n)	0.01	0.016	6
	^{103}Nb(α,n)	0.01	0.011	6
	^{103}Mo(α,n)	100	0.010	6

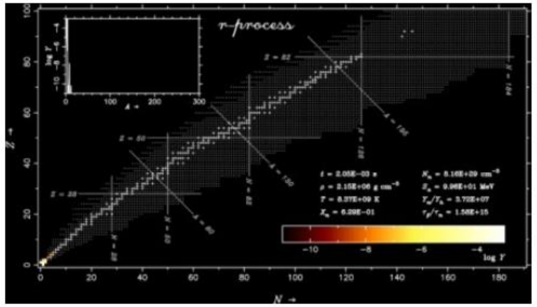
SUGAR@LNL coupled with NEDA



PHASE B

^{12}C PRODUCTION IN EXPLOSIVE SCENARIOS

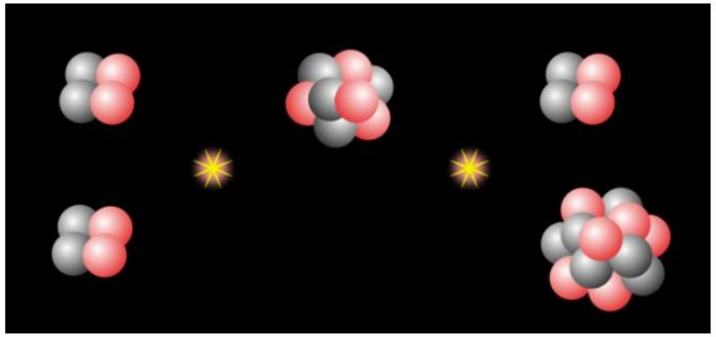
r-process escenario



^{12}C is the seed nucleus for the creation of heavier nuclei (A=50-80)

^{12}C formation

Triple alpha process



Binary system of two neutron stars. Site where r-process can take place

E. Pian et al, Nature 551, 67–70 (2017)

^{4}He(αn, γ)^{9}Be

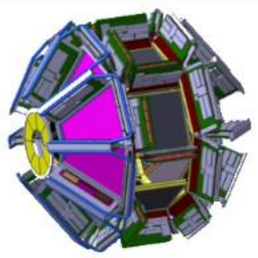
^{4}He(nn, γ)^{6}He(α,n)^{9}Be

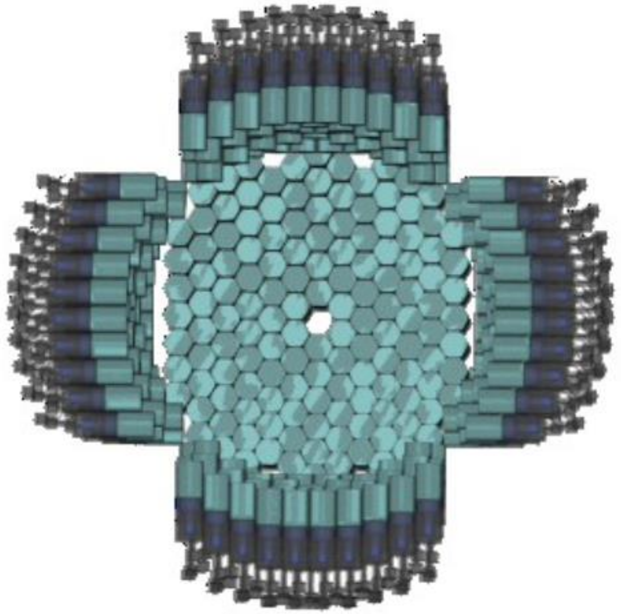
^{9}Be(α,n) ^{12}C

Favored by a factor ~10

^{9}Be(α,n)12C

- **Direct kinematic.** ^{9}Be target.
  - For instance: detector **GRIT (charged particles** and **NEDA (neutrons)** . Possible coincidence n - ^{12}C





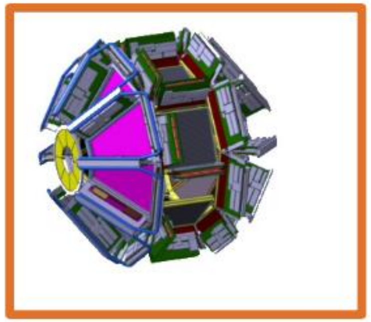
- α+α+α+n Q=-1.57 MeV
- ^{8}Be+n+α Q=-1.66 MeV
- ^{5}He+ 2α Q=-2.31 MeV

