End of Lecture I.

Take away messages:

Elements heavier than Fe are produced by neutron capture processes

There exists two major categories of processes with low and high densities

s-process nucleosynthesis is observed and ongoing in AGB stars

r-process site(s) is so far unknown: supernova, neutron star mergers…

Observation in EMP display similar pattern above Z=56 -> robust r

Below Z=56, many more flucututaions -> weak r process

Other signature of weak r process exist in CEMP-i stars and in meteorites

Need measurements to better understand the corresponding processes

Experiments relevant for a better understanding of explosive neutron capture scenarios …

I. Reminder of essential properties required for the r process
II. Studies of atomic masses
III. Studies of Beta decay lifetimes
IV. Studies of neutron-delayed emission probabilities
V. Studies of neutron capture rates

With material from S. Nishimura, G. Lorusso, K.-L. Kratz, V. H. Phong

CERN, May 10th 2017

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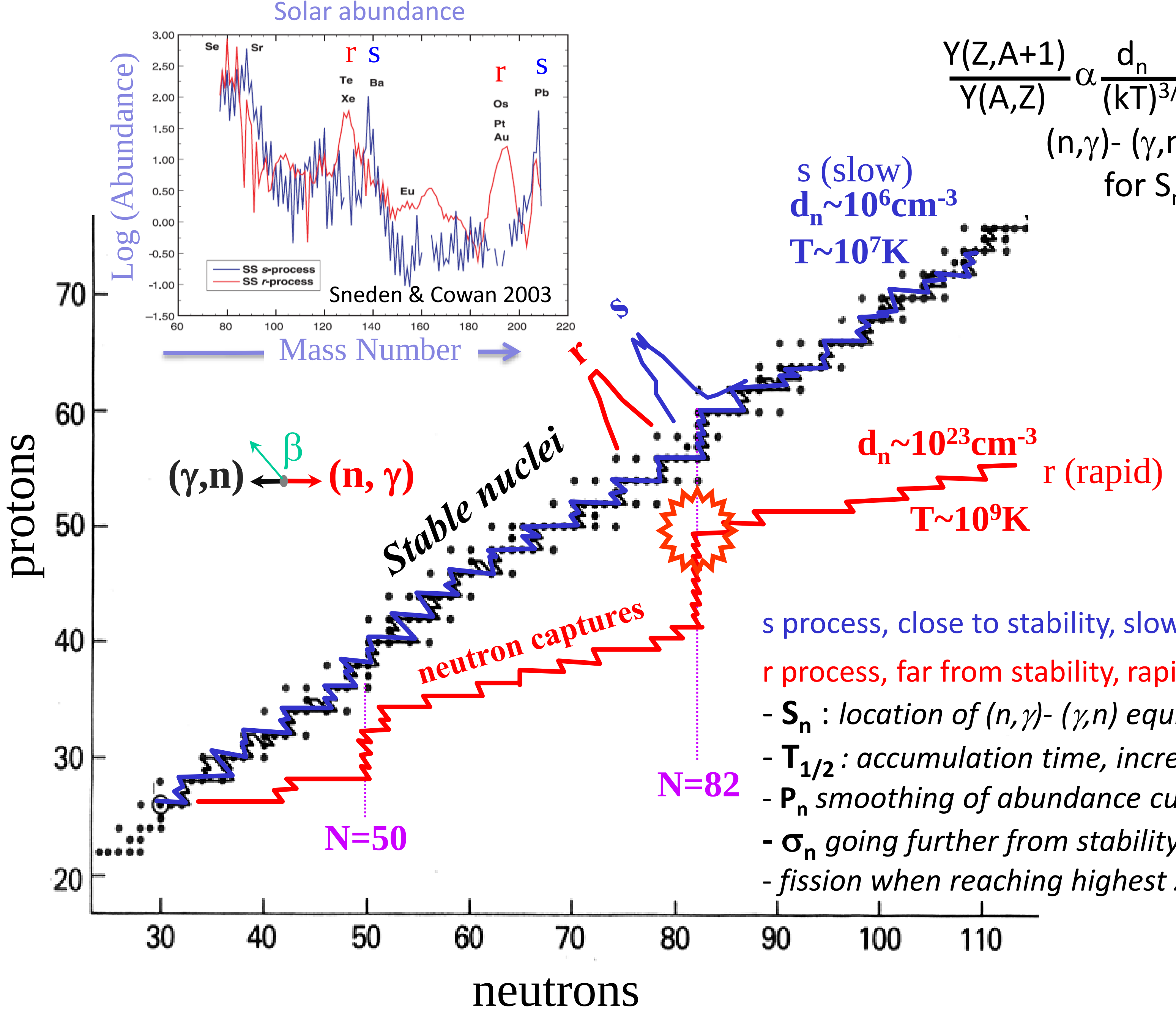
With material from S. Nishimura, G. Lorusso, K.-L. Kratz, V. H. Phong

Neutron capture processes



$$\frac{Y(Z,A+1)}{Y(A,Z)} \alpha \frac{d_n}{(kT)^{3/2}} \exp(-S_n(A+1)/kT)$$

(n,γ)- (γ,n) equilibrium
for $S_n \approx 2$ MeV

s process, close to stability, slow neutron captures

r process, far from stability, rapid neutron captures

- **S_n** : *location of (n,γ)- (γ,n) equilibrium*
- **$T_{1/2}$** *: accumulation time, increase Z*
- **P_n** *smoothing of abundance curve*
- **σ_n** *going further from stability*
- *fission when reaching highest Z.*

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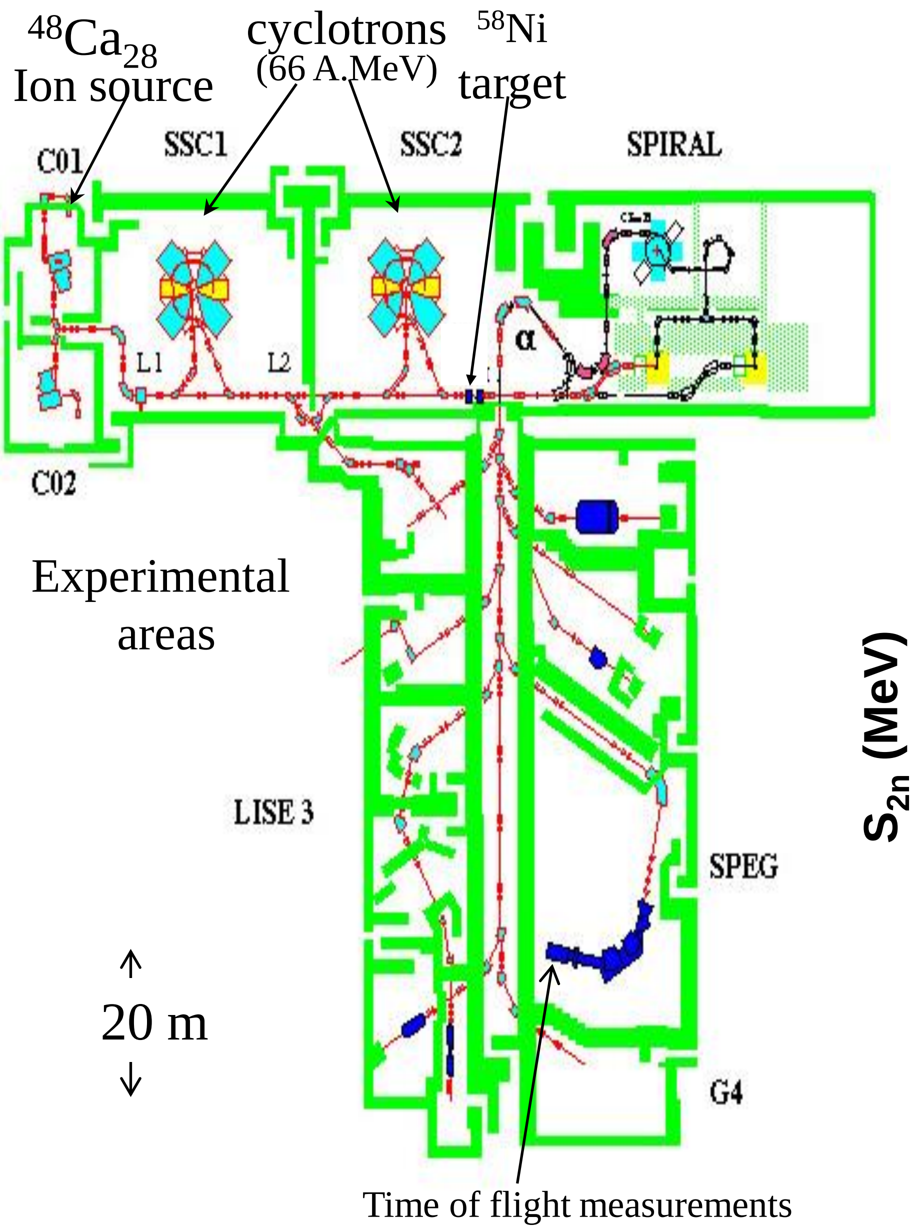
Mass measurements of neutron-rich P-Ar nuclei at GANIL/SPEG



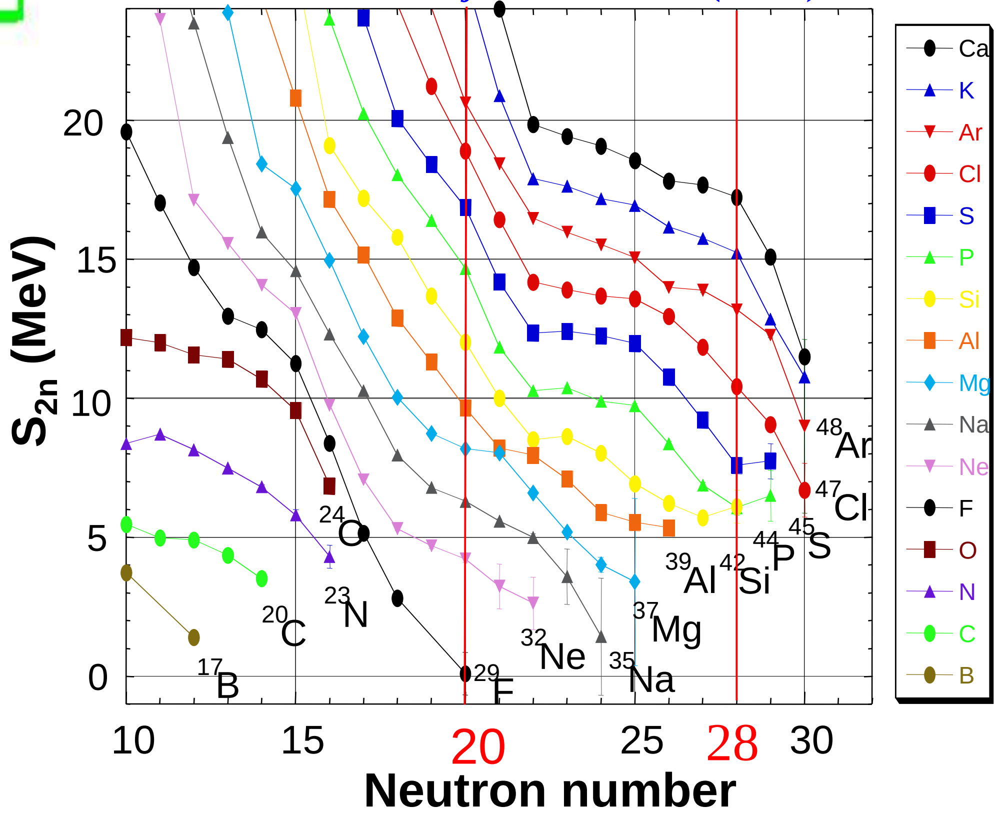
Mass measurement by time of flight (over L=80m)

$$BR \sim M(A,Z)\ v / Z$$

$$t \propto M(A,Z)\ L / Z$$

$$S_{2n}(A,Z) = M(A,Z) - M(A-2,Z) - 2M_n$$

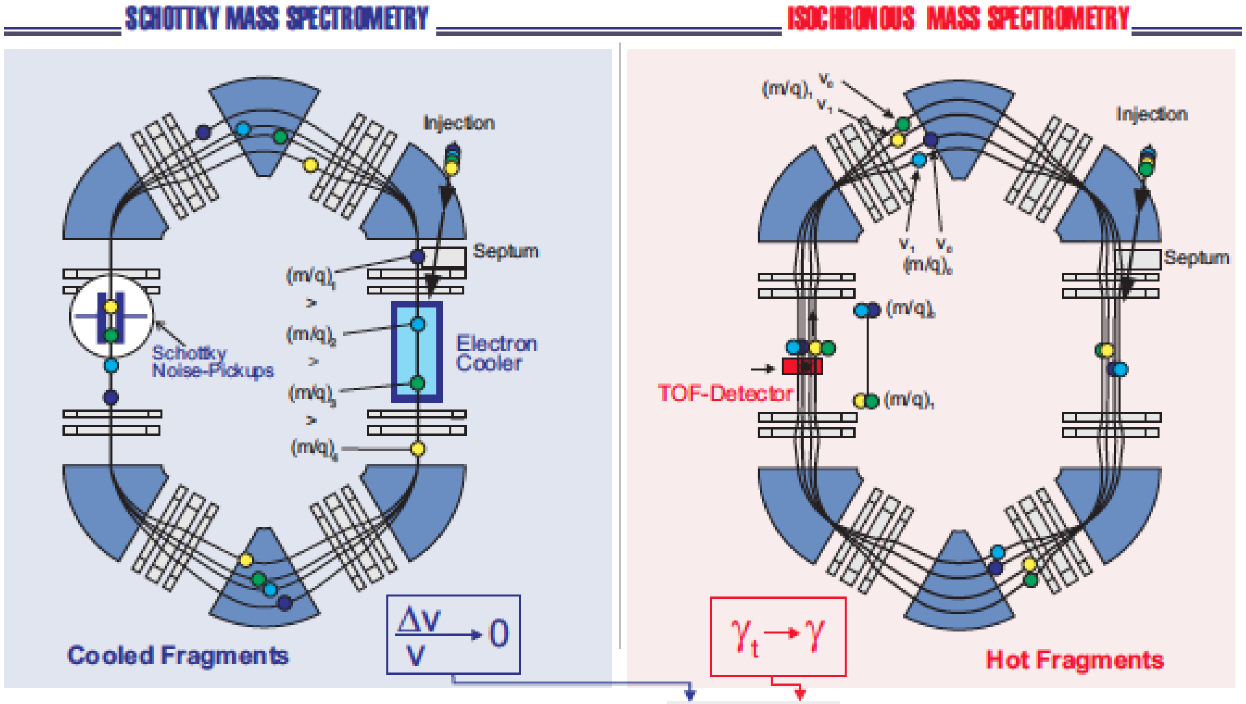
B. Jurado, H. Savajols et al PLB (2006).



