Approaches to LEPP measuring nuclear reactions

René Reifarth

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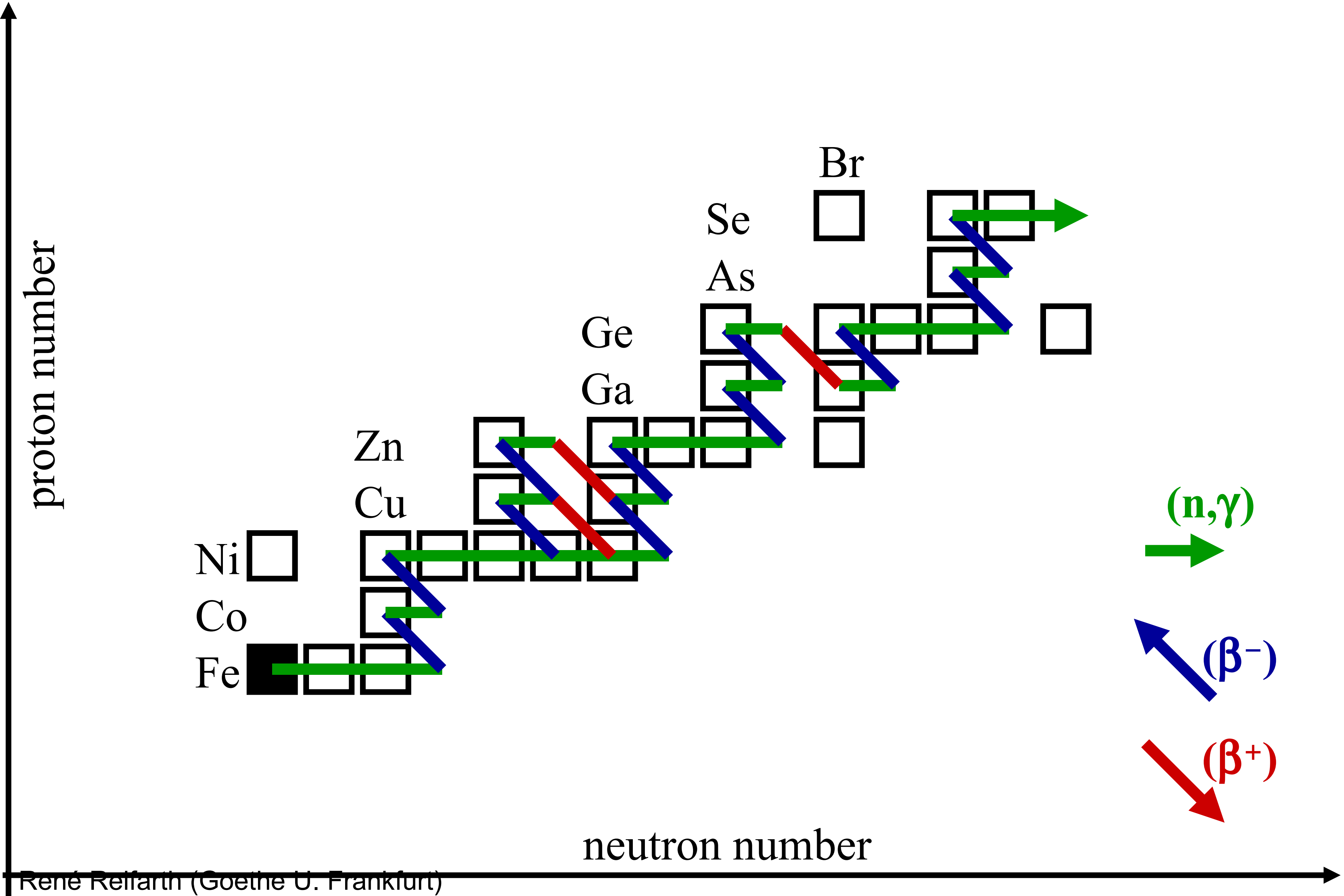
EMMI Workshop

Nucleosynthesis beyond iron and the lighter element primary process

Darmstadt, Germany, Oct. 10–12, 2011

Motivation Astrophysics: the s-process



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s-process nucleosynthesis

Two components were identified and connected to stellar sites:

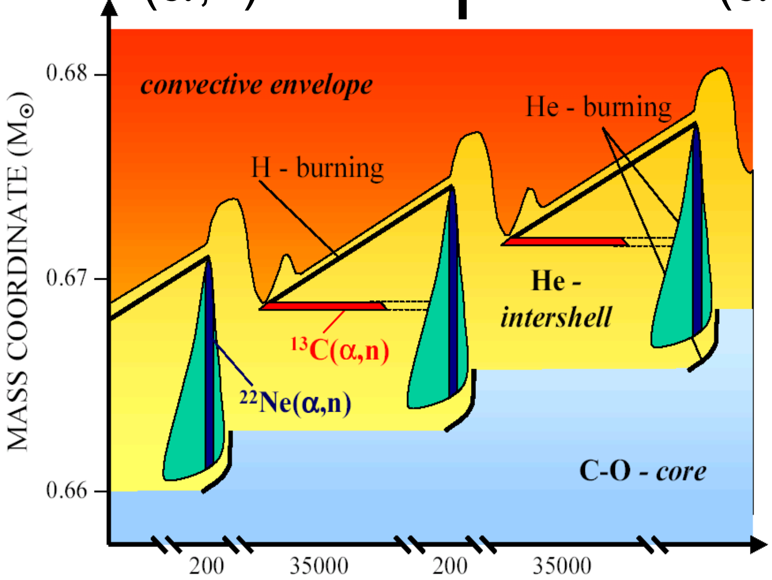
Main s-process $90<A<210$

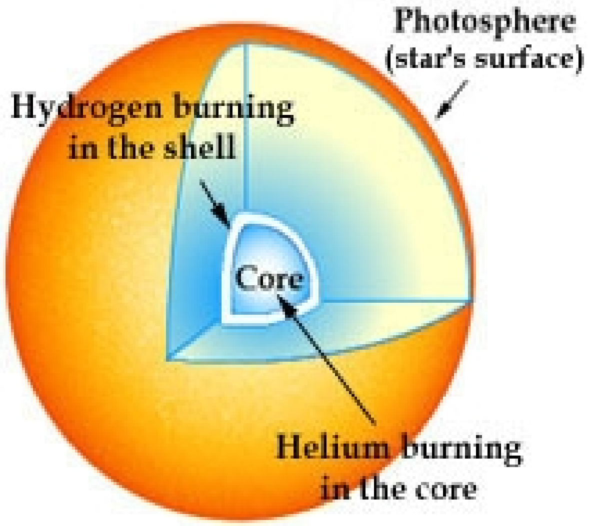
TP-AGB stars 1-3 $M_\odot$

Weak s-process $60<A<90$

massive stars > 8 $M_\odot$

shell H-burning	He-flash	core He-burning	shell C-burning
$0.9\cdot10^8$ K	$3\text{-}3.5\cdot10^8$ K	$3\text{-}3.5\cdot10^8$ K	$\sim1\cdot10^9$ K
kT=8 keV $10^7\text{-}10^8$ cm^{-3}	kT=25 keV $10^{10}\text{-}10^{11}$ cm^{-3}	kT=25 keV 10^6 cm^{-3}	kT=90 keV $10^{11}\text{-}10^{12}$ cm^{-3}
$^{13}C(\alpha,n)$	$^{22}Ne(\alpha,n)$	$^{22}Ne(\alpha,n)$	





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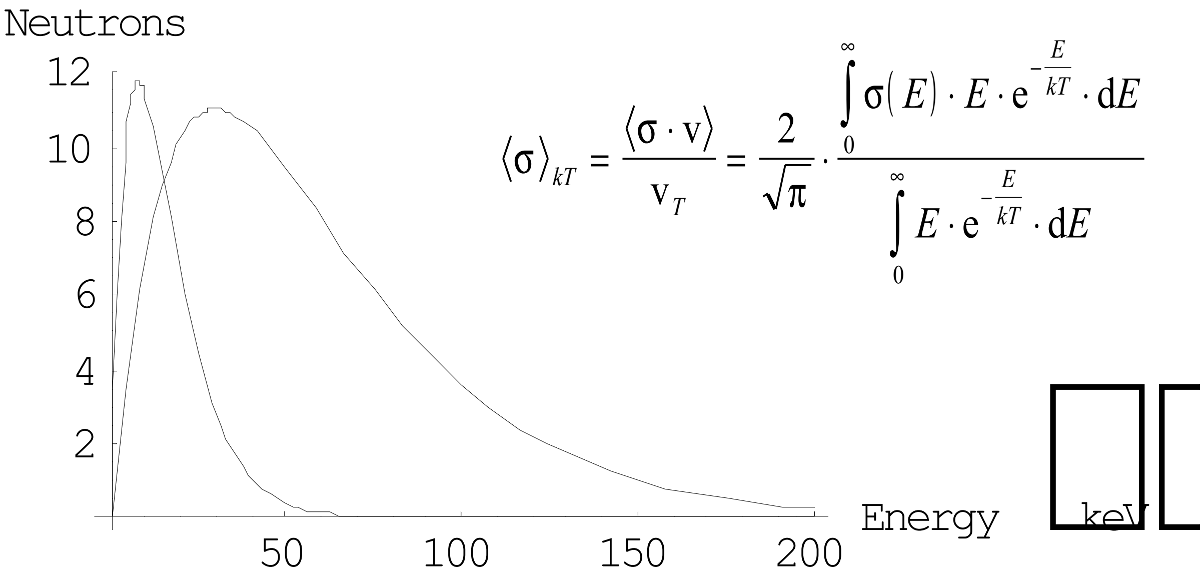
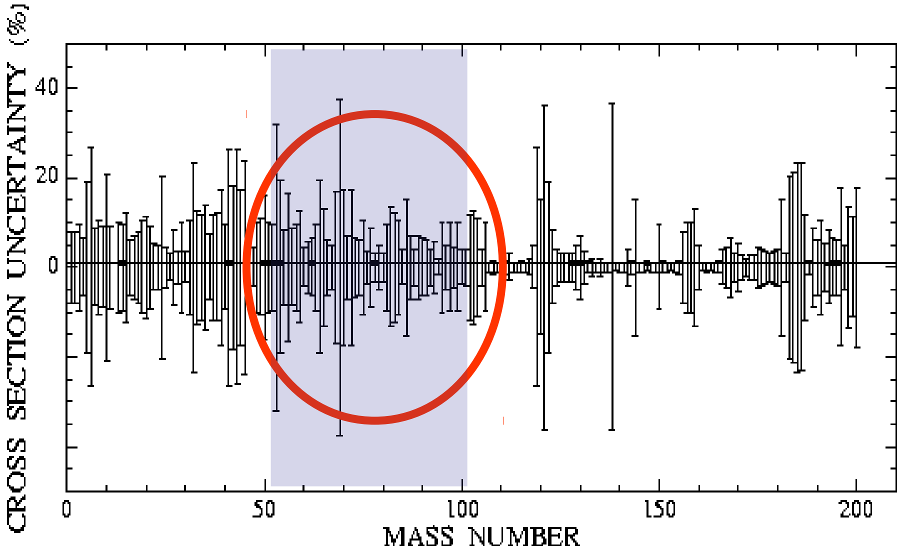
What nuclear physics input is needed?