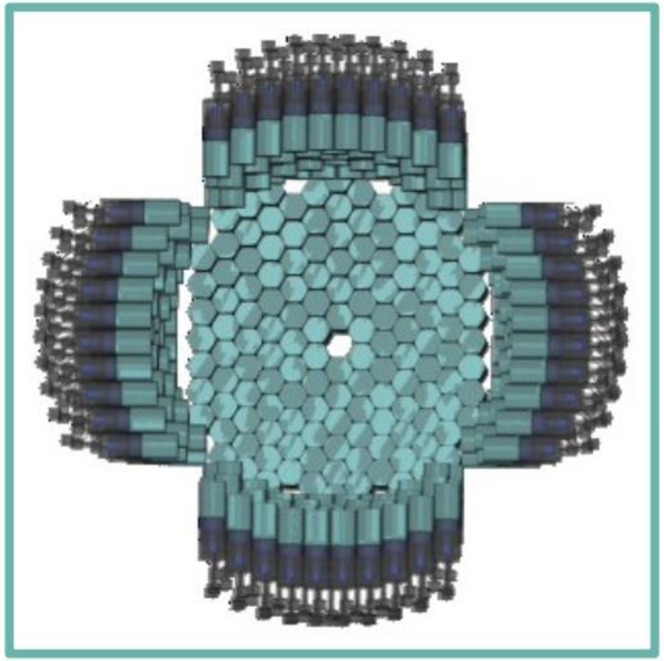
$^{9}Be(\alpha,n)^{12}C$

- **Inverse kinematic.** ^{4}He target.
  - Gas target (CTADIR or **SUGAR**)
  - For instance: detector **GRIT (charged particles)** and **NEDA (neutron)**.

Possible coincidence n - ^{12}C

^{9}Be beam at LNL???





- α+α+α+n Q=-1.57 MeV
- ^{8}Be+n+α Q=-1.66 MeV
- ^{5}He+ 2α Q=-2.31 MeV

PHASE C

$^{4}He(nn,\gamma)^{6}He$

- **Inclusive Coulomb breakup of ^{6}He on heavy target** → **Reaction rate $^{4}He(nn,\gamma)$ ^{6}He**

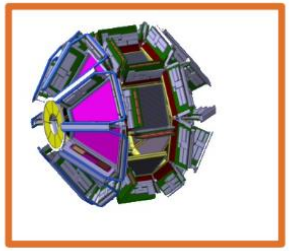
  J. Casal et al., Phys. Rev C 93 (2016) 041602(R);

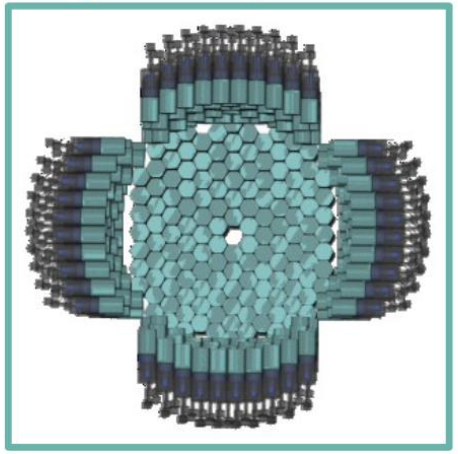
  For instance: detector **GRIT (charged particles)**

- **Exclusive breakup measurements ^{6}He+A**

  For instance: detector **GRIT (charged particles)** and **NEDA (neutrons)**.

  Possible coincidence n - ^{4}He





- **Study the reaction $^{6}He(^{4}He,\gamma)^{10}Be$**

  The ^{6}He+^{4}He cluster structure of ^{10}Be is under study at the LNS with a ^{10}Be beam

  For instance: detector **AGATA (gamma)**

  Gas target (CTADIR or SUGAR)

$^{6}He(^{4}He,\gamma)^{10}Be$	Q= 7.4 MeV
$^{6}He(^{4}He,n)^{9}Be$	Q= 0.6 MeV

PHASE C

SUMMARY

- ✓ Decay properties of neutron-rich nuclei at the first and second r-process peak : $T_{1/2}$, Pn, decay schemes

- ✓ Neutron capture cross sections :
  - ✓ s-process : activation measurements and surrogate reaction approach
  - ✓ i-and r-process nucleosynthesis via surrogate reaction approach