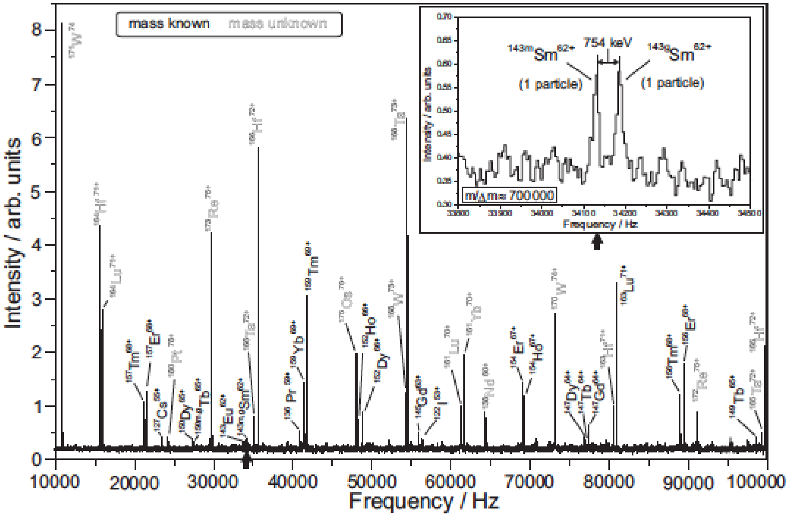
Mass measurement in the FRS-ESR storage ring

Y. Litvinov EJC school 2015

In principle M/ΔM ≈10^6
30 keV for heavy ions…



$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

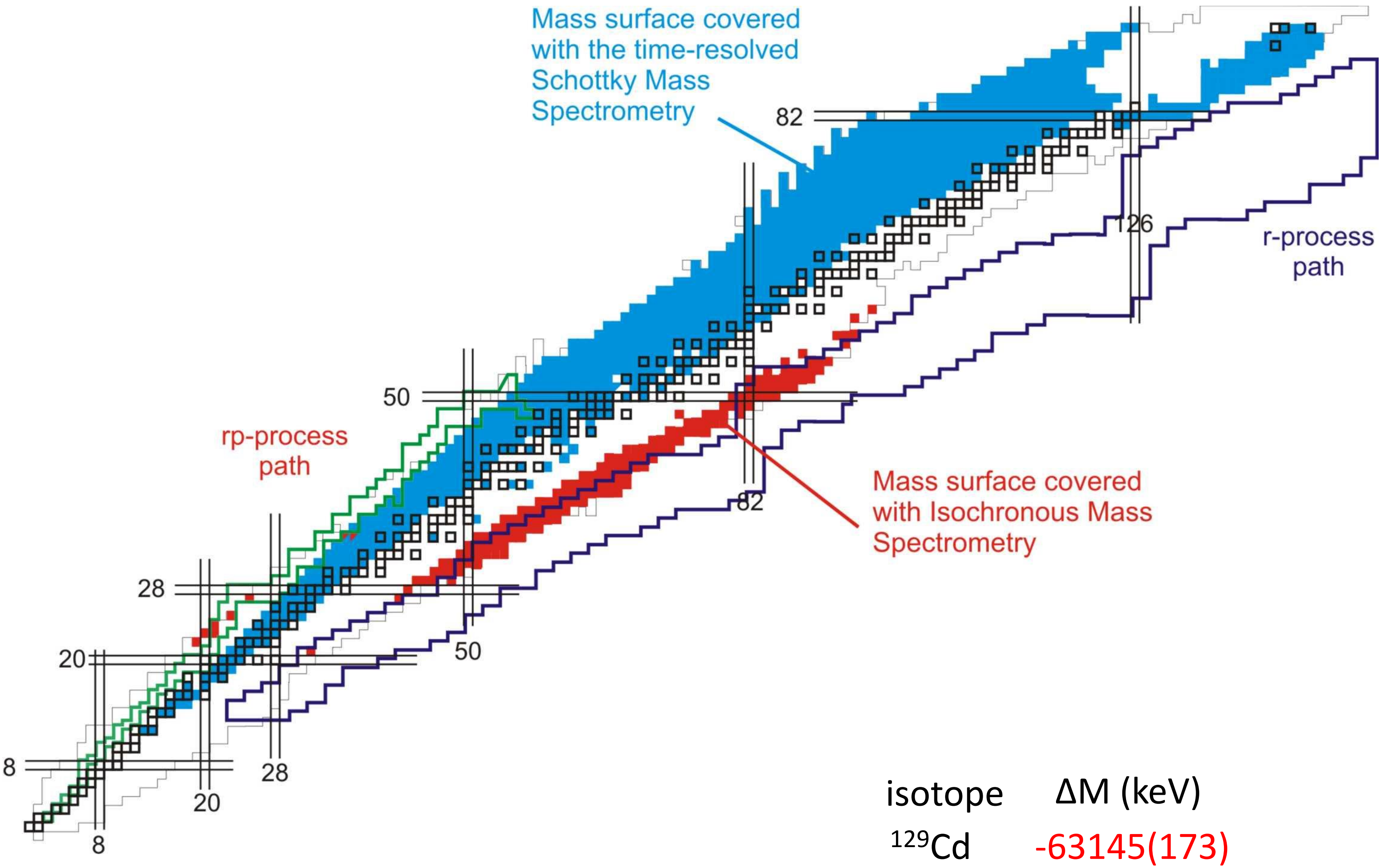


Many species measured at the same time

Need of a Brho tagging from the FRS

Need of known masses together with new ones to correct from systematic errors (e.g. frequency dependence with A/Q and with the number of revolutions in the ring) R. Knöbel et al. EPJA 52 (2016)

Mass measurements in the FRS-ESR storage ring



Mass surface covered with the time-resolved Schottky Mass Spectrometry

rp-process path

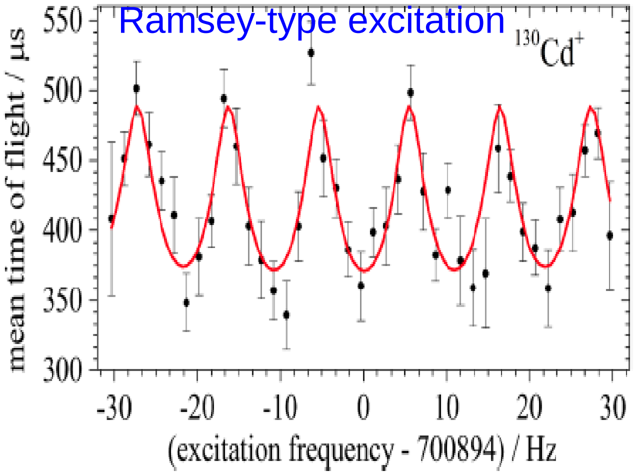
Mass surface covered with Isochronous Mass Spectrometry

r-process path

isotope	ΔM (keV)
^{129}Cd	-63145(173)
^{130}Cd	-62131(411)
^{131}Cd	--55583(953)

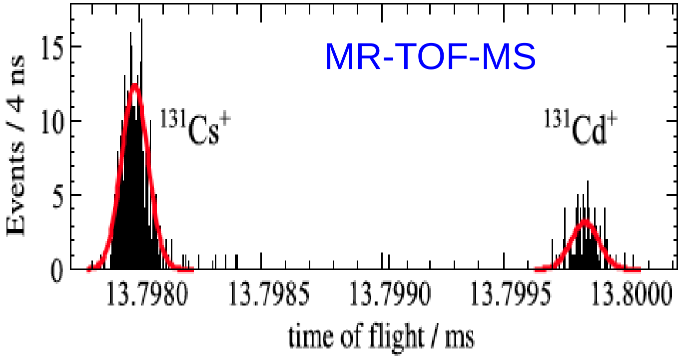
R. Knöbel, PLB 754 (2016)

Precision mass measurements of $^{129-131}$Cd isotopes

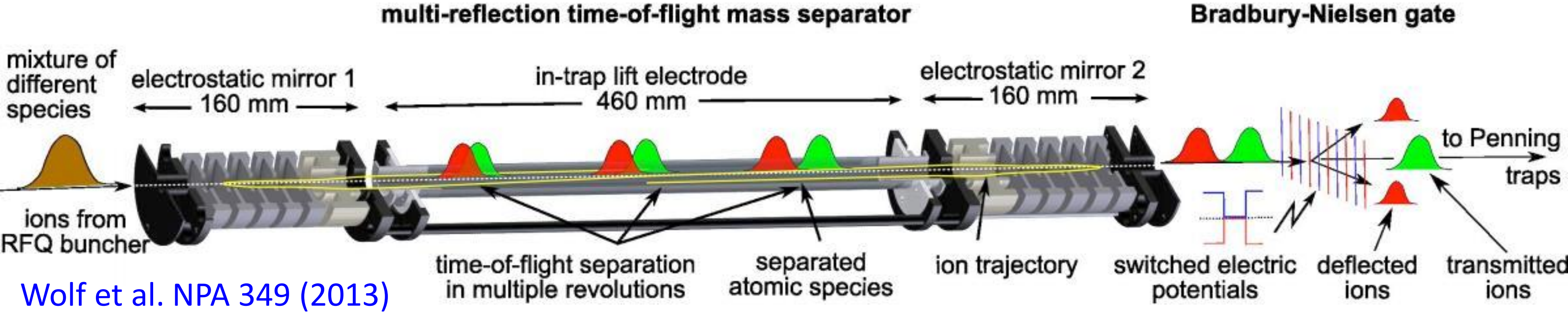


Atanasov et al. PRL 115 (2015) 232501
K. Blaum et al. J. Phys. B, At. Mol. Opt.Phys. 42 (2009)

Beams are accumulated and bunched into an RFQ, injected in a MR-TOF-MS and transported to a Penning trap (if lifetime long enough) to measure their cyclotron frequency $\nu_c = qB/(2\pi M)$



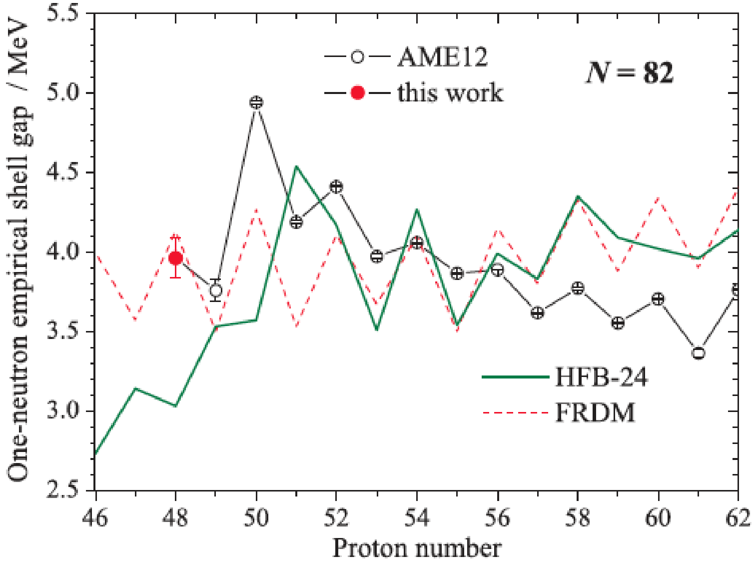
	ΔM (keV)		
isotope	Isolde	GSI	S_n(MeV)
^{129}Cd	-63148(74)	-63145(173)	3.977(74)
^{130}Cd	-61118(22)	-62131(411)	6.131(29)
^{131}Cd	-55215(100)	-55583(953)	2.169(103)

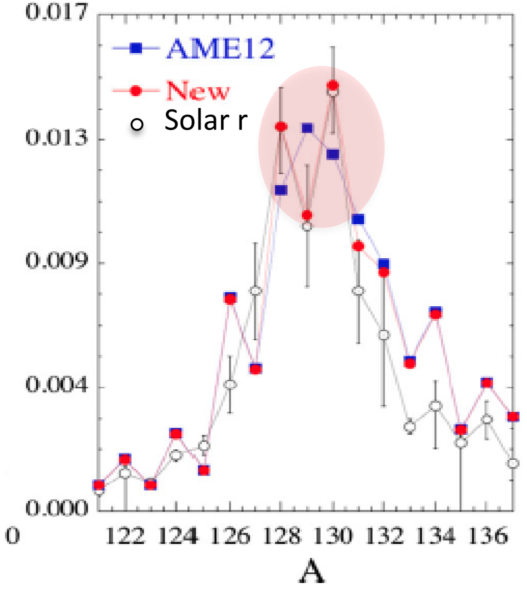


Wolf et al. NPA 349 (2013)

Precision mass measurements of $^{129-131}$Cd isotopes

Atanasov et al. PRL 115 (2015) 232501





AME12 is complemented by HFB-24 when unknown

CCSNe

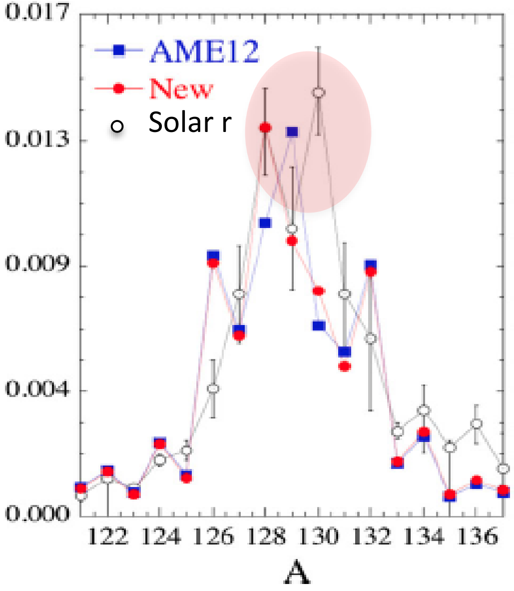
$$\text{GAP} \approx S_n(N=82)-S_n(N=83)$$

No strong quenching of the N=82 gap observed in Cd

HFB-24 does not give a statisfactory trends below Z=50

Some physics ingredients missing

Better extrapolation is needed …



NS-BH merger

Experiments relevant for a better understanding of explosive neutron capture scenarios …

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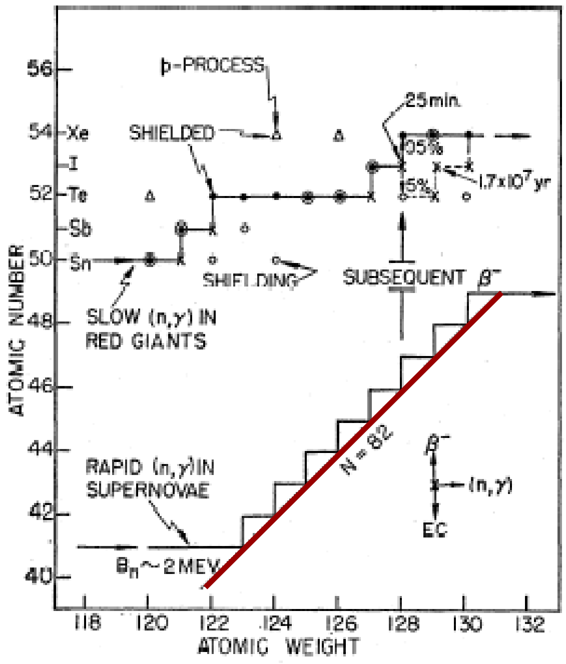
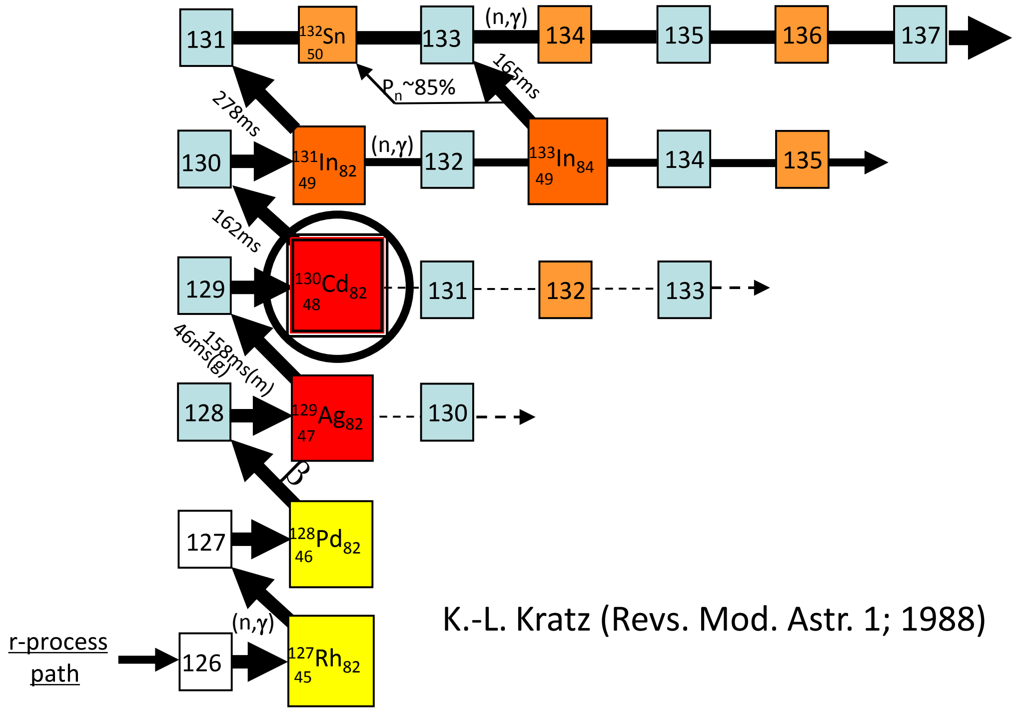
With material from S. Nishimura, G. Lorusso, K.-L. Kratz, V. H. Phong

First studies of r process nuclei: the case of ^{130}Cd

already B^{2}FH (Revs. Mod. Phys. 29; 1957)
C.D. Coryell (J. Chem. Educ. 38; 1961)



...hunting for nuclear properties of waiting-point isotope ^{130}Cd...