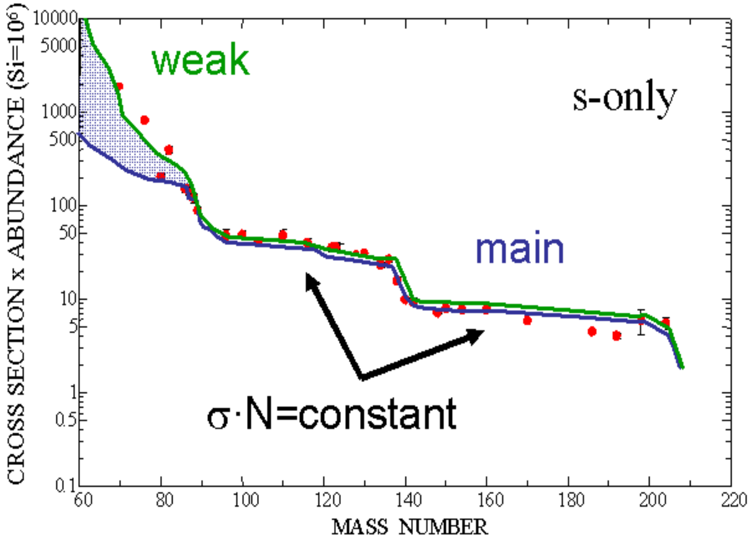
- Reaction rates
  - Neutron induced
  - Charged particles
- Half-lives



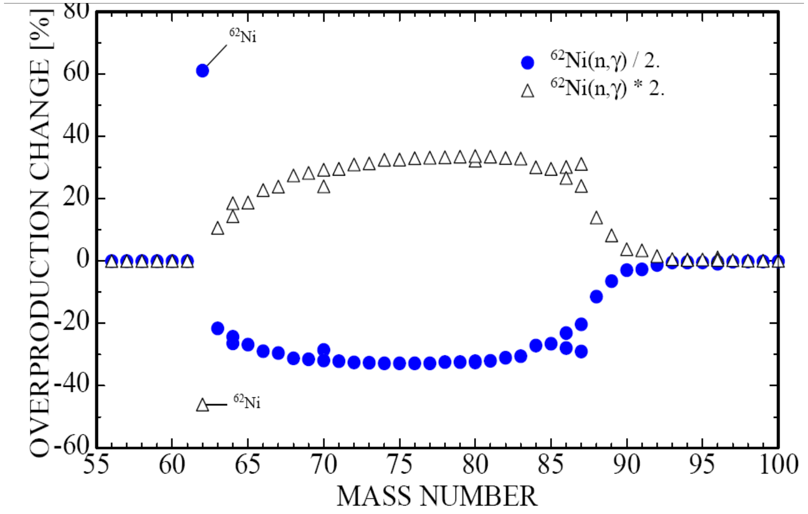
$$\langle\sigma\rangle_{kT} = \frac{\langle\sigma\cdot \mathrm{v}\rangle}{\mathrm{v}_T} = \frac{2}{\sqrt{\pi}}\cdot\frac{\int_0^\infty \sigma(E)\cdot E\cdot \mathrm{e}^{-\frac{E}{kT}}\cdot \mathrm{d}E}{\int_0^\infty E\cdot \mathrm{e}^{-\frac{E}{kT}}\cdot \mathrm{d}E}$$

Challenges for the weak s-process

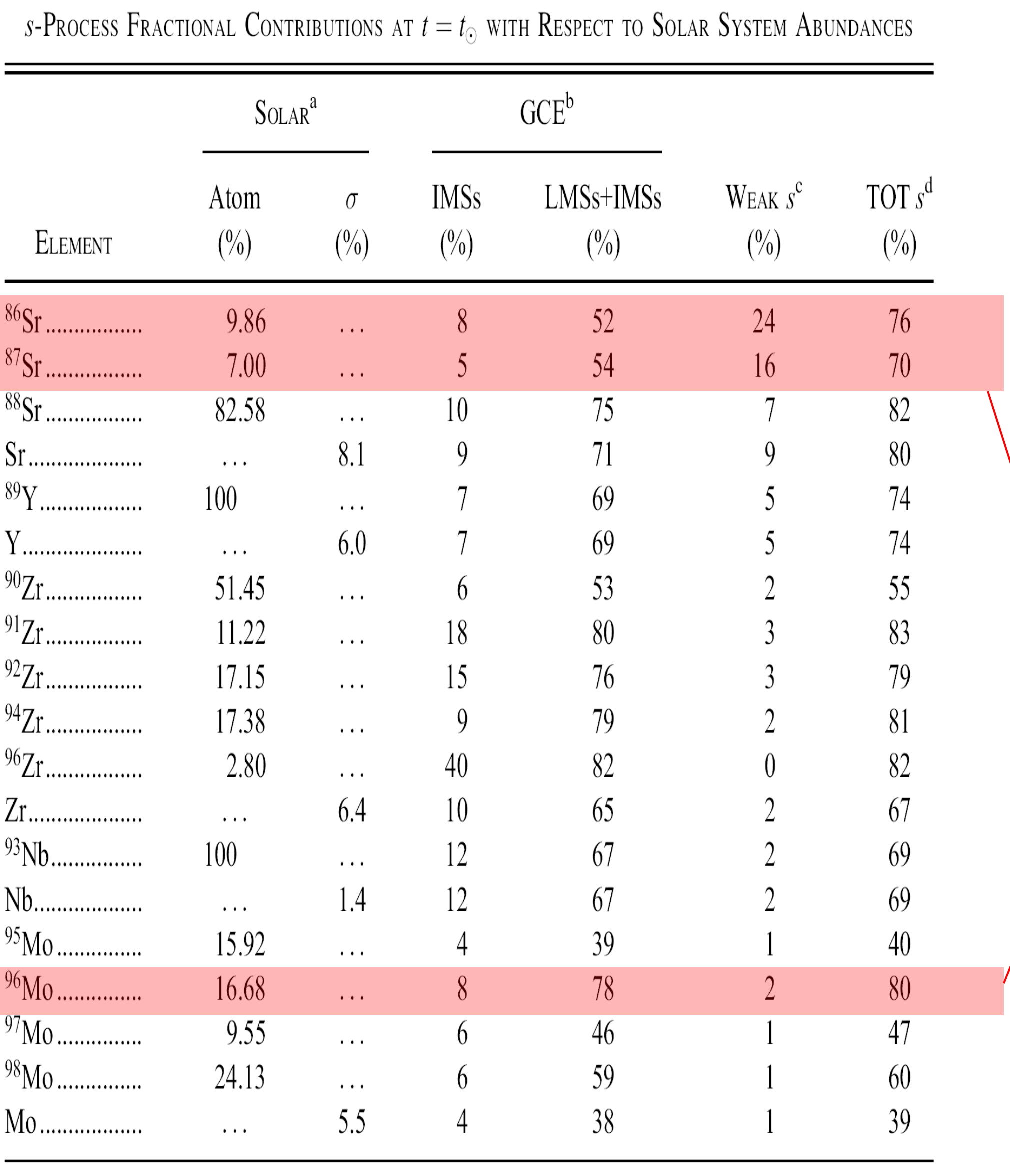




Problems:
- small cross sections
- resonance dominated
- contributions from direct capture
- propagation effects