- ✓ Abundances of the elements at the first r-process peak: (α,n) reactions

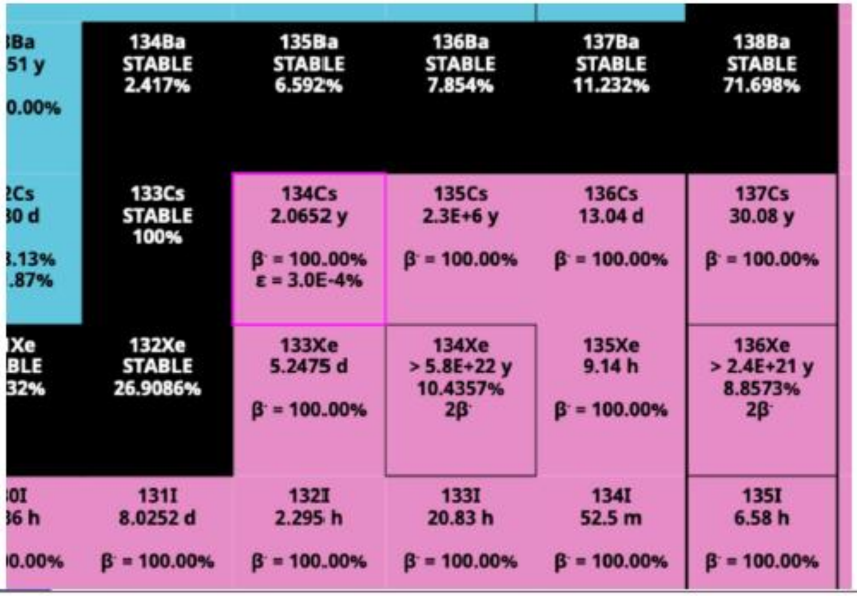
- ✓ R-process seeds: $^{9}Be(\alpha,n)^{12}C$; $^{4}He(2n,\gamma)^{6}He$

For a very long term: fission of heavy neutron-rich
Separator able to cope with overlapping A/q

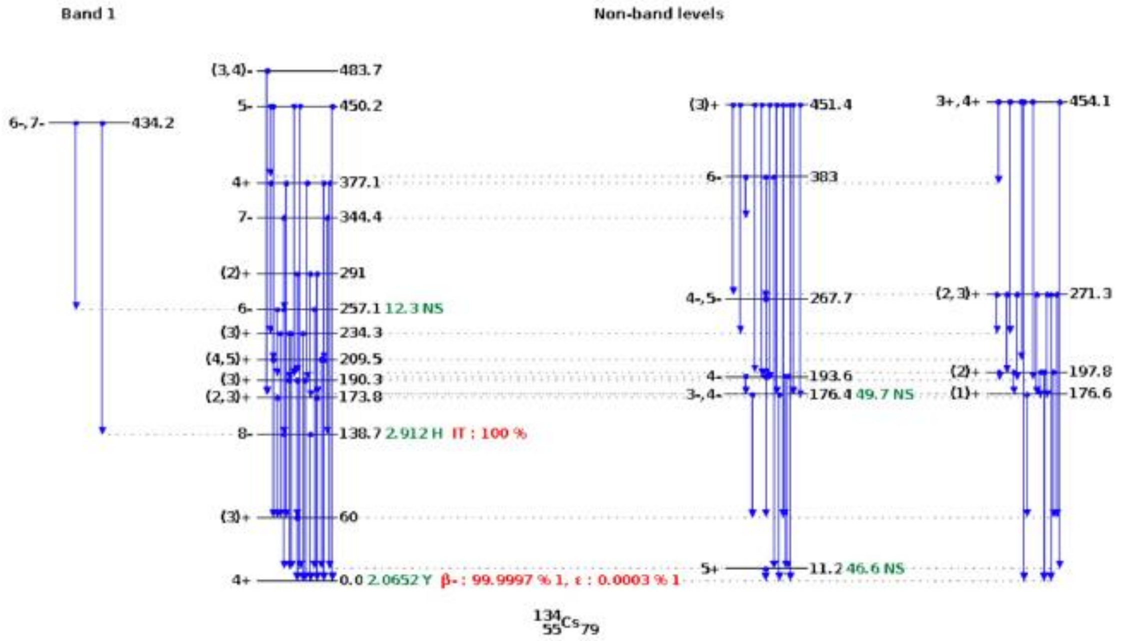
Extra

Measurement of the **^{134}Cs** excited state at 60.03 keV, whose SPIN is not known: it is currently identified as (3)+.
It may be 3+, 4+ or 5+.

- Population via b-decay not viable
- Access via different technique
- MOS technique could help accessing low-energy state
- Dedicated set of magnets for low-energy electrons transport
- Colling of Si(Li) might not be needed



The beta-decay rate in astrophysical plasmas may change depending on the spin of that state, even at relatively low temperatures.



Possible measurement from
$^{134}Xe + ^{208}Pb$
or
$^{133}Cs(d,p)$ beams?