K.-L. Kratz (Revs. Mod. Astr. 1; 1988)

"climb up the staircase" at N=82;
major waiting point nuclei;
"break-through pair" ^{131}In, ^{133}In;

"association with the rising side of major peaks in the abundance curve"

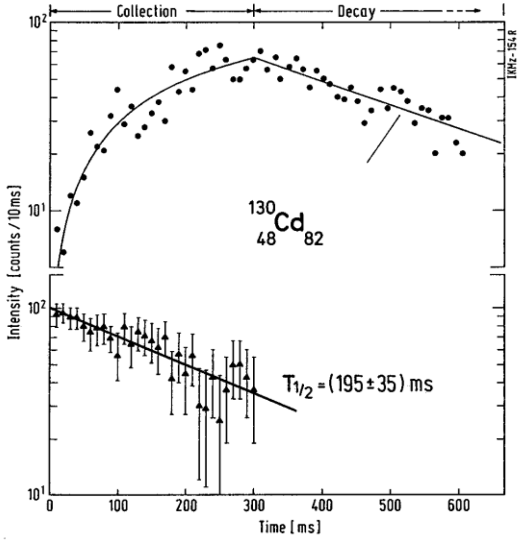
climb up the N= 82 ladder ... (n,γ)-(γ,n) equilibrium
Wait for beta-decay to increase Z

$\Sigma T_{1/2}$ at closed shells -> total duration of the r-process τ_r

Beta decay lifetime of ^{130}Cd

First $T_{1/2}$ of **^{130}Cd** at SC-ISOLDE (1986)

- non-selective plasma ion-source
- selective quartz transfer line
- selective ßdn-counting



Obviously not sufficient

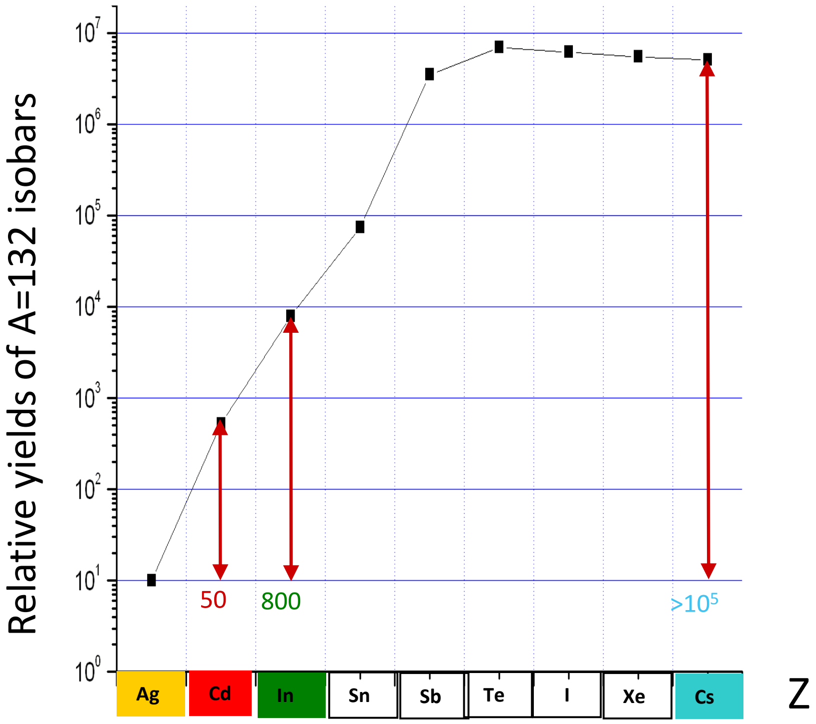
High background from

- surface-ionized ^{130}In, ^{130}Cs
- molecular ions $[^{40}Ca^{90}Br]^+$

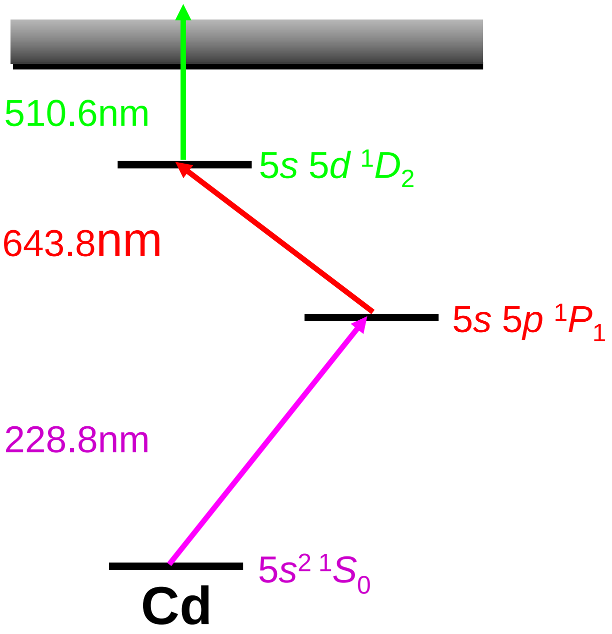
Request: additional selectivity steps

- Fast UC_x target
- **Neutron converter**
- **Laser ion-source**
- Hyperfine splitting
- Isobar separation
- Repeller
- **Chemical separation**
- Multi-coincidence setup

developed since 1993

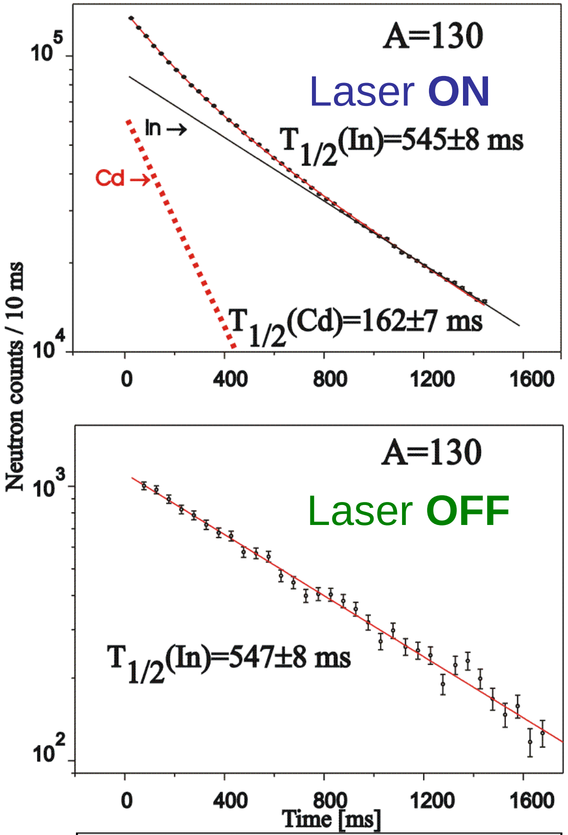


Laser ion-source (RILIS)

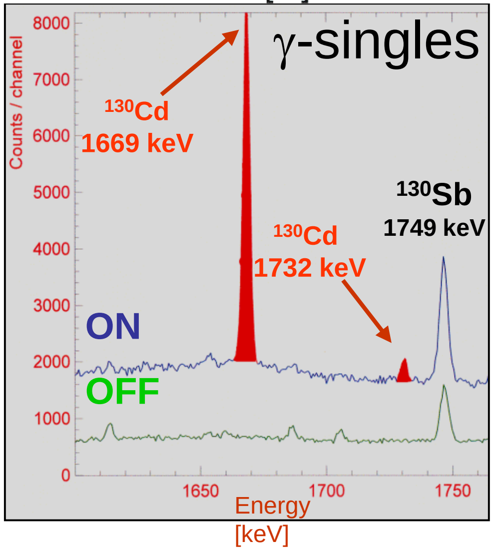


Chemically selective, three-step laser ionisation of Cd into continuum

Efficiency ≈ 10%
Selectivity ≈ 10^3

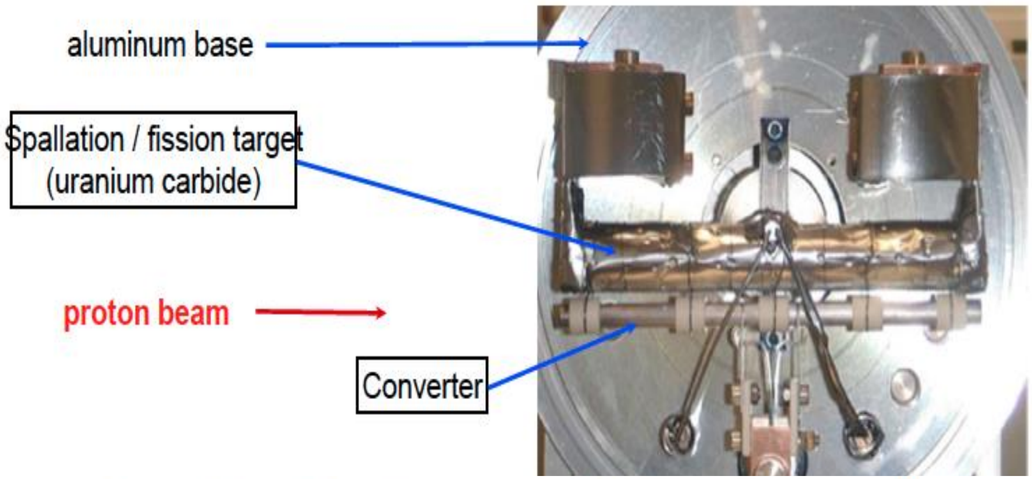


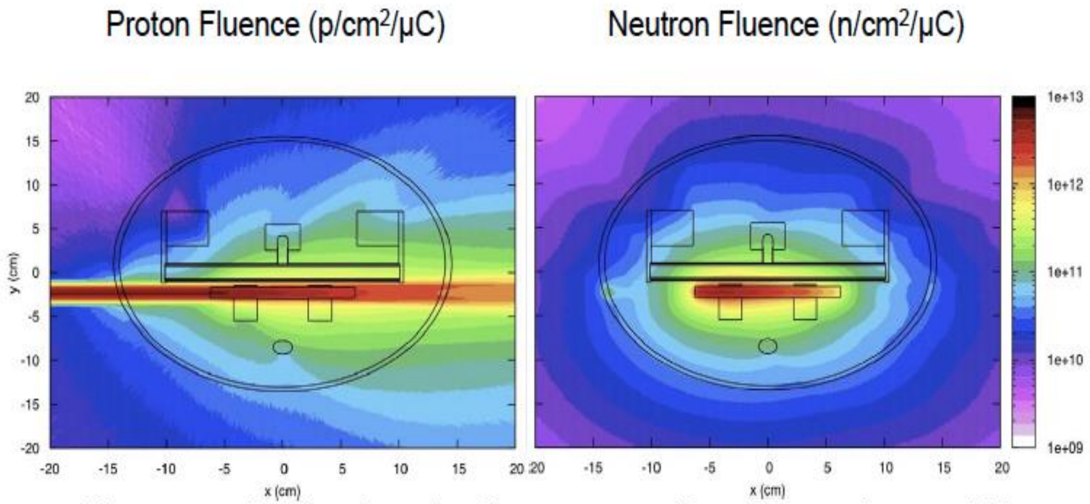
More accurate lifetime



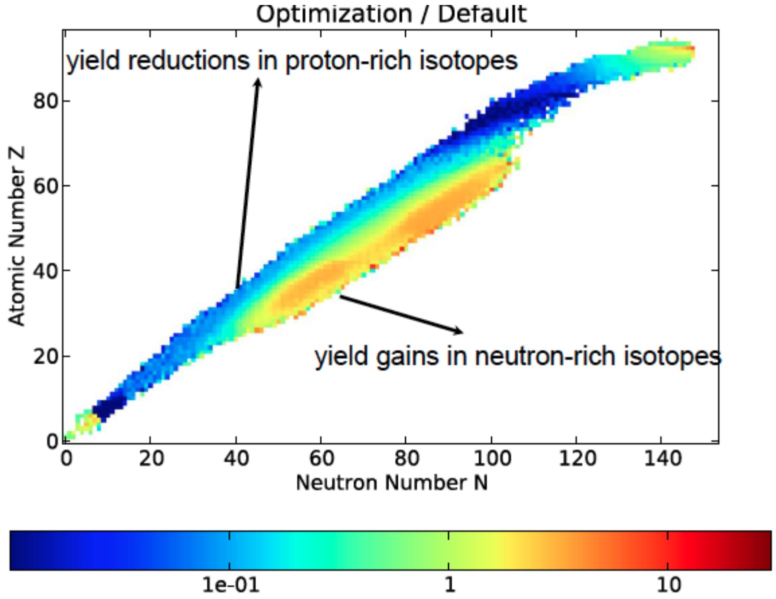
γ spectroscopy becomes possible

A Neutron converter to optimize fission rates




Proton Fluence (p/cm²/μC)

Neutron Fluence (n/cm²/μC)

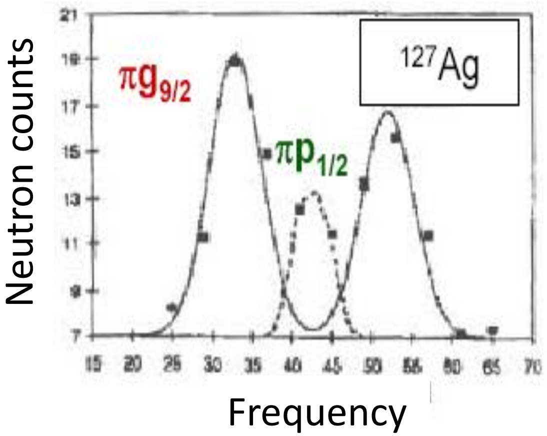

Optimization / Default

Fragmentation and spallation are significatly reduced

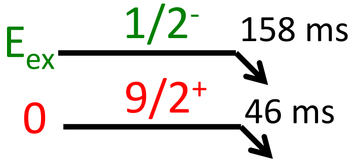
R. Luis et al. Eurisol-Net 2011

Beta Decay of ^{129}Ag (N=82)

Use the spin-dependent hyperfine splitting to favor the production of one state over the other



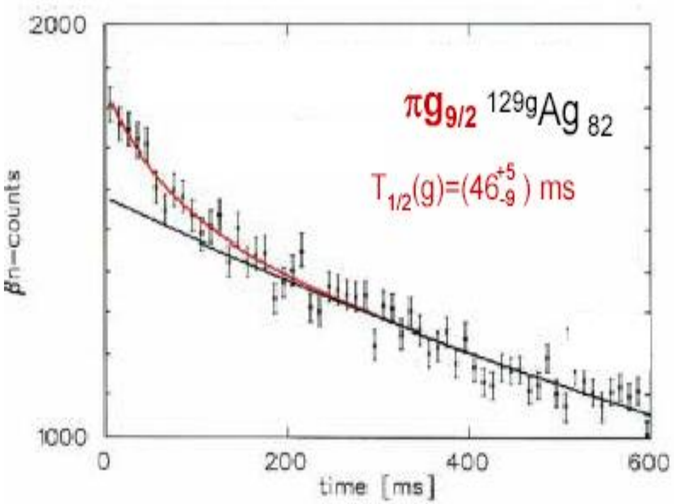
Thermally excited in stars ?

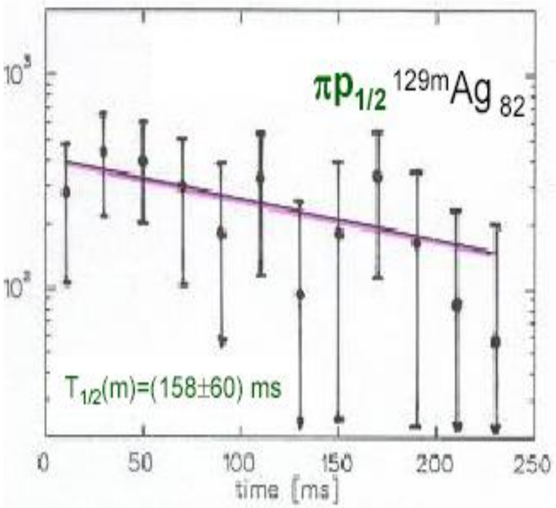


$G(T) = (2J_{ex}+1)/(2J_{g.s.}+1) \exp(-E_{ex}/kT)$

Can E_{ex} be determined in traps ?

Ordering between $9/2^+$ and $1/2^-$?