Missing s-yield



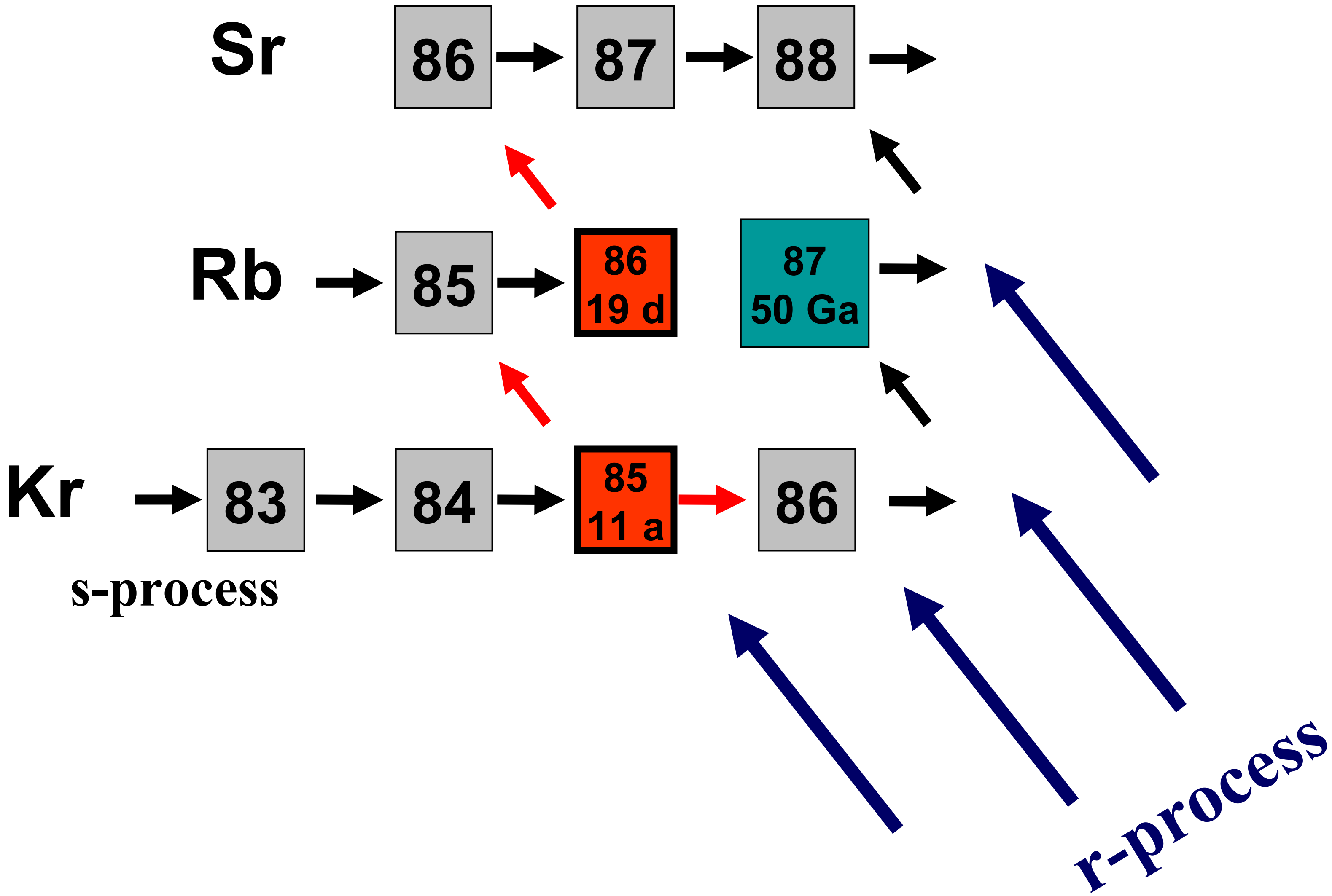
s-PROCESS FRACTIONAL CONTRIBUTIONS AT $t = t_\odot$ WITH RESPECT TO SOLAR SYSTEM ABUNDANCES

	SOLAR[a]		GCE[b]			
ELEMENT	Atom (%)	σ (%)	IMSs (%)	LMSs+IMSs (%)	WEAK s[c] (%)	TOT s[d] (%)
^{86}Sr	9.86	...	8	52	24	76
^{87}Sr	7.00	...	5	54	16	70
^{88}Sr	82.58	...	10	75	7	82
Sr	...	8.1	9	71	9	80
^{89}Y	100	...	7	69	5	74
Y	...	6.0	7	69	5	74
^{90}Zr	51.45	...	6	53	2	55
^{91}Zr	11.22	...	18	80	3	83
^{92}Zr	17.15	...	15	76	3	79
^{94}Zr	17.38	...	9	79	2	81
^{96}Zr	2.80	...	40	82	0	82
Zr	...	6.4	10	65	2	67
^{93}Nb	100	...	12	67	2	69
Nb	...	1.4	12	67	2	69
^{95}Mo	15.92	...	4	39	1	40
^{96}Mo	16.68	...	8	78	2	80
^{97}Mo	9.55	...	6	46	1	47
^{98}Mo	24.13	...	6	59	1	60
Mo	...	5.5	4	38	1	39

Travaglio et al. 2004

only 3 s-only

^{85}Kr(n,γ) affects the s-production of ^{86,86}Sr



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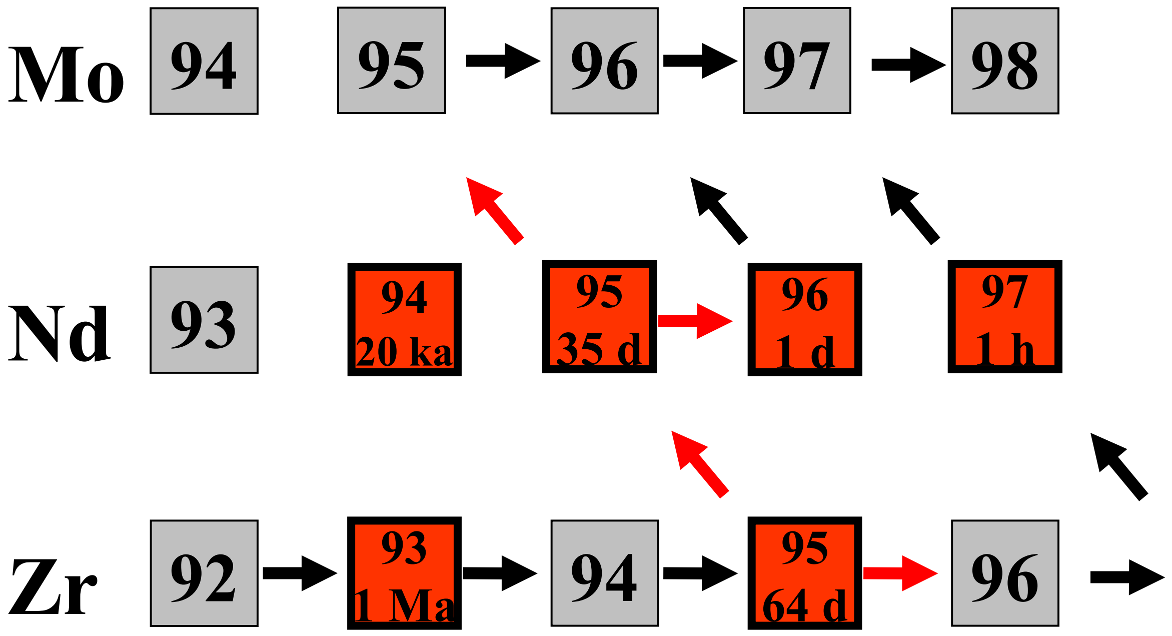
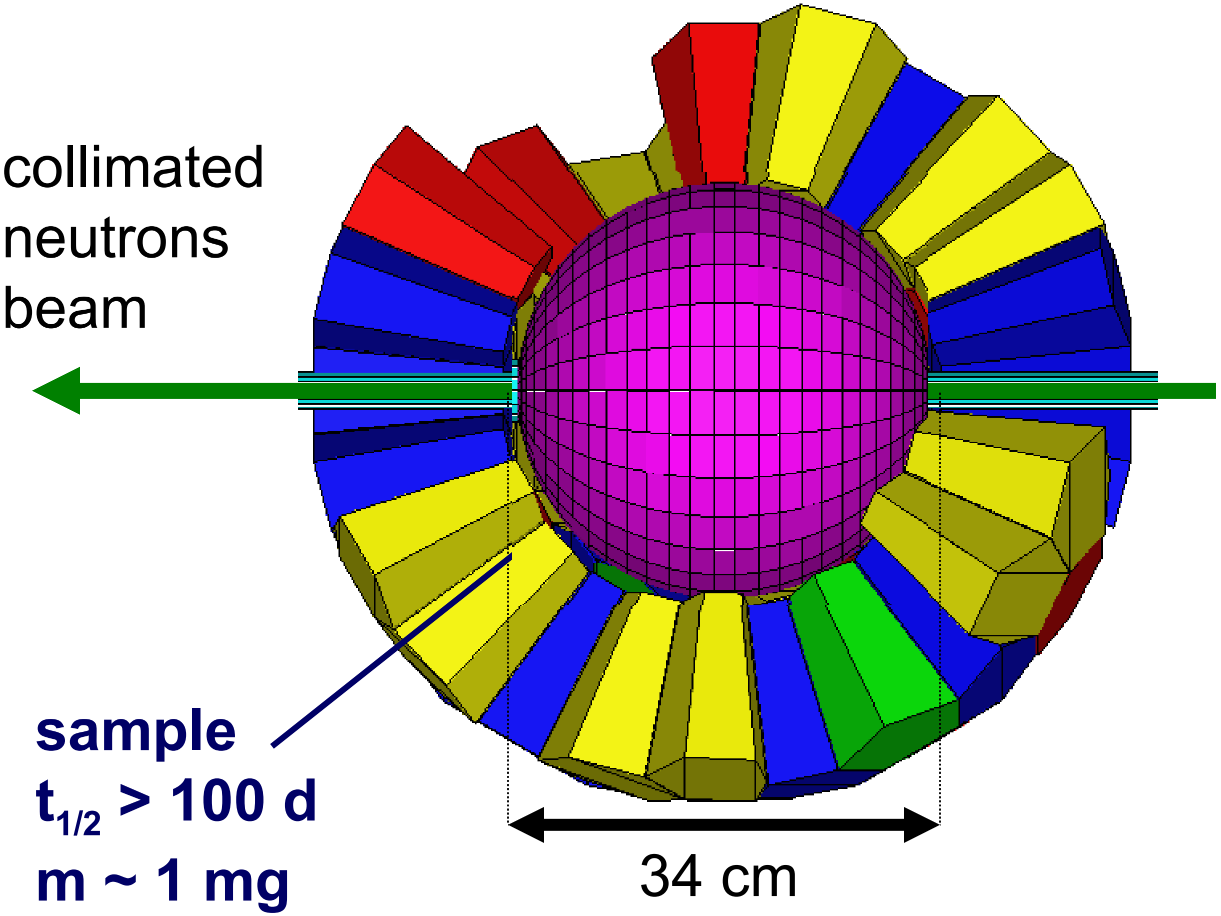
^{95}Zr(n,γ) affects the s-production of ^{96}Mo