Pfeiffer et al. NPA 693(2001)282

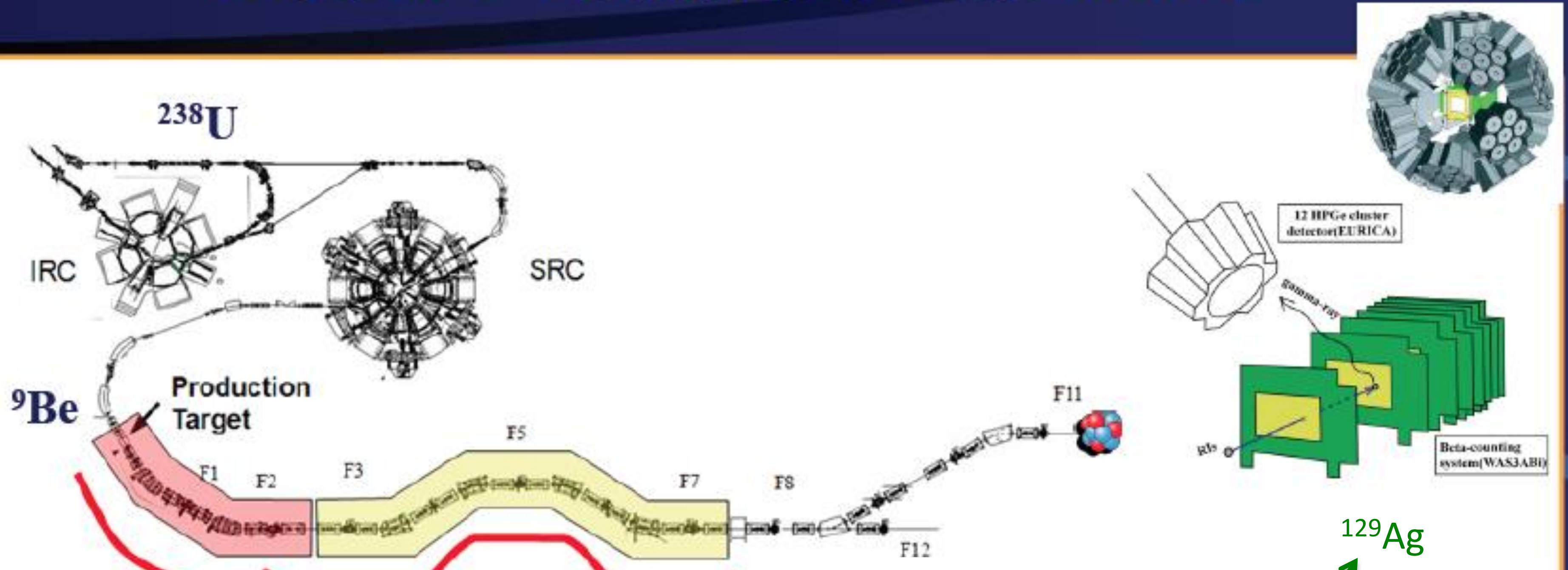
Future: Determine the energy of the $1/2^-$ isomer, study its neutron capture cross section

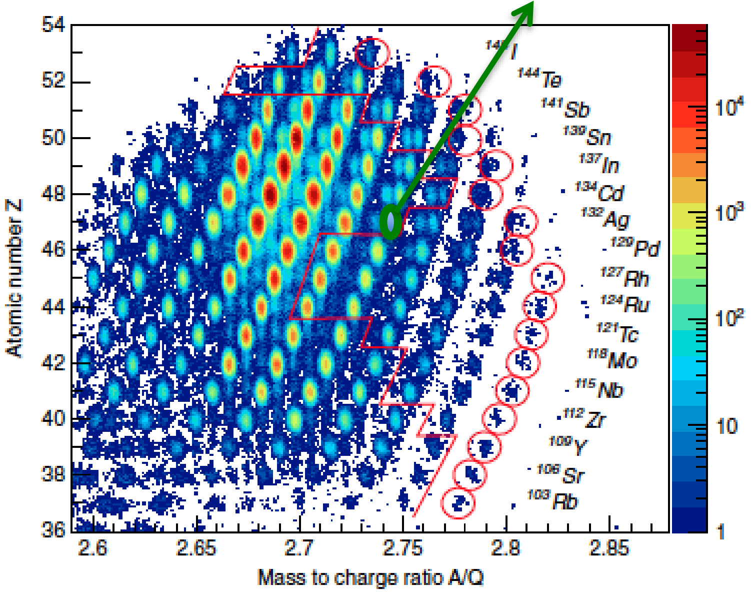
Experiments relevant for a better understanding of explosive neutron capture scenarios …

I. Reminder of essential properties required for the r process
II. Studies of atomic masses
III. Studies of Beta decay lifetimes (non Isolde method)
IV. Studies of neutron-delayed emission probabilities
V. Studies of neutron capture rates

With material from S. Nishimura, G. Lorusso, K.-L. Kratz, V. H. Phong

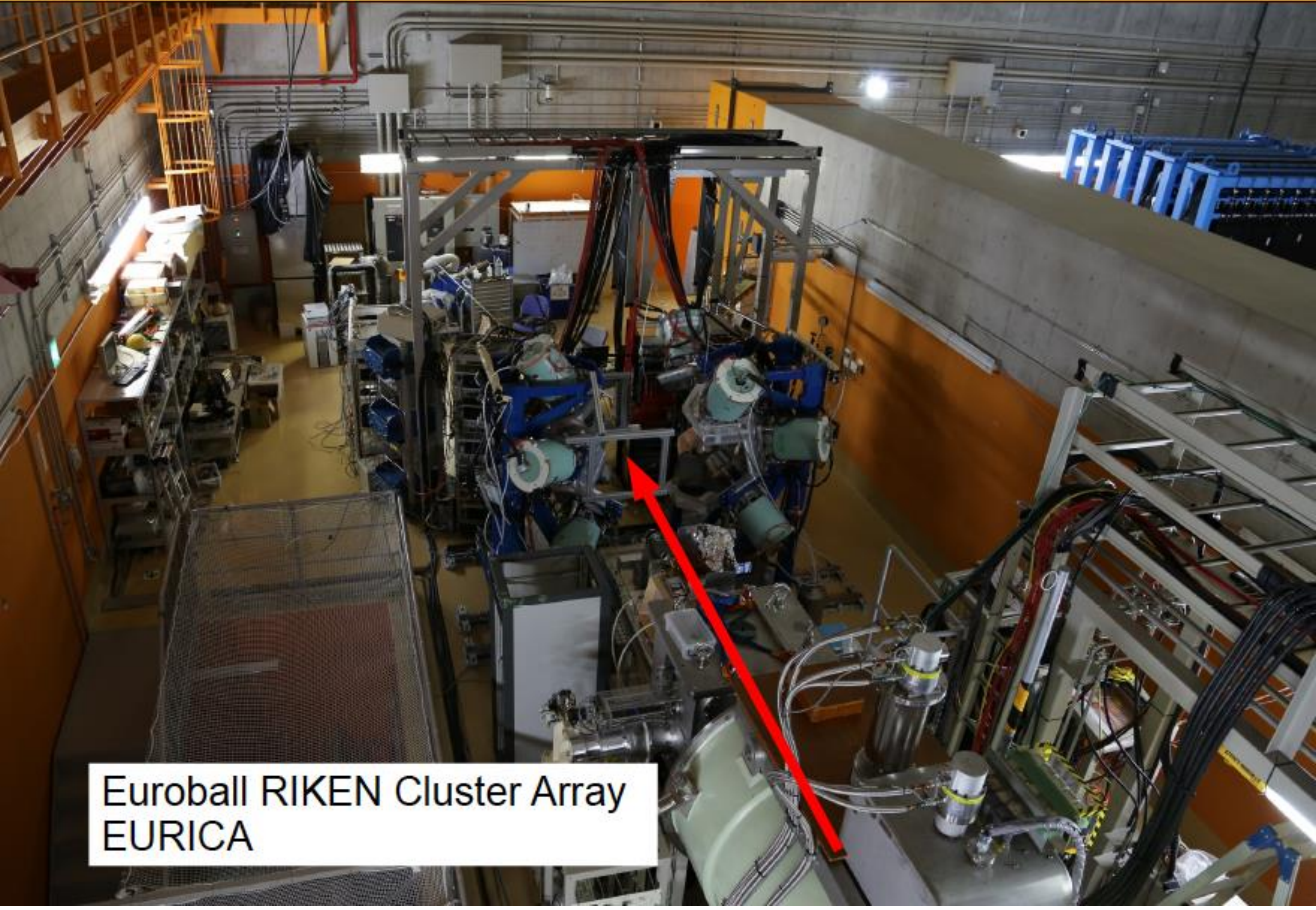
Beam Production at RIBF





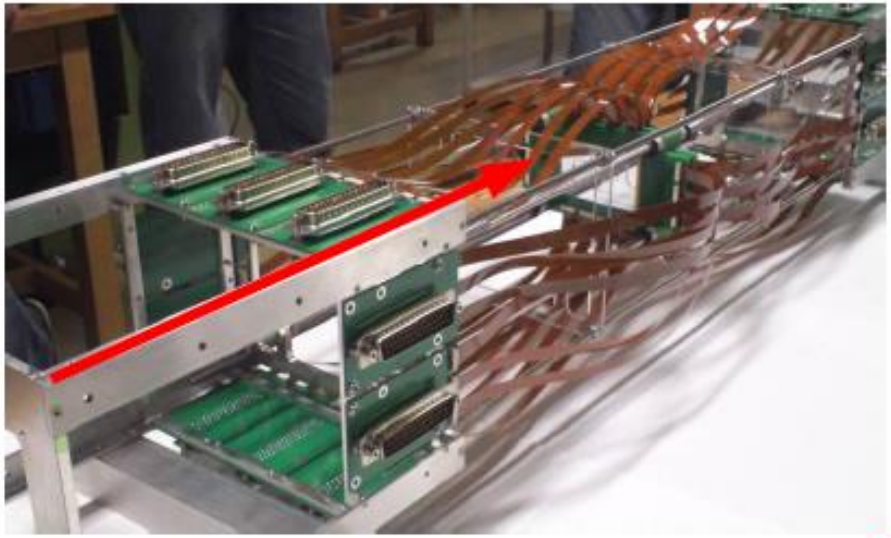
- The implantation of an identified RI is associated with the following β-decay events that are detected in the same silicon pixel (DSSSD).

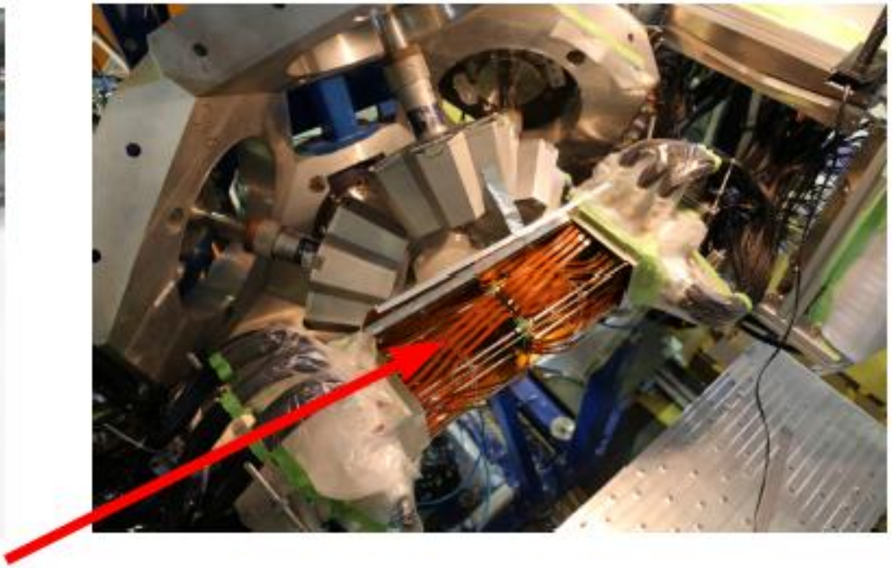
Decay spectroscopy station

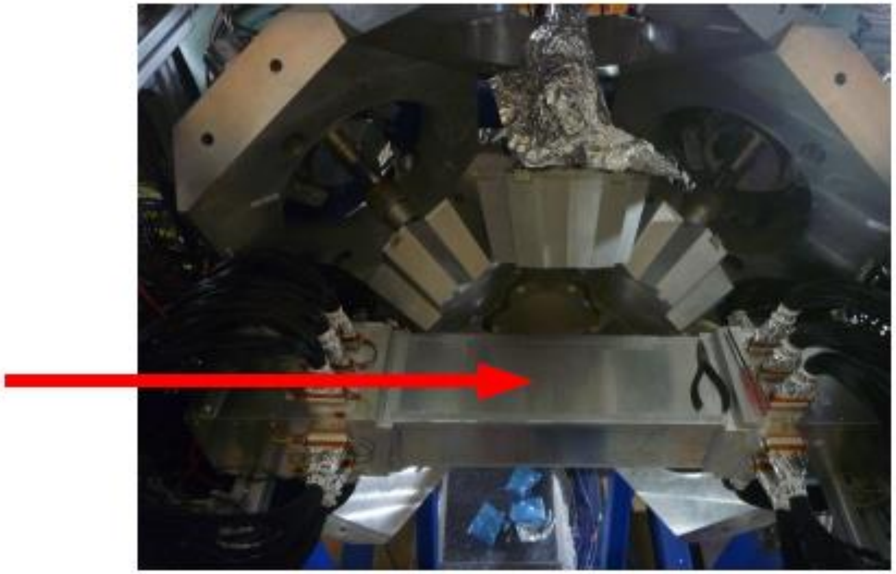


Euroball RIKEN Cluster Array
EURICA

WAS^{3}ABi
(Wide-range Active Silicon Strip Stopper for beta and ions)





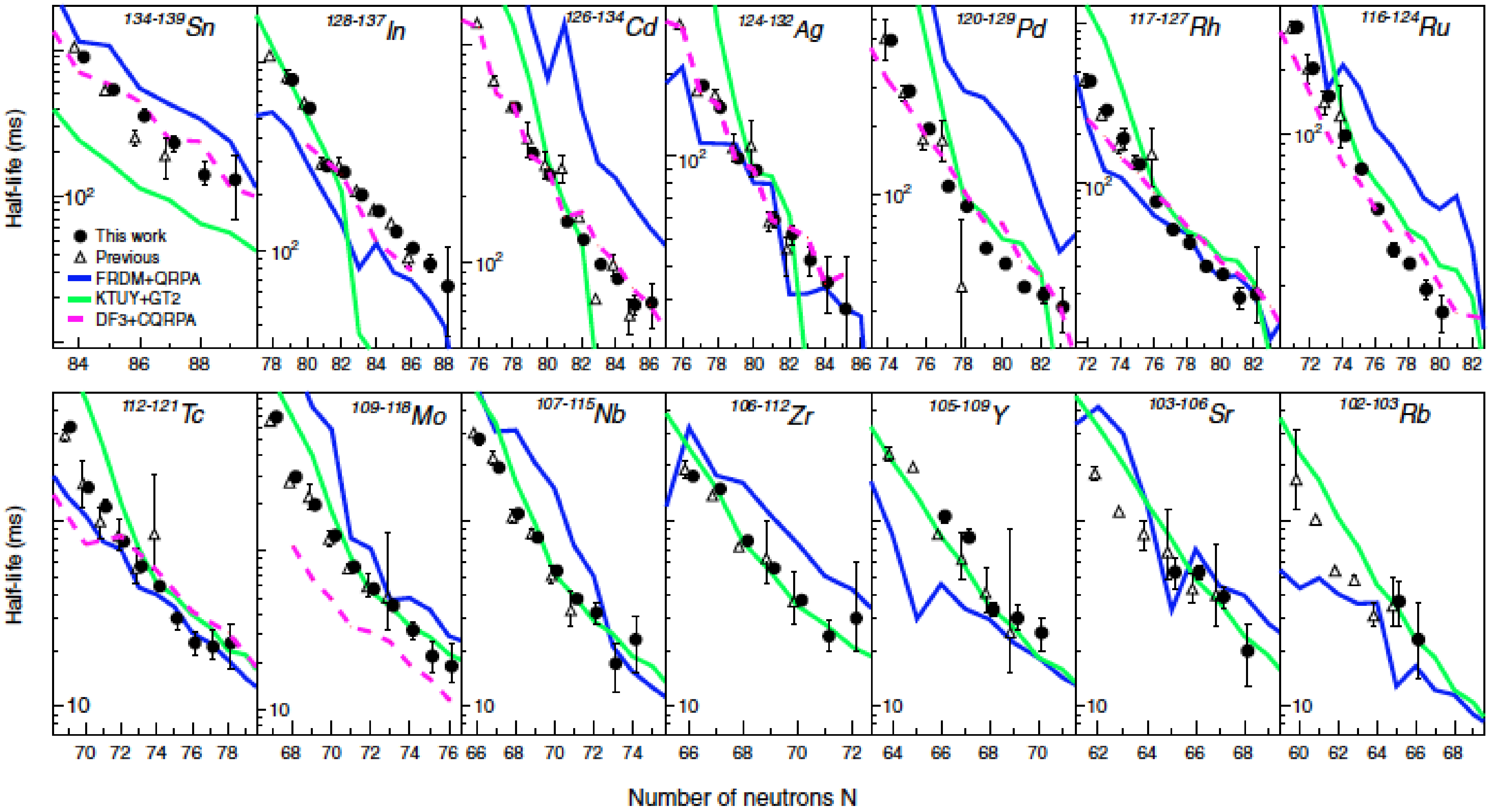


Collaboration RIKEN / TUM / IBS

- 8 DSSD 1-mm thick
- 20 keV threshods
- 20 keV energy resolution
- 100—200 pps Maximum rate
- cooled at 10 ^{0}C
- Q value capability?
- 2 10^4 pixels

EUroball RIKEN Cluster Array (2012—2015)

New lifetime measurements

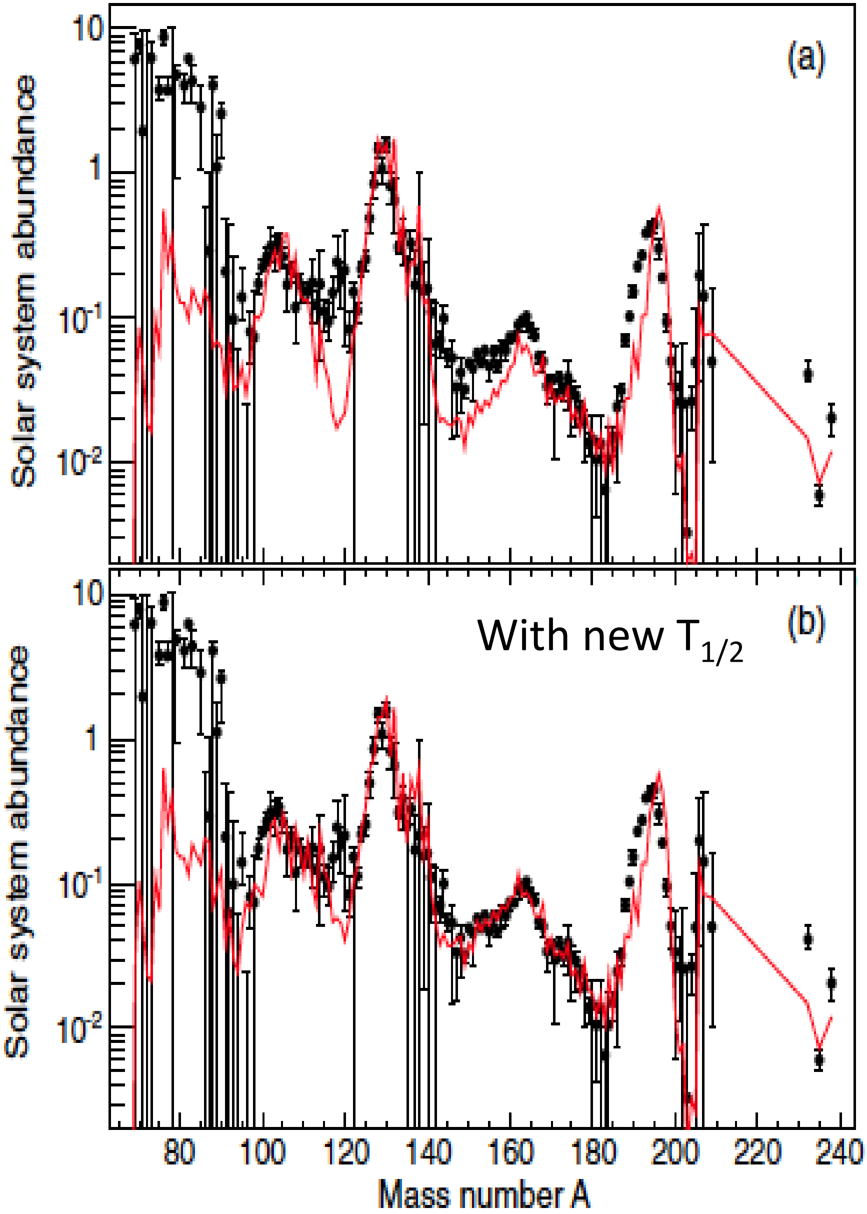


Too strong odd-even effect for FRDM+QRPA model

Too steep decrease of lifetimes for KTUY+GT2

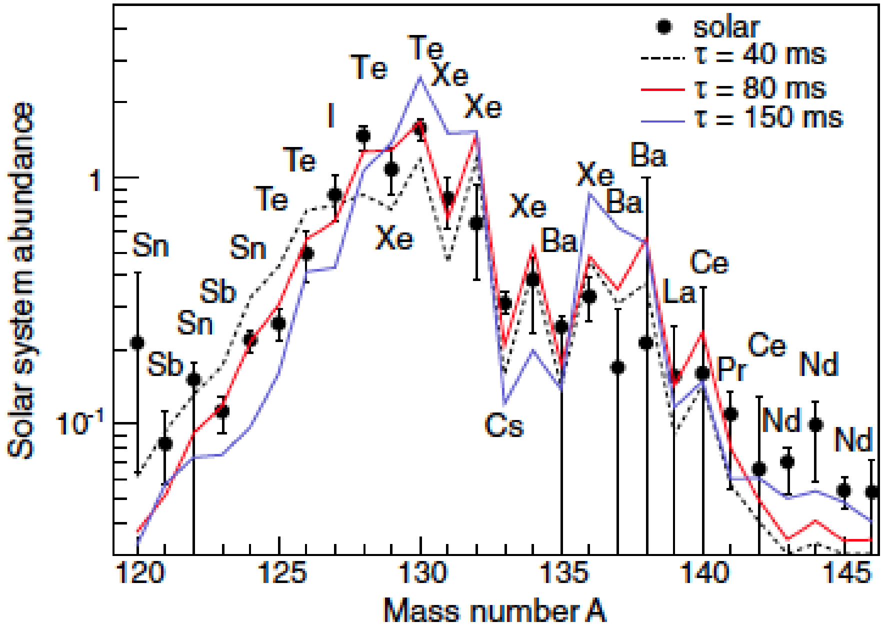
Lorusso et al. PRL 114, 192501 (2015)

r- process implications



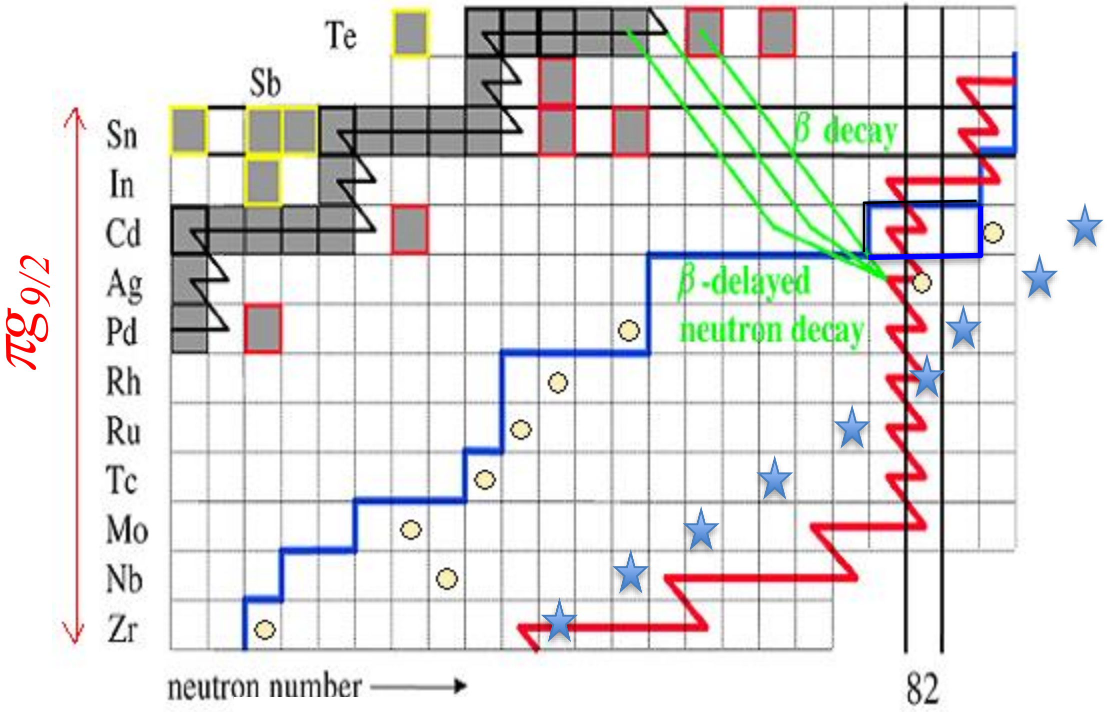
Results of a parametrized explosion with a superposition of entropy values (T^3/ρ) , a proton to nucleon ratio of 0.3 and a time scale of about 100ms show a better agreement with SS observations

New measurements have an impact on SS abundance curve



Lorusso et al., PRL 114 (2015) 192501

Limits of current lifetime / mass measurements



○ $T_{1/2}$ until 2013

★ $T_{1/2}$ new RIKEN data

— Limits of mass measurements

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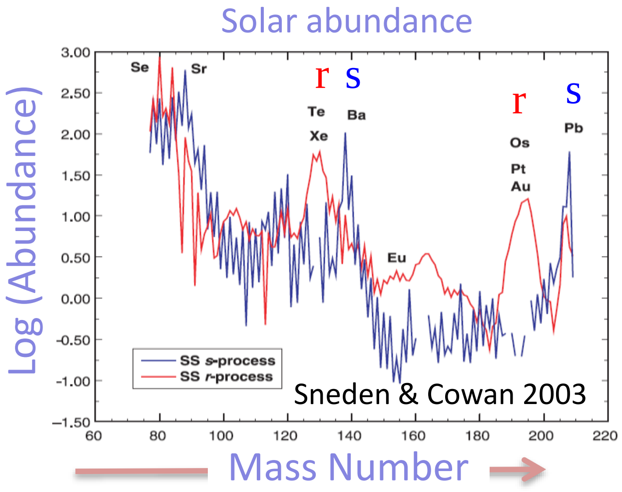
P_n values



Sneden & Cowan 2003

Smoothening of the r abundance curve
No more odd-even effect as for s elements

Emitted eutrons can be further captures by other nuclei, modifying the resulting abundance of the elements

Neutron-delayed emission probability P_n

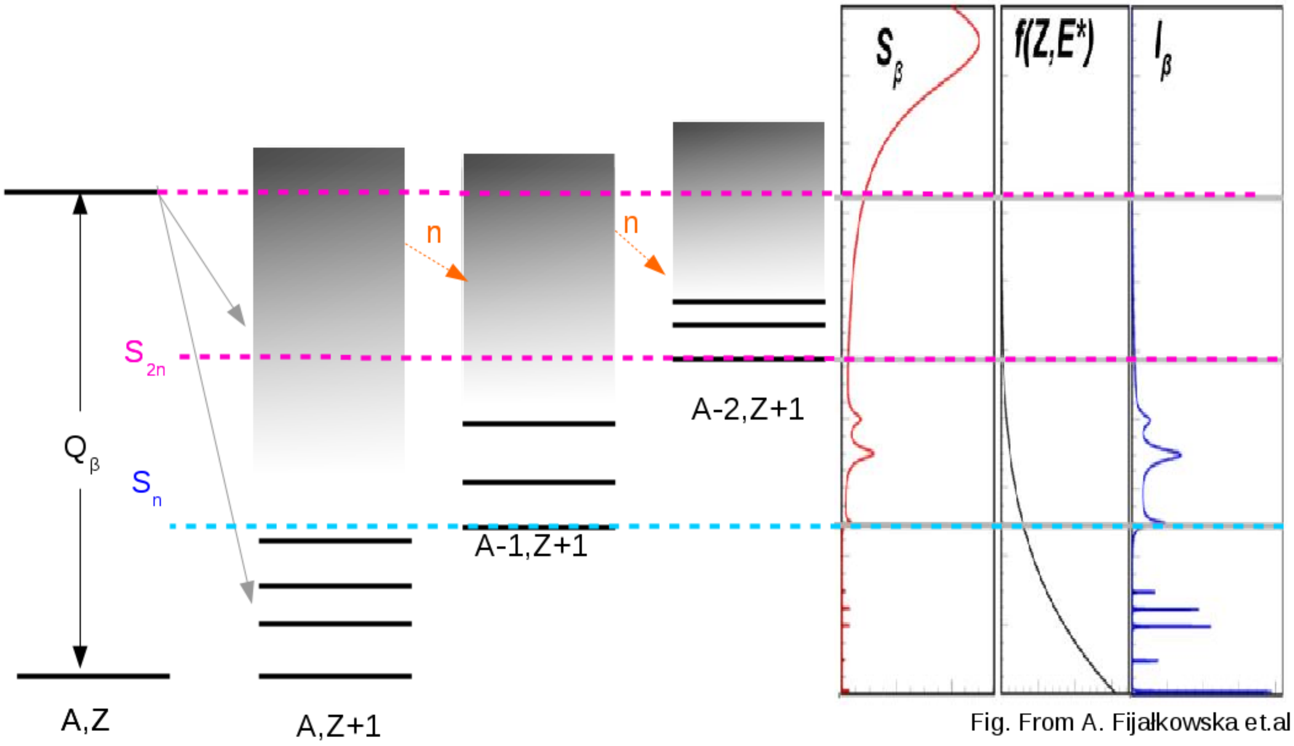
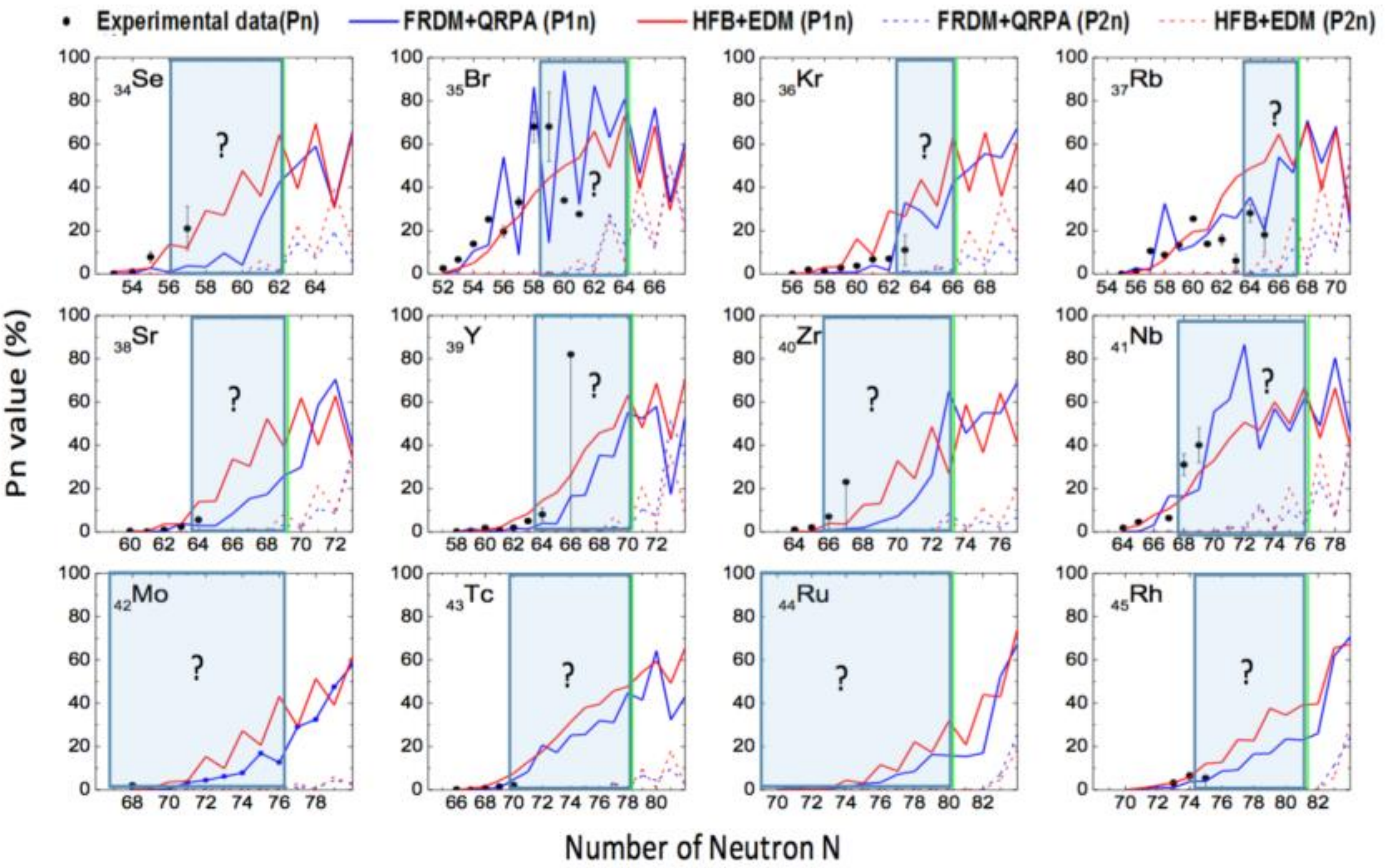