Detector for Advanced Neutron Capture Experiments



neutrons:

- **spallation source**
- **thermal .. 500 keV**
- **20 m flight path**
- **3 10^5 n/s/cm^2/decade**

γ-Detector:

- **160 BaF_2 crystals**
- **4 different shapes**
- **R_i=17 cm, R_a=32 cm**
- **7 cm ^{6}LiH inside**
- **$\varepsilon_\gamma \approx$ 90 %**
- **$\varepsilon_{casc} \approx$ 98 %**

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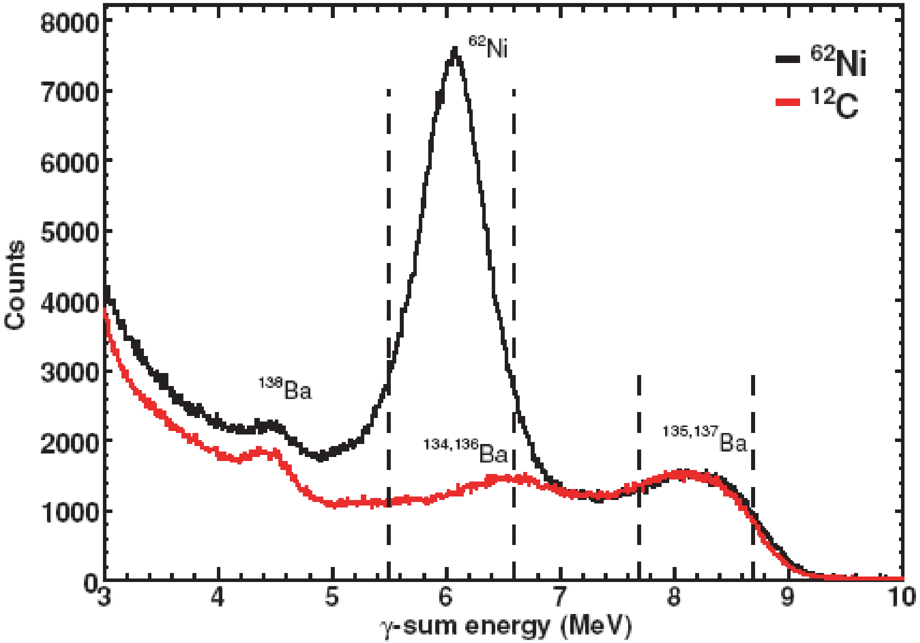
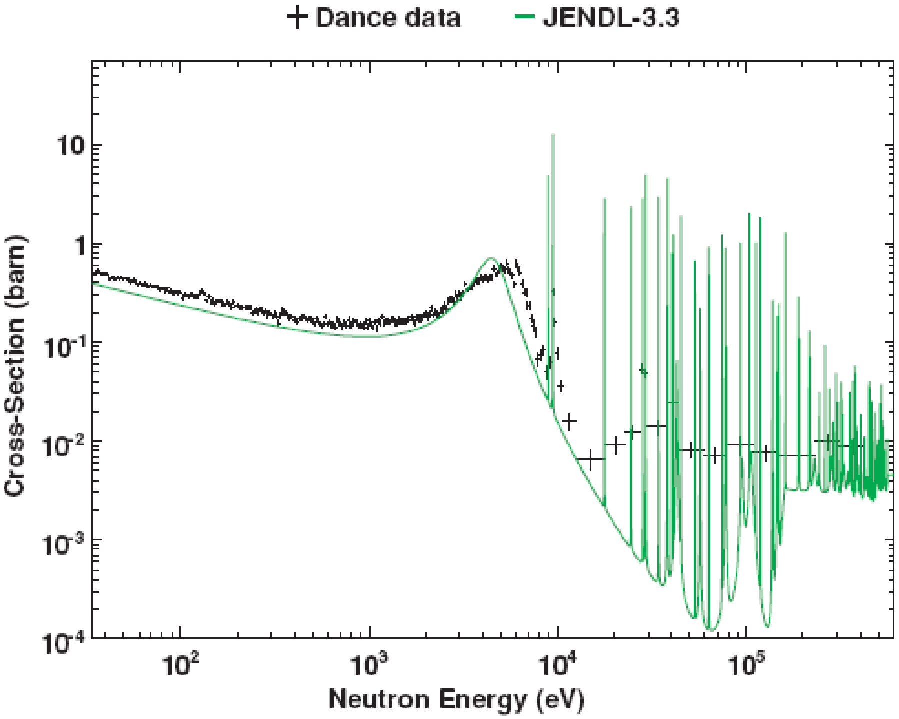
^{62}Ni(n,g) at DANCE





A. M. ALPIZAR-VICENTE et al., PRC **77**, 015806 (2008)

New high-resolution campaign been performed at n_TOF

Activation Method

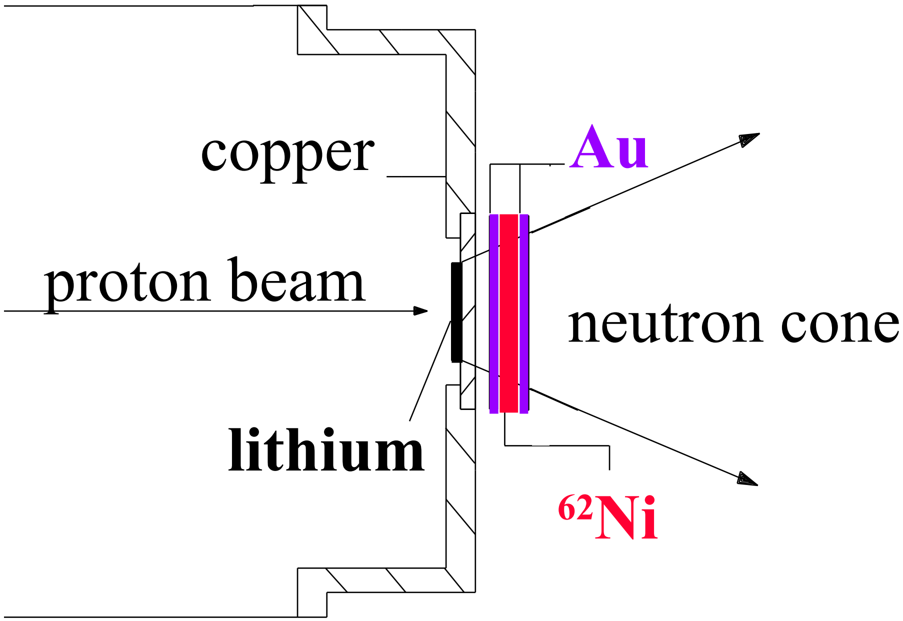
$^{62}\mathrm{Ni}(n,\gamma)^{63}\mathrm{Ni}$ reaction detected via **$^{63}\mathrm{Ni}/^{62}\mathrm{Ni}$** ratio, AMS ($t_{1/2}$=100 years)

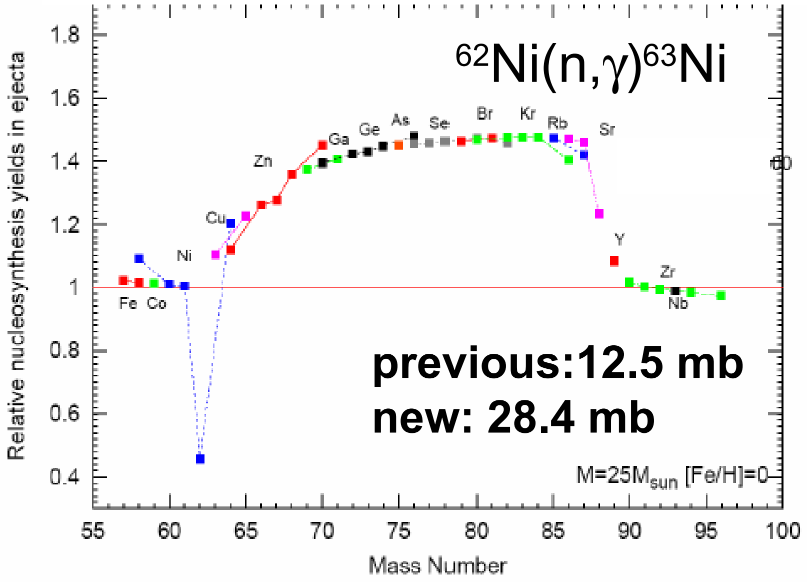
Determination of neutron flux via

$^{197}\mathrm{Au}(n,\gamma)^{198}\mathrm{Au}$

Neutron source:

$^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$





previous:12.5 mb
new: 28.4 mb

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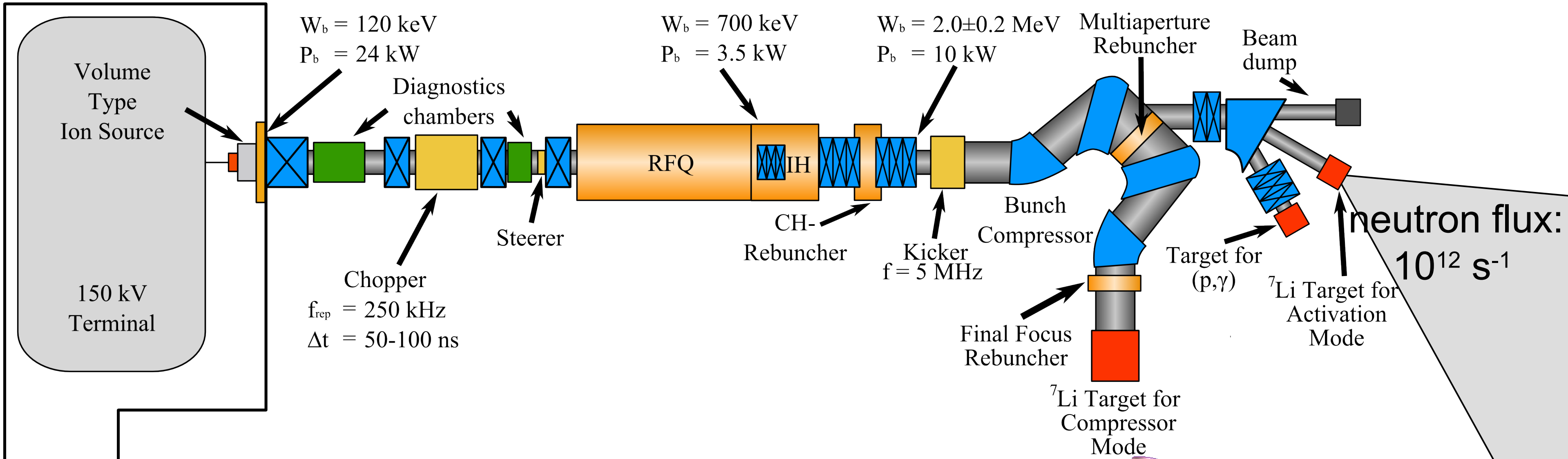
Nassar et al. PRL. 94, 092504 (2005)

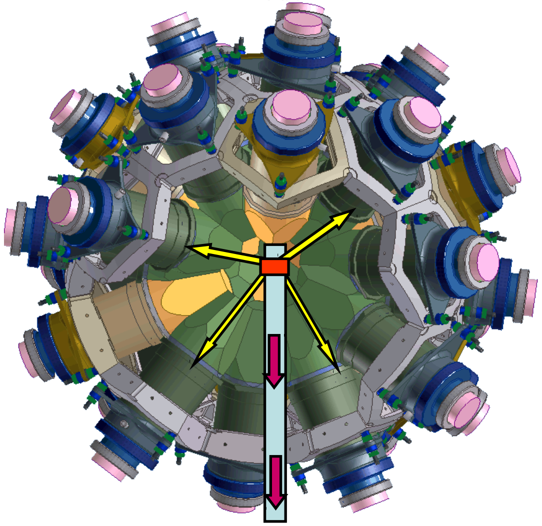
Future developments - neutrons

- if $t_{1/2}$ goes down: Activity ~ atoms/ $t_{1/2}$ goes up
- hence: number of atoms needs to go down
- since: captures ~ atoms * neutrons

- **Ever more neutrons**
- **Indirect methods**

The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)





2 mA proton beam (8 A peak current)
250 kHz
< 1ns pulse width
neutron flux at 1 m: 10^7 s^{-1} cm^{-2}
neutron flux at 0.1m: 10^9 s^{-1} cm^{-2}

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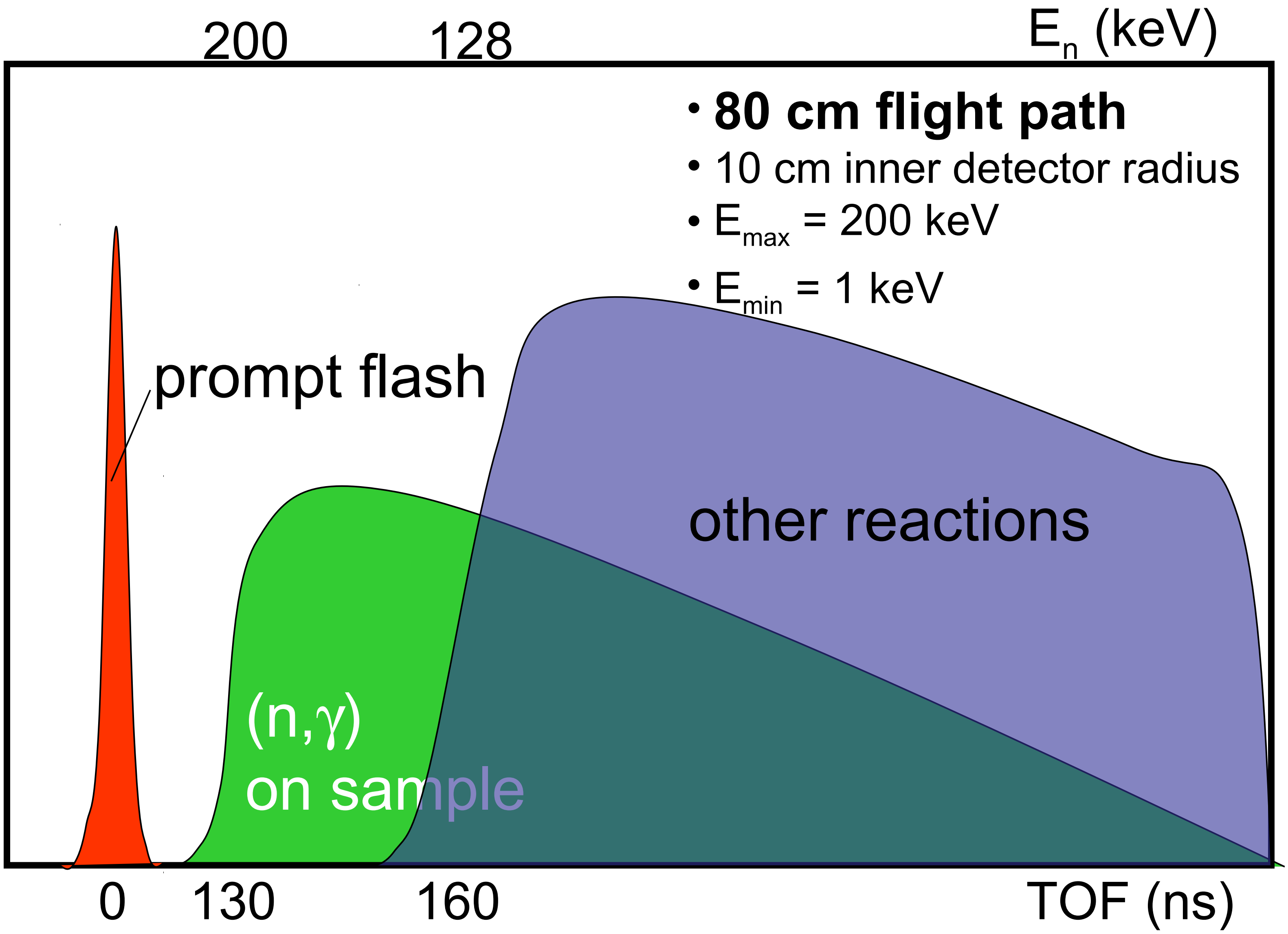
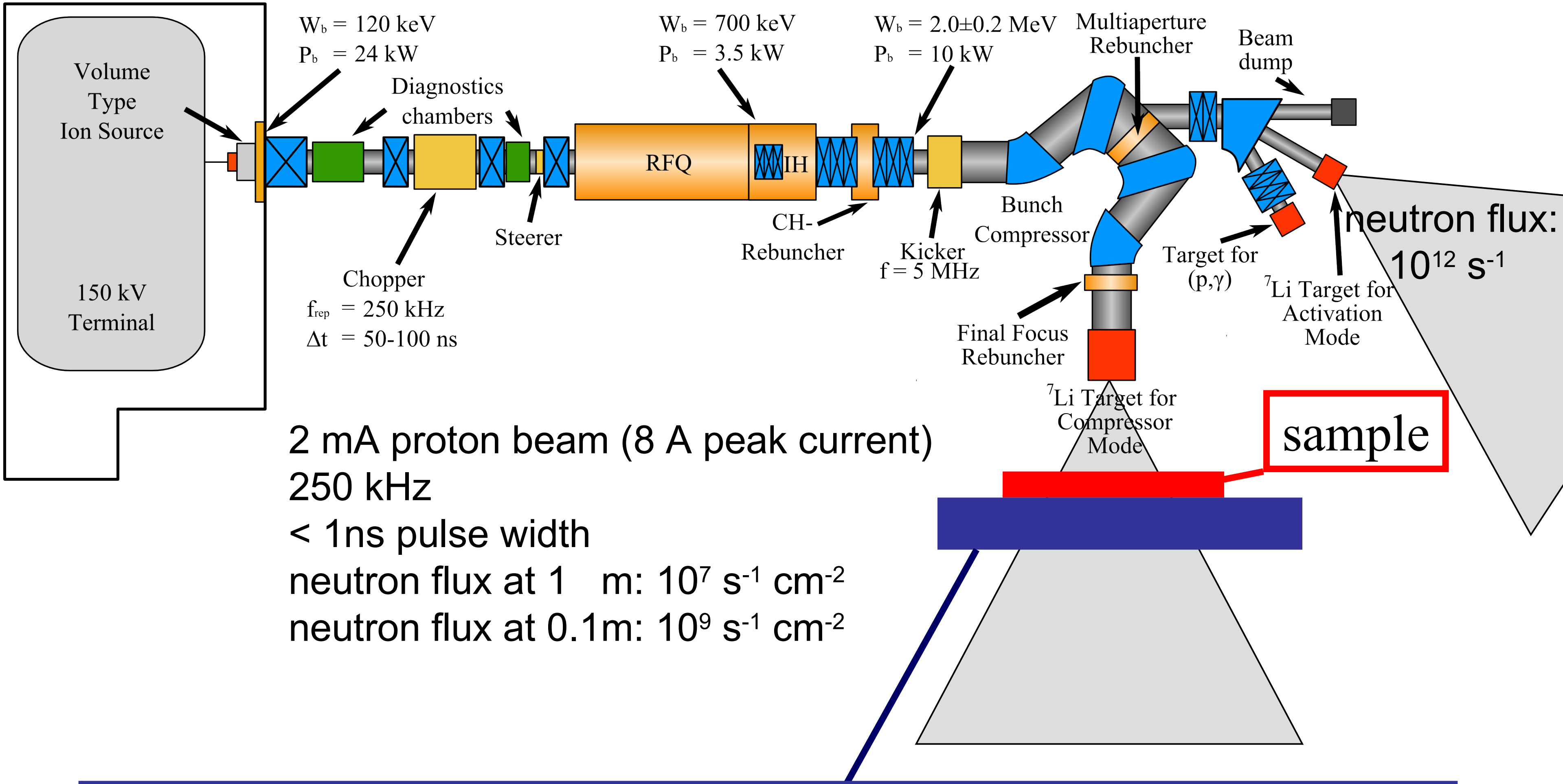
Schematic TOF spectrum