Fig. From A. Fijałkowska et.al

$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,dE_x$$

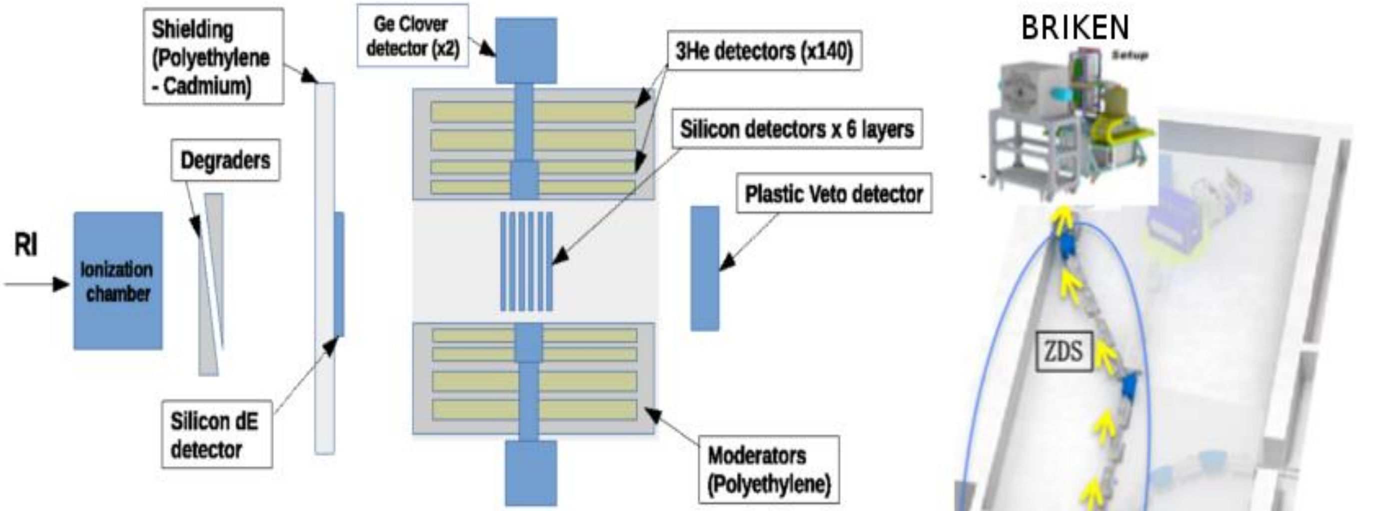
$$P_n = \frac{\int_{S_n}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,\frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma}\,dE_x}{\int_0^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,dE_x}$$

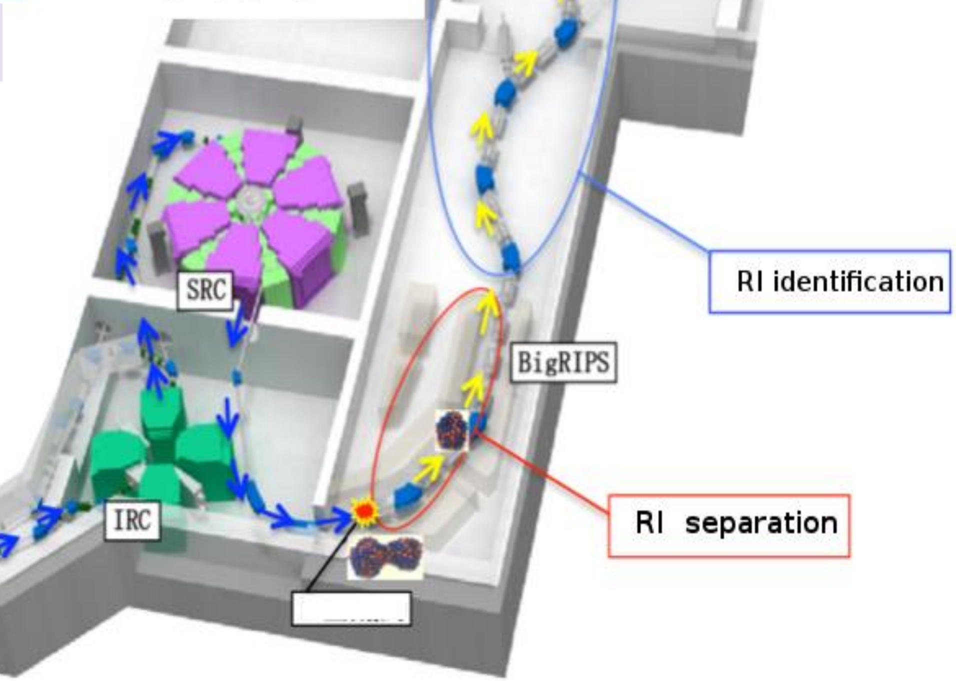
Status of P_n values in some isotopic chains / plans at RIKEN



V. H. Phong

Beta-delayed neutron studies at BRIKEN

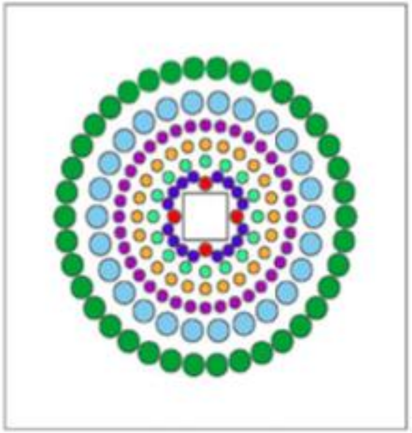


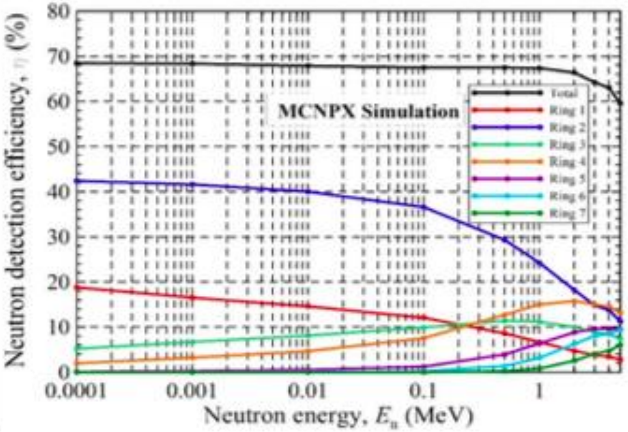


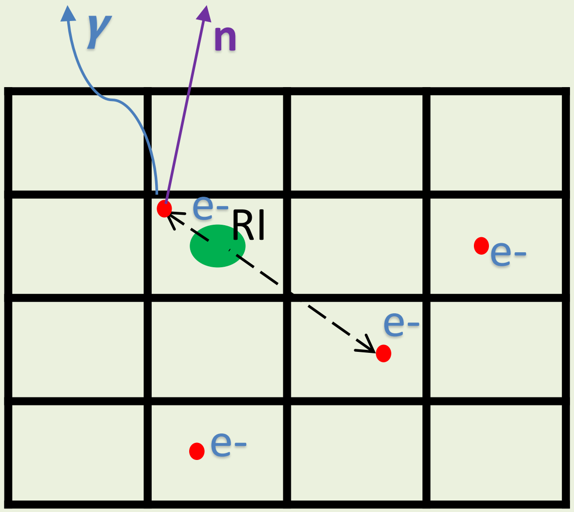
F11 focal plane setup

- Advanced implantation detector array AIDA (UK)
- 140 ^{3}He counters from ORNL, GSI, UPC and RIKEN, about 68% neutron detection efficiency at 1 MeV
- 2 Clover detectors 2.7-3.4 keV FWHM for 1.3 MeV γ-rays

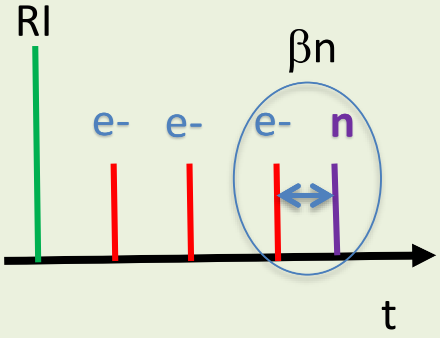
Beta-delayed neutron studies at BRIKEN







Position correlation in Si strips detectors



\+ Beta-neutron timing correlation

$$P_n(\%) = \frac{N_{\beta n}}{(N_{RI}\ \varepsilon_{\beta n})}$$

Experiments relevant for a better understanding of explosive neutron capture scenarios …

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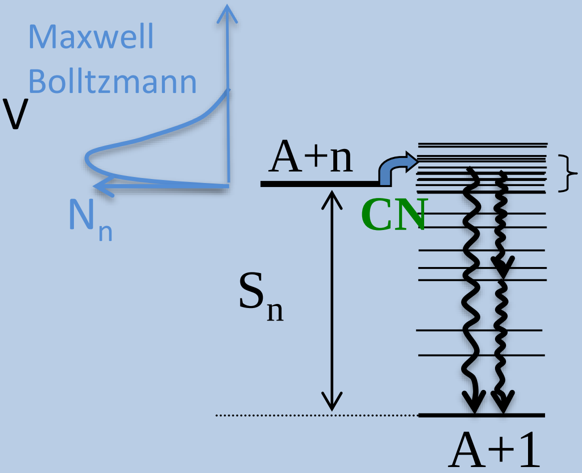
Determination of neutron capture rates

What for ? : s process, r process freeze-out, neutron bursts, cooling of neutron stars

↳ High excitation energy / heavy nuclei : large density of levels

E_n ≈kT≈ 100 keV
for T ≈10^9K



Statistical Hauser Feshbach model

Assumes:
- Statistical distribution of J and a certain density distribution of states
- Two steps process: formation of a compound nucleus + γ decay

Calculate transmission coefficients in the entrance and exit channels

optical models giant dipole resonance

Measurements:

Usually stable nuclei or long-lived

Use neutron beams on targets (p+^{7}Li source, or neutrons from nTOF)

Determine (n,γ) capture rates using activation or in-flight techniques

Determination of neutron capture rates

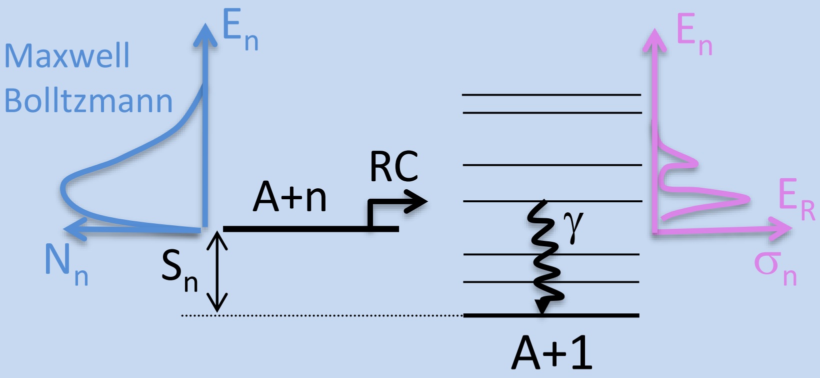
What for ? : r process freeze-out, neutron bursts, cooling of neutron stars

Far from stability, around closed shells

- $S_n(A+1)$ is small
- Few states contribute, mainly low L
- Resonant or / and Direct capture

$E_n \approx kT \approx 100$ keV for $T \approx 10^9$K

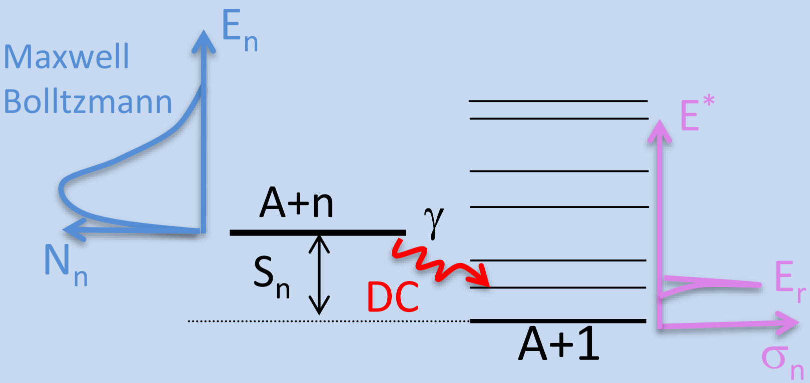
Resonant capture



$$\sigma_{BW}(E) = \omega(J_1,J_2,J)\ \pi ƛ^2 \frac{\Gamma_n \Gamma_\gamma}{(E-E_R)^2+(\Gamma_{tot}/2)^2}$$

Measure E_R, Γ_n and Γ_γ

Direct capture



$$\frac{d\sigma}{d\Omega} \approx S \left| \int \Phi_f\ \theta_{EM}\ \Phi_i\ d\vec{r} \right|^2$$

Bound state

Folding potential

θ_{EM}: E1,M1 operators strongly dominant

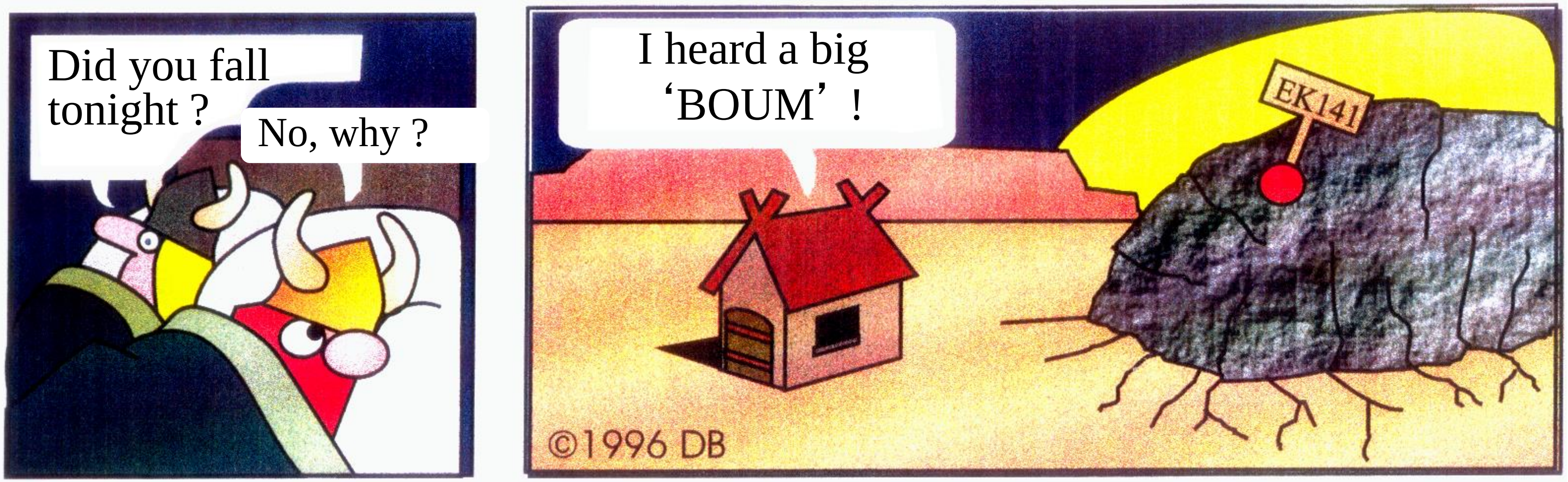
Determine J, L, S, E_r, S_n

Transfer (d,p) reactions can provide S_n, E, L, SF required for n captures

Comparison of (n,γ) versus (d,p)-derived cross section (*Kraussmann et al. PRC 53 (1996)*)