- **80 cm flight path**
- 10 cm inner detector radius
- E_{max} = 200 keV
- E_{min} = 1 keV

The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)



2 mA proton beam (8 A peak current)
250 kHz
< 1ns pulse width
neutron flux at 1 m: 10^7 s^{-1} cm^{-2}
neutron flux at 0.1m: 10^9 s^{-1} cm^{-2}

TOF with 10 cm flightpath using fast charged particle detectors:
Si-diode, C-diamond, ionization chamber

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Experimental program at FRANZ

The Frankfurt neutron source will provide the highest neutron flux in the astrophysically relevant keV region (1 – 500 keV) worldwide.

Factor of 1000 higher than at FZK!!!

Neutron capture measurements of small cross sections:

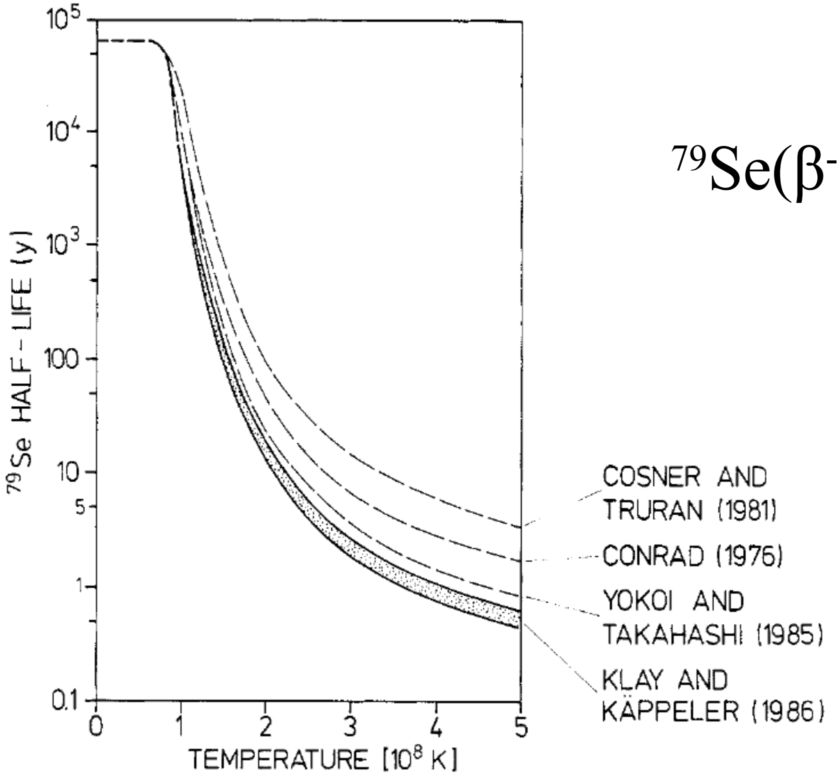
- Big Bang nucleosynthesis: $^{1}H(n,\gamma)$
- Neutron poisons for the s-process: $^{12}C(n,\gamma)$, $^{16}O(n,\gamma)$, $^{22}Ne(n,\gamma)$.
- ToF measurements of medium mass nuclei for the weak s-process.

Neutron capture measurements with small sample masses:

- Radio-isotopes for γ-ray astronomy $^{59}Fe(n,\gamma)$ and $^{60}Fe(n,\gamma)$
- Branch point nuclei, e.g. $^{85}Kr(n,\gamma)$, $^{95}Zr(n,\gamma)$, $^{147}Pm(n,\gamma)$, $^{154}Eu(n,\gamma)$, $^{155}Eu(n,\gamma)$, $^{153}Gd(n,\gamma)$, $^{185}W(n,\gamma)$

Future developments – half-lifes

- **can strongly depend on temperature and electron density**
- **main effects are:**
    - thermally populated low-lying states contribute to β-decay
    - ionization and electron density affect electron capture probability
    - ionization affects Q-value of β^--decay (bound state decay)



^{79}Se(β^-)

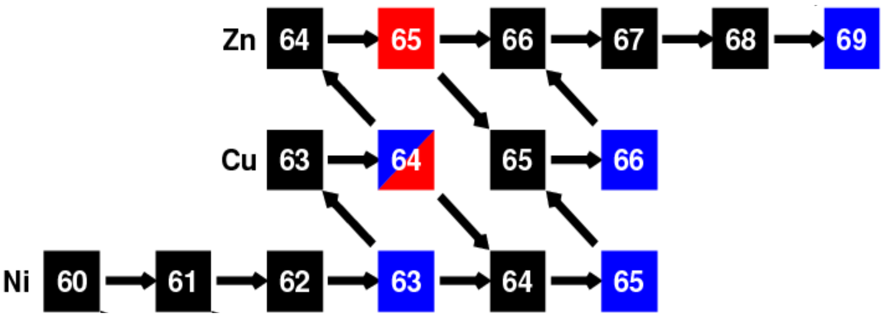
(Käppeler '88)

- (β^-) with ESR@GSI via Schottky analysis (^{187}Re, more to come)
- (β^-) from (p,n) reactions

Why p(^{64}Ni,^{64}Cu)n

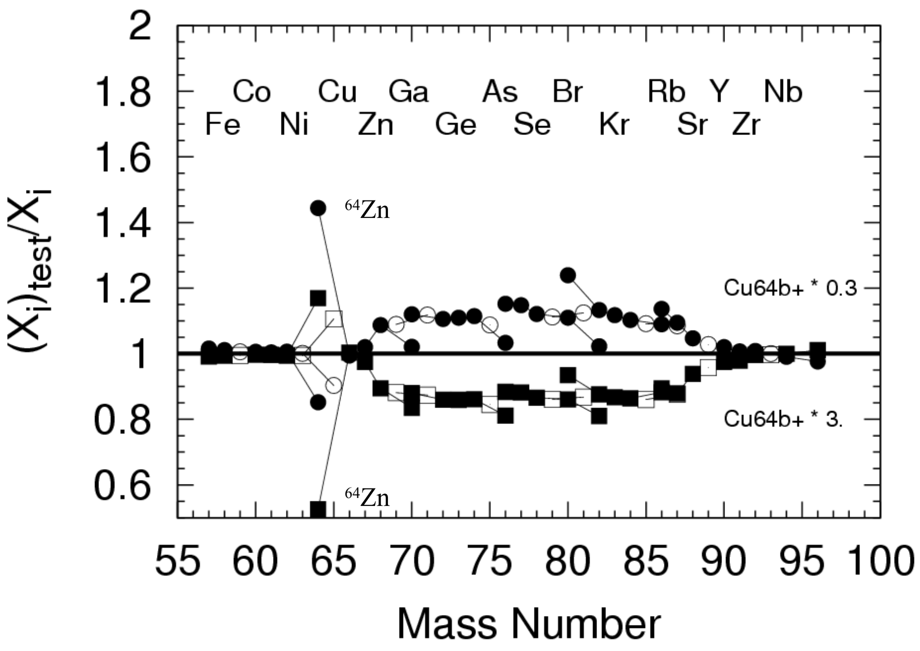
Weak s process in massive stars (56<A<90)

- determines composition of supernova progenitor
- needed for r-process residuals
- branching allow to calculate temperature inside stars (easy to observe via ratio ^{63}Cu/^{65}Cu)



The EC rate of ^{64}Cu is expected to change within a factor of three between T_8=0.5 and T_8=5

One needs to know the temperature-dependence of the EC/β^+ rate of ^{64}Cu accurately.

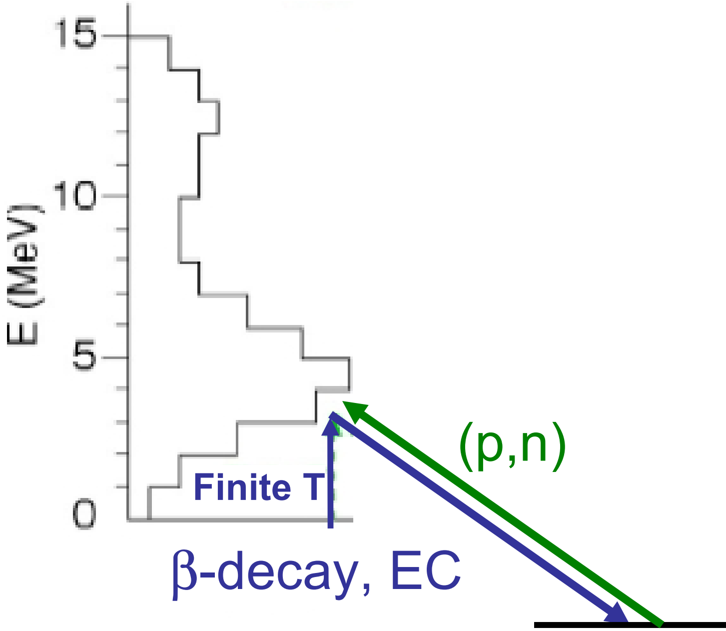


β-decay in stellar environments

β GT-decay from thermally excited states make the b-decays temperature dependent.

This can **not** be measured in the laboratory. **Theory is needed**!

Distribution of B(GT) is needed!
Solution: charge exchange cross sections



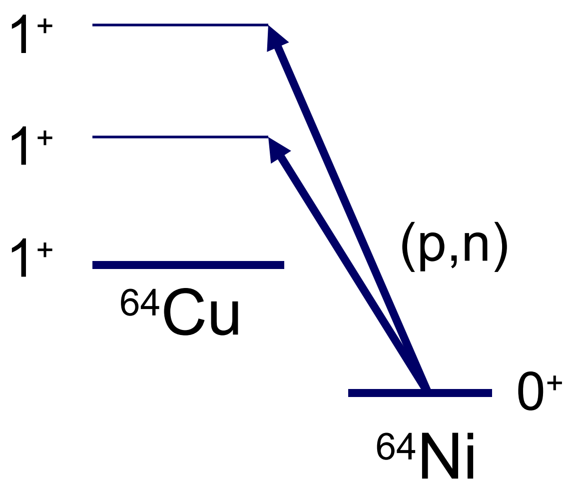
$$\frac{d\sigma^{CE}}{d\Omega}(q=0) = \hat{\sigma}_{GT}(q=0)B(GT)$$

(p,n) in inverse kinematics

Task: Measure low lying 1^+ states

This has been done already:

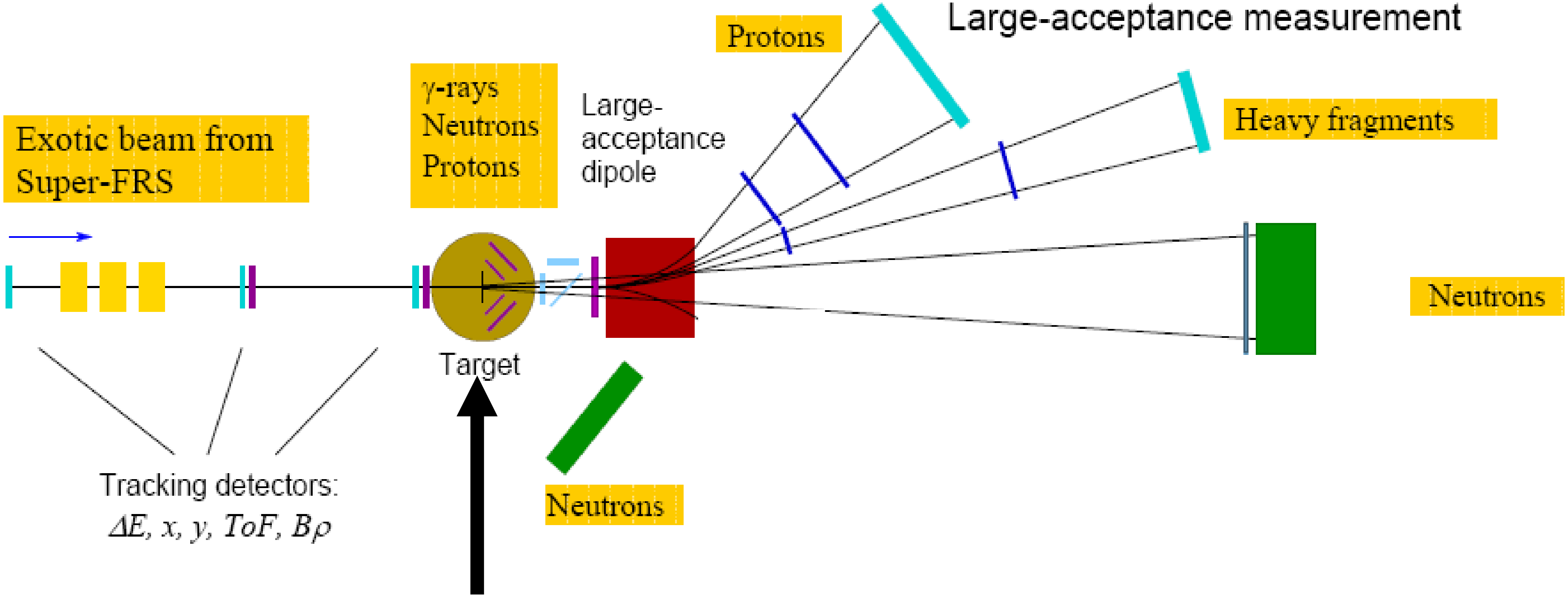
^{64}Ni(p,n)^{64}Cu Anantaraman et al. (2008),
^{64}Ni(^{3}He,t)^{64}Cu Popescu et al. (2009),



We want to establish the method in
inverse kinematics for later use with unstable nuclei.

Existing data can be used for validation of the method.

R³B setup at GSI



Targets:
(CH_2, C, empty…)

Standard R³B setat Cave C.
In addition, a low energy neutron detector (LENA) will be installed

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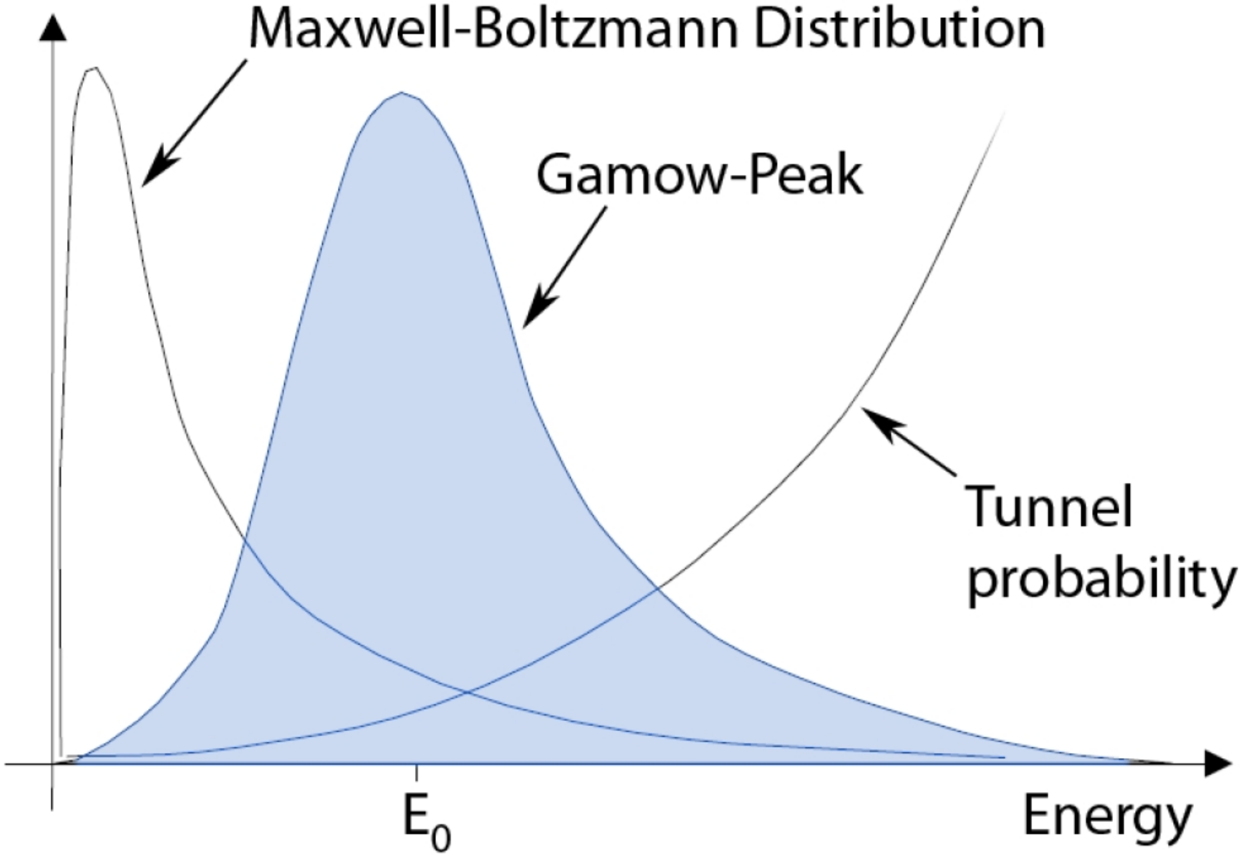
Charged-particle induced