Choose the appropriate energy for momentum matching (v/c~0.1) , RIB of ~10^5pps

^{48}Ca overabundance in EK 1-4-1 inclusion of meteorite



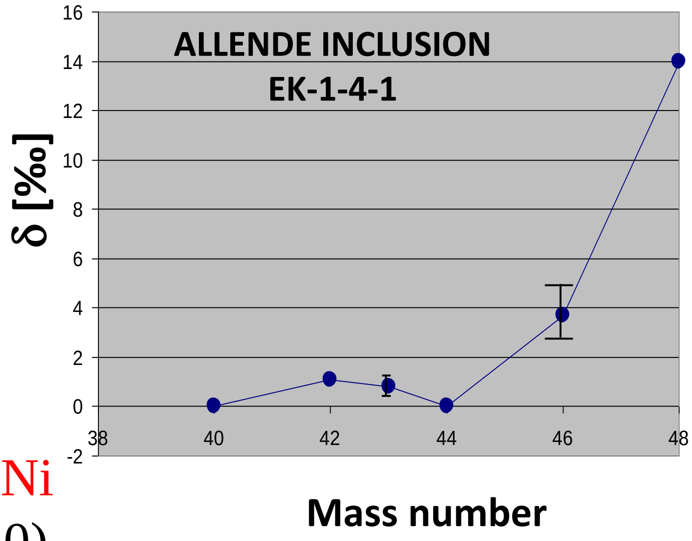
^{48}Ca/^{46}Ca ≈ 250 (solar =53)

Allende meteorite:

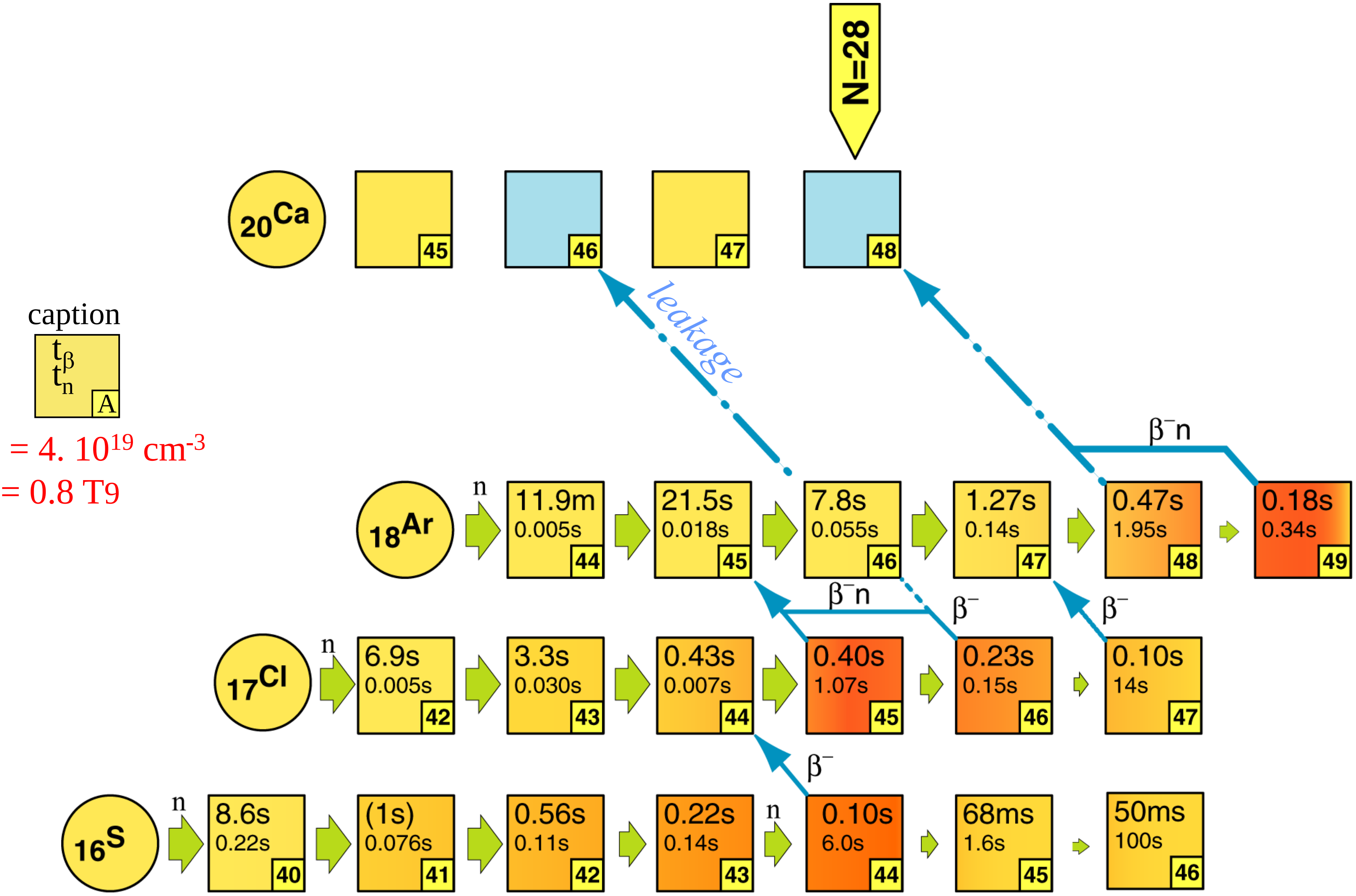
fell in 1969
weight 2t
chondraneous carbide
several CaAl-rich inclusions

EK1-4-1 inclusion :

spherical shape, white colour
diametre 1cm
Fusion temperature 1500-1900K
Correlated over-abundances ^{48}Ca-^{50}Ti-^{54}Cr-^{58}Fe-^{64}Ni
Underabundance of ^{66}Zn, r process Nd, Sm (A~150)



Explain the abundance ratio $^{48}Ca/^{46}Ca = 250$

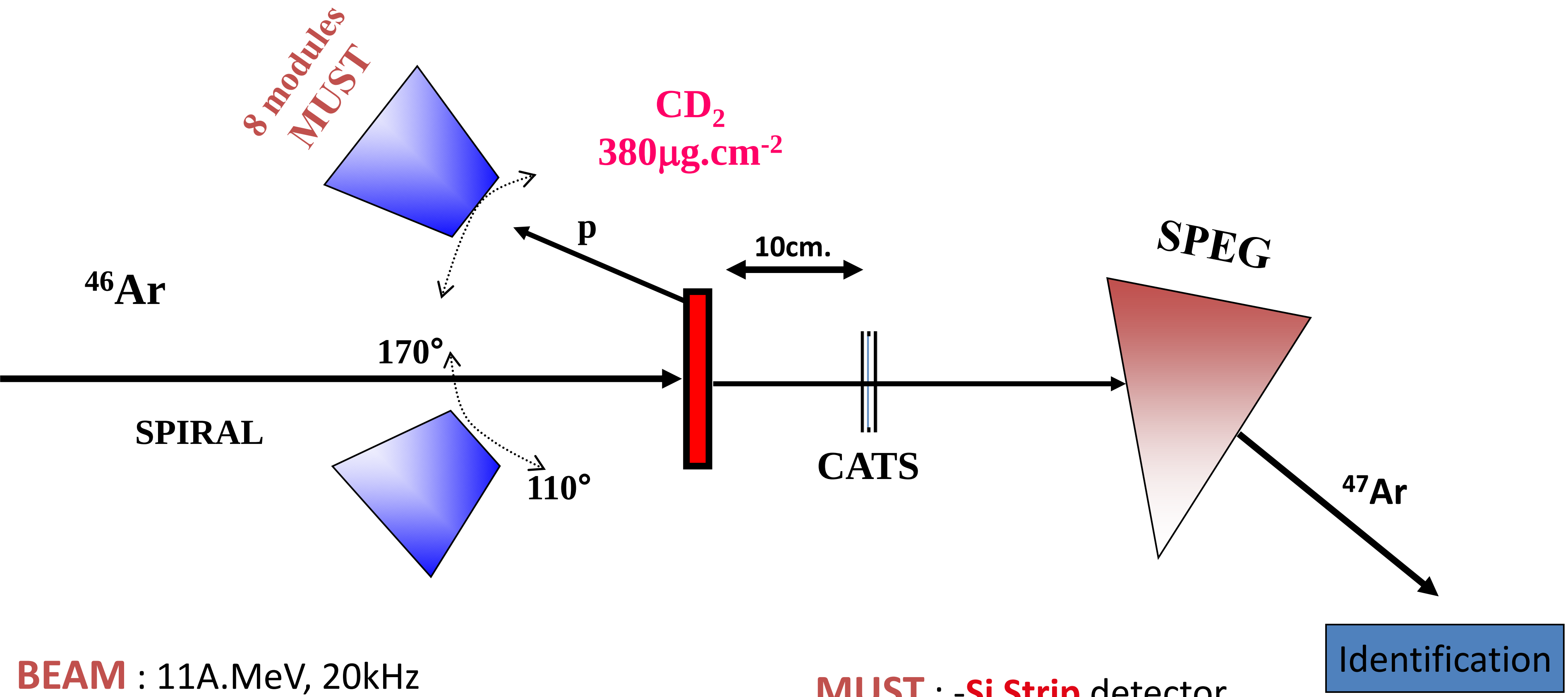


$d_n = 4.\ 10^{19}\ \text{cm}^{-3}$

$T = 0.8\ T9$

➡ Determine experimental (n,γ) rates on unstable Ar nuclei.

Determine ^{46}Ar(n,γ)^{47}Ar using ^{46}Ar(d,p)^{47}Ar reaction



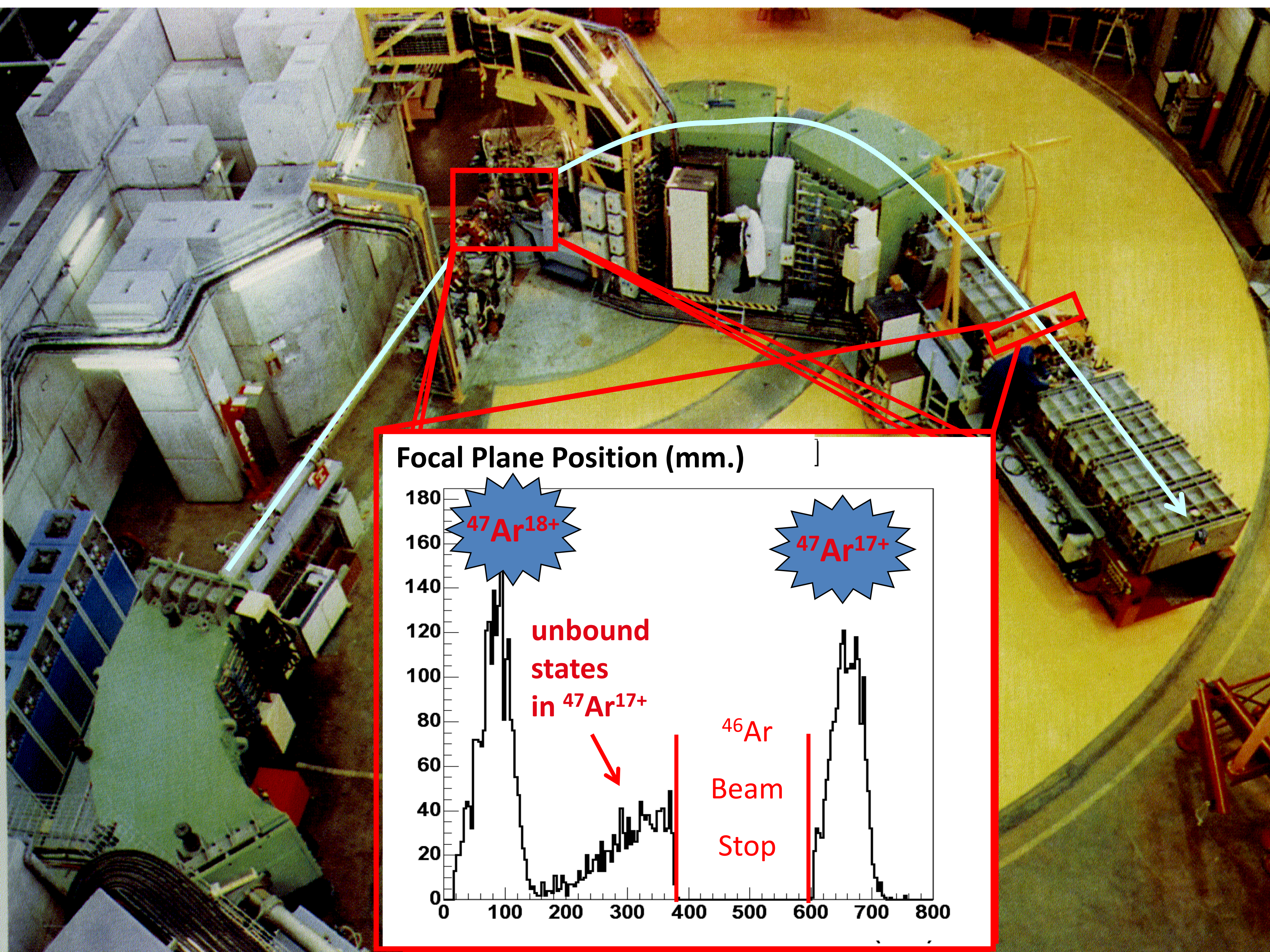
BEAM : 11A.MeV, 20kHz

CATS : -**beam**-tracking detector

- Proton **emission point**.
  resolution : ~0.6 mm

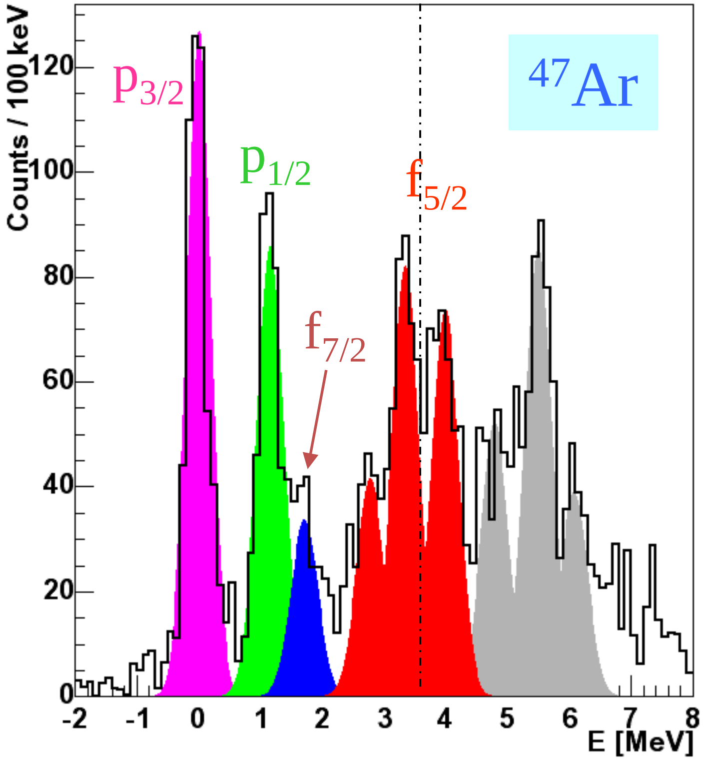
MUST : -**Si Strip** detector
-Proton **impact localisation**
resolution : 1 mm
-Proton **energy** measurement.
resolution : 50 KeV
Efficiency >30%