- (p,γ), (a,γ) in the Gamow window
- for heavy elements during p-process: ~ several MeV



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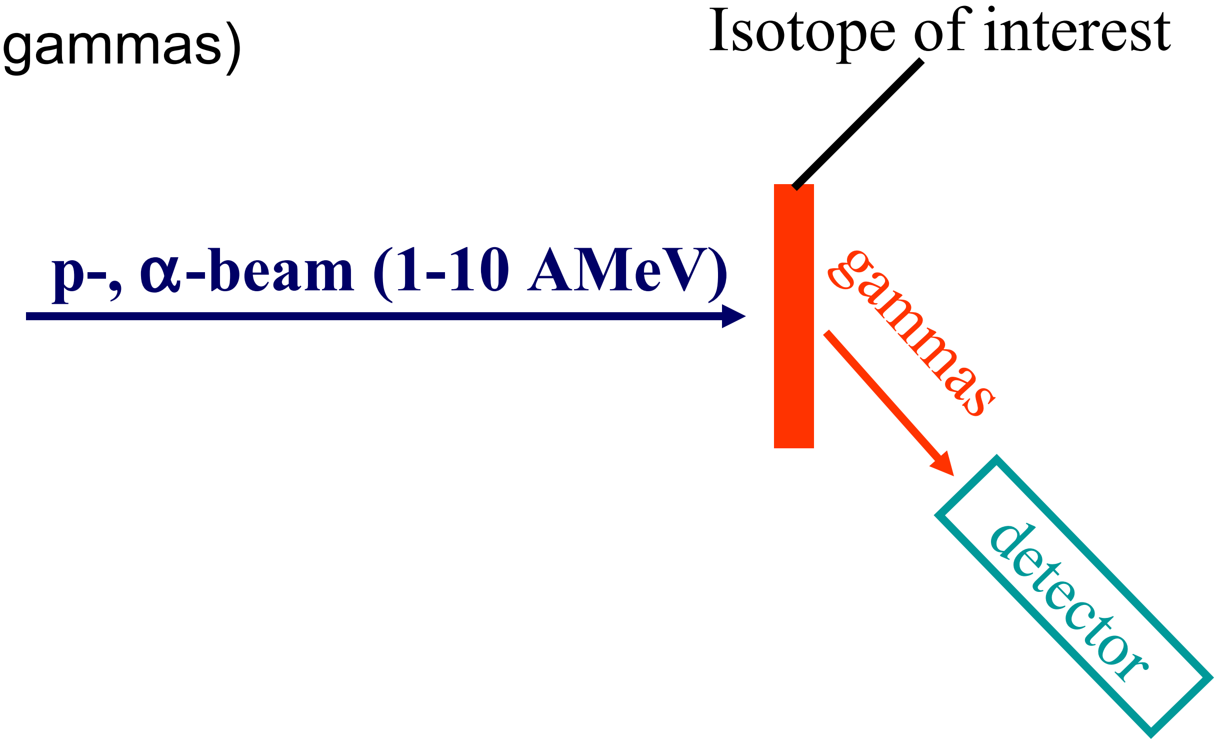
Experimental determination of cross sections

- Traditional method:
  - Produce target, irradiate with H, He beam
  - Detect products
    - Delayed (activation)
    - Prompt (gammas)



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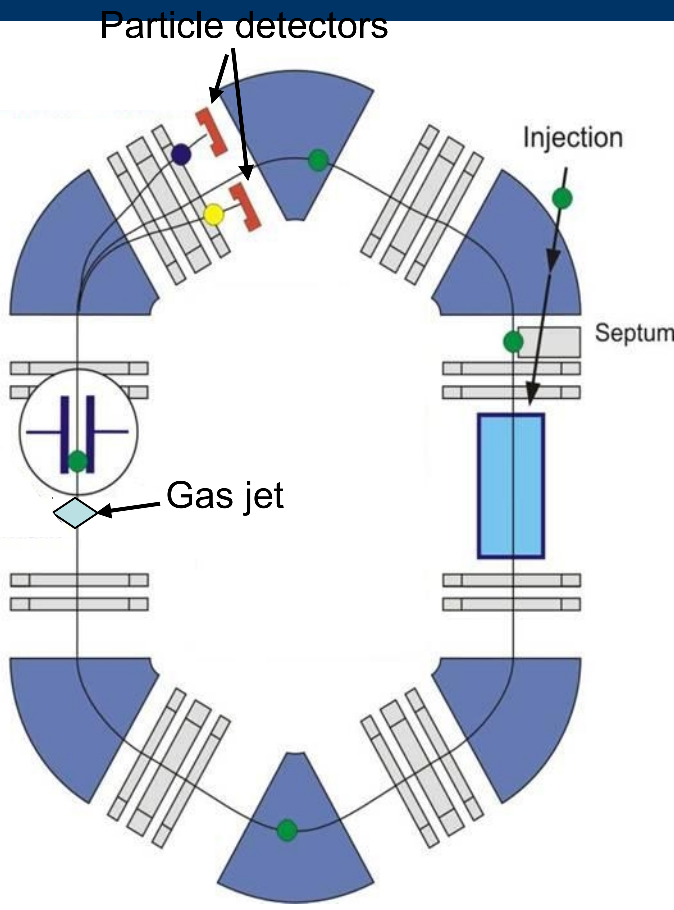
Reaction Studies at the ESR

Measurements of (p,γ) or (α,γ) rates in the Gamow window of the p-process in inverse kinematics.

Advantages:

- **Applicable to radioactive nuclei**
- **Detection of ions via in-ring particle detectors (low background, high efficiency)**
- **Knowledge of line intensities of product nucleus not necessary**
- **Applicable to gases**



ESR

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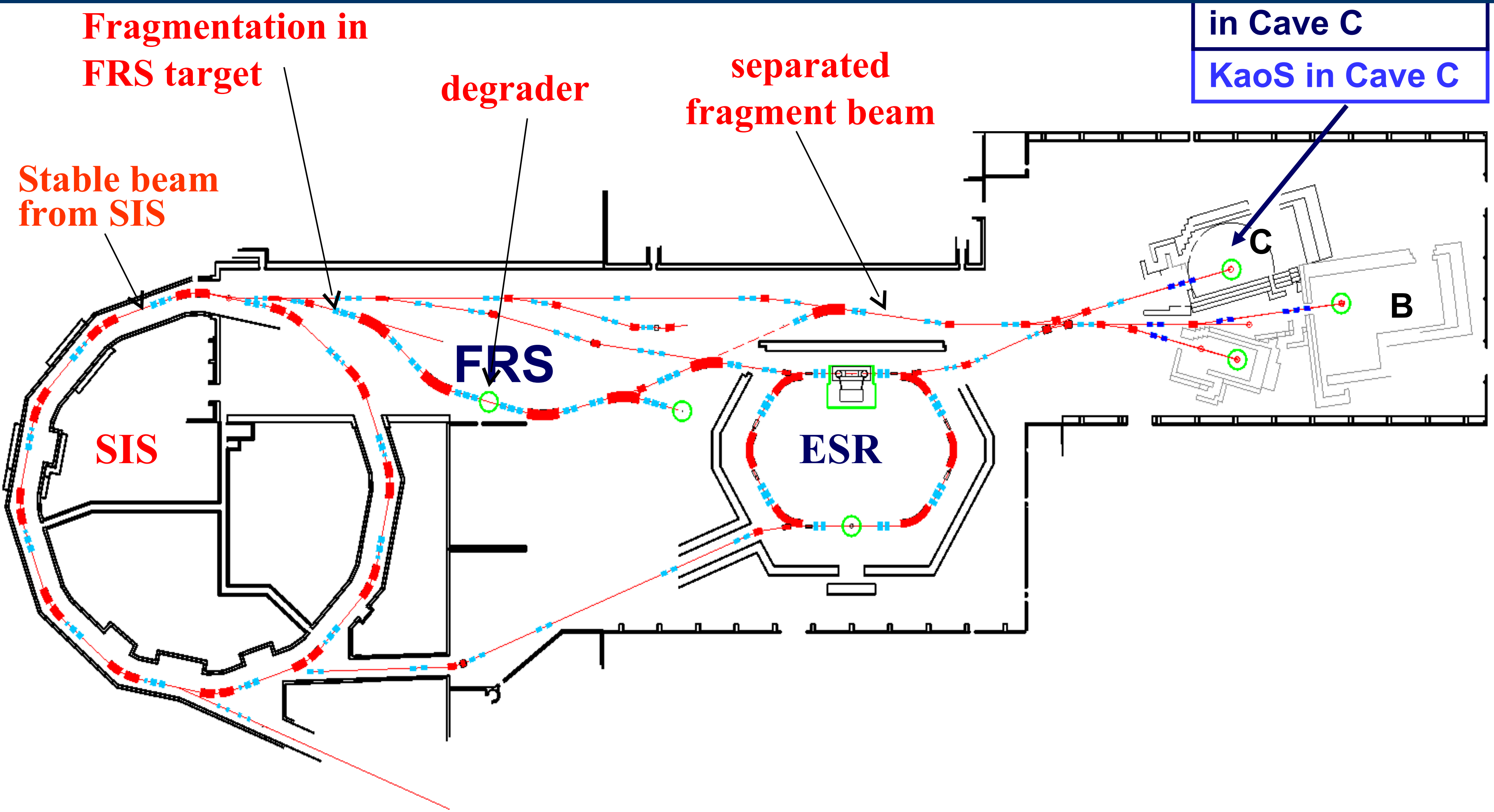
Layout of the experimental facilities at GSI



in Cave C

KaoS in Cave C

Fragmentation in FRS target

degrader