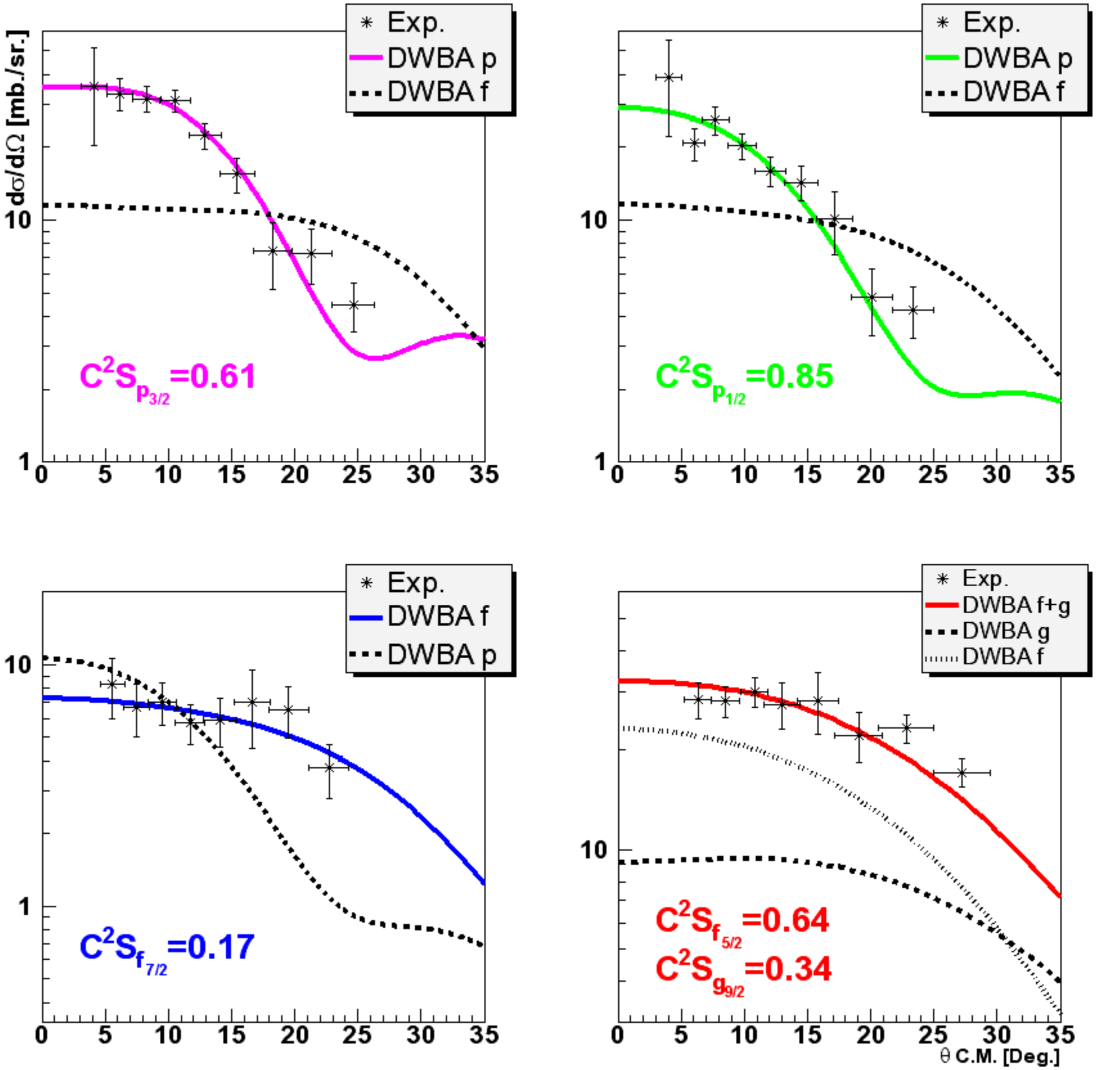
SPEG : Energy loss spectrometer : **recoil ion** identification → transfert-like products


Focal Plane Position (mm.)
$^{47}Ar^{18+}$
$^{47}Ar^{17+}$
unbound states in $^{47}Ar^{17+}$
^{46}Ar Beam Stop
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800

Excitation energy spectrum for ^{47}Ar

N=28 gap : 4.47(8)MeV
S_n=3.55(20)MeV
Gaudefroy et al. PRL (2006)

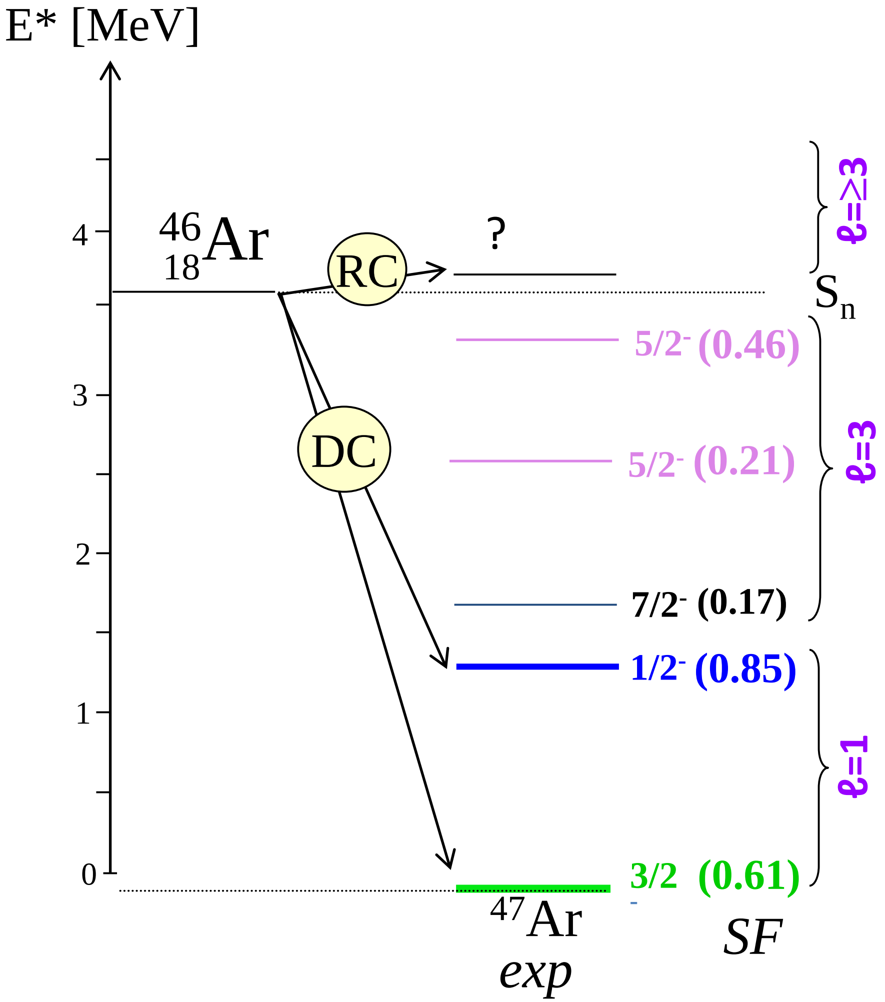


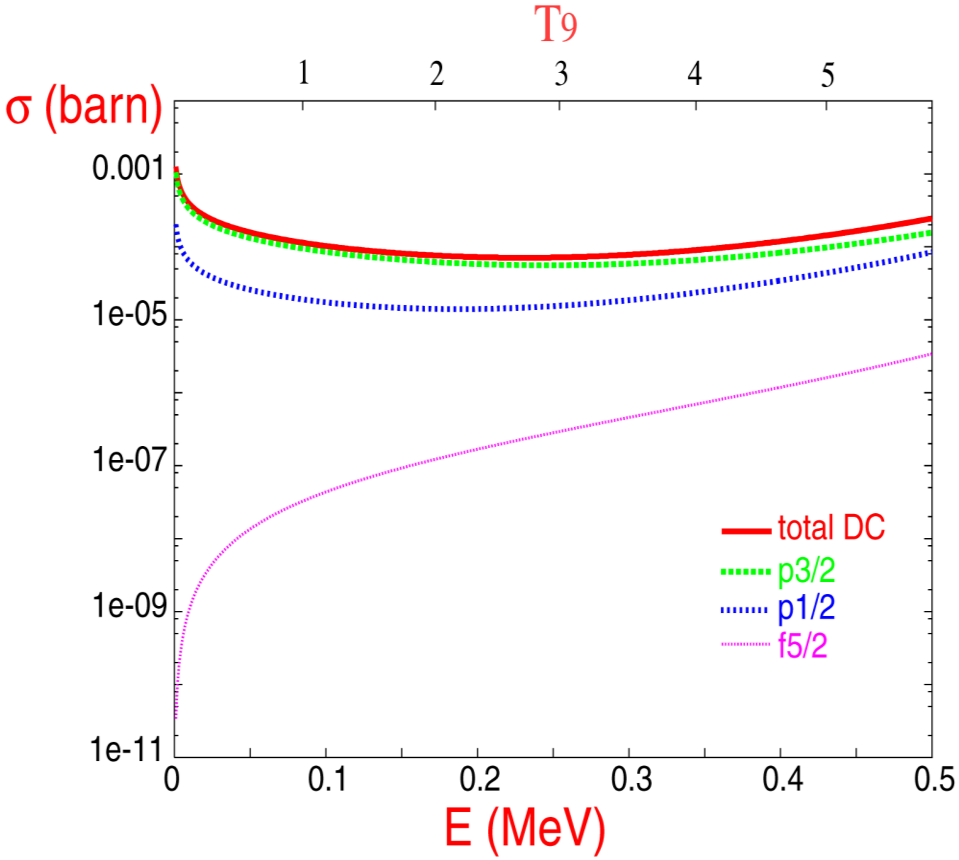


Use of spectrometer suppress C induced background -> good mass resolution

Can be complemented by gamma-ray spectroscopy to achieve better energy resolution

Neutron capture rate at N=28 (^{46}Ar)





(d,p) access to E*, SF., spins ⟶ derive (n,γ) stellar rates

Direct capture (E1) with *ℓ$_n$ = 0* on *p* states dominates

Speed up neutron-captures at the N=28 closed shell

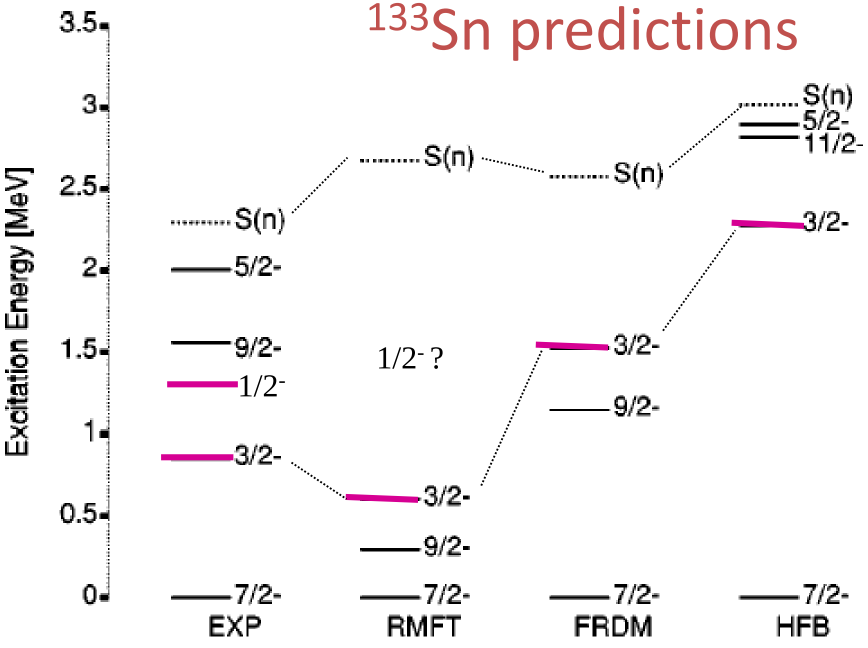
Favor the enhancement of ^{48}Ca over that of ^{46}Ca using d_n= 3 10^{21} cm^{-3}

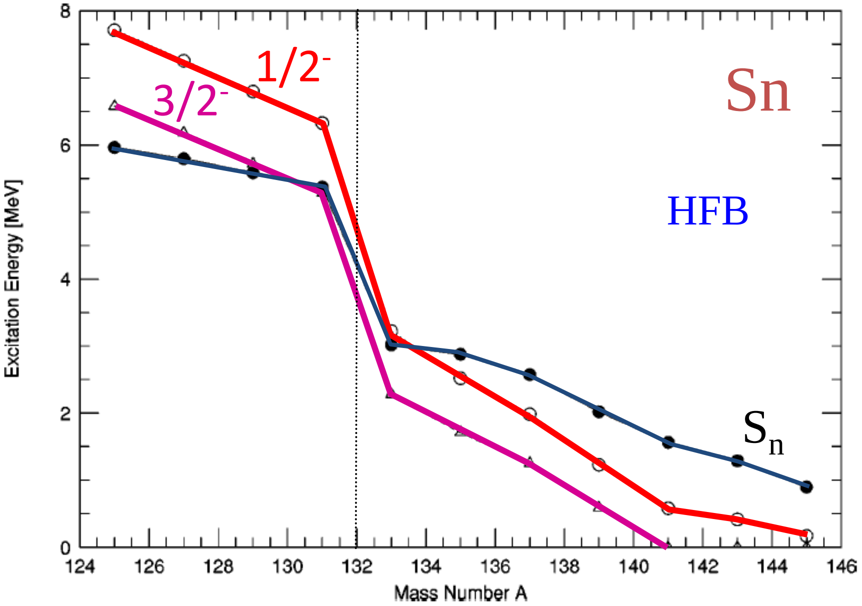
O. Sorlin et al. CR Phys 4 (2003)

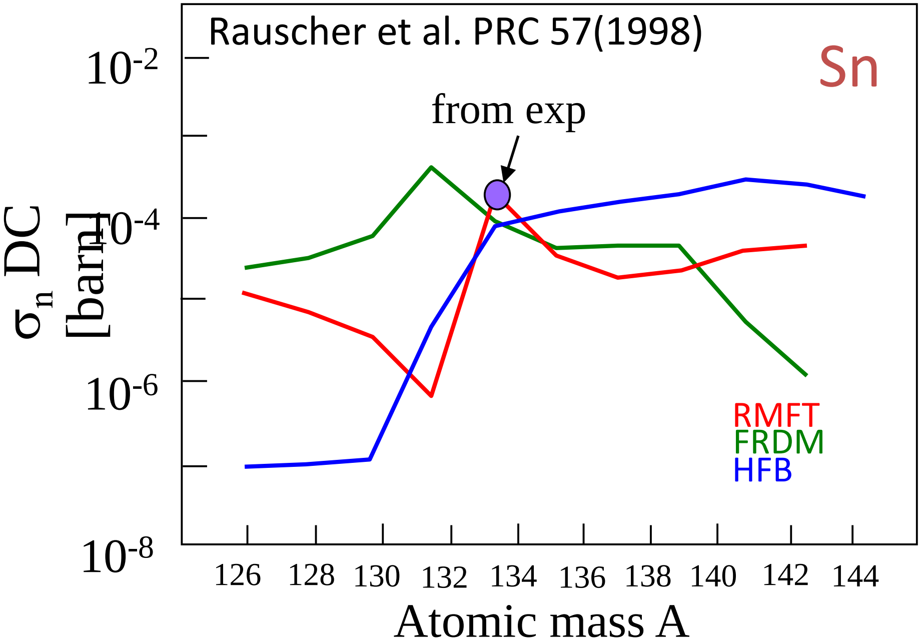
L. Gaudefroy et al., EPJA (2006)

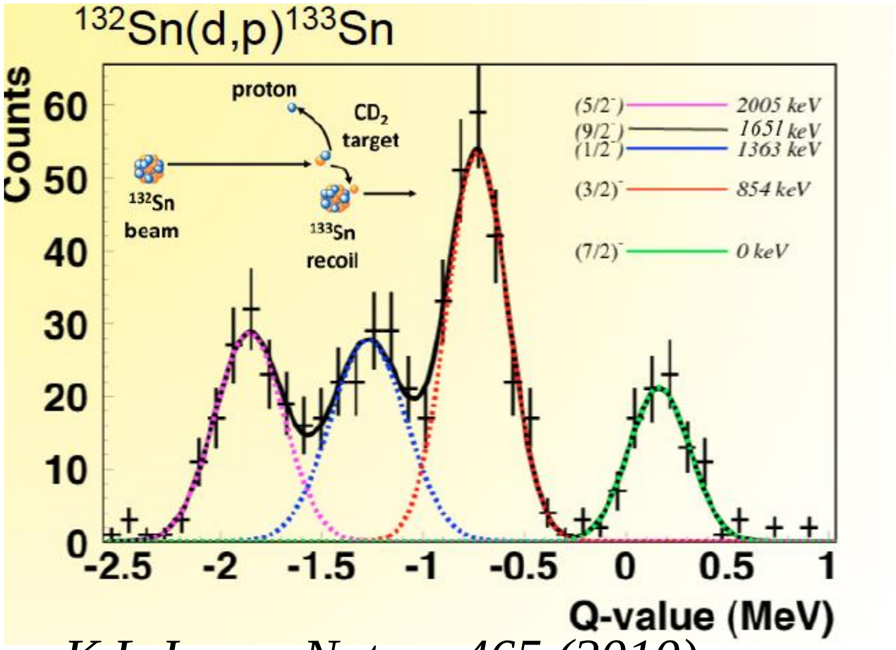
Neutron captures at the N=82 shell closure

Go to more neutron
Study the Cd chain…


^{133}Sn predictions




Rauscher et al. PRC 57(1998)



K.L Jones, Nature 465 (2010)

Conclusions of Lect II.

Experimental masses, lifetimes, P_n values and neutron capture cross sections must be measured in order to be used in the various explosive scenarios in which weak or strong r process conditions are found.

These properties are needed for many nuclei, but mainly those at closed shells.

New generations of accelerator / detectors will continue to bring new results in the forthcoming years.

As all nuclei involved in explosive conditions cannot be reached experimentally (yet), extrapolations are required with the use of theoretical models that are implementing suitable physics ingredients.

A better understanding of the synthesis of heavy elements can only be obtained from the combined progresses in stellar modeling, galactic chemical evolution, astronomy, geochemistry, nuclear structure and reactions.

It is a fantastic endeavour that encompasses many aspects modern physics and foster synergies between different disciplines of nuclear astrophysics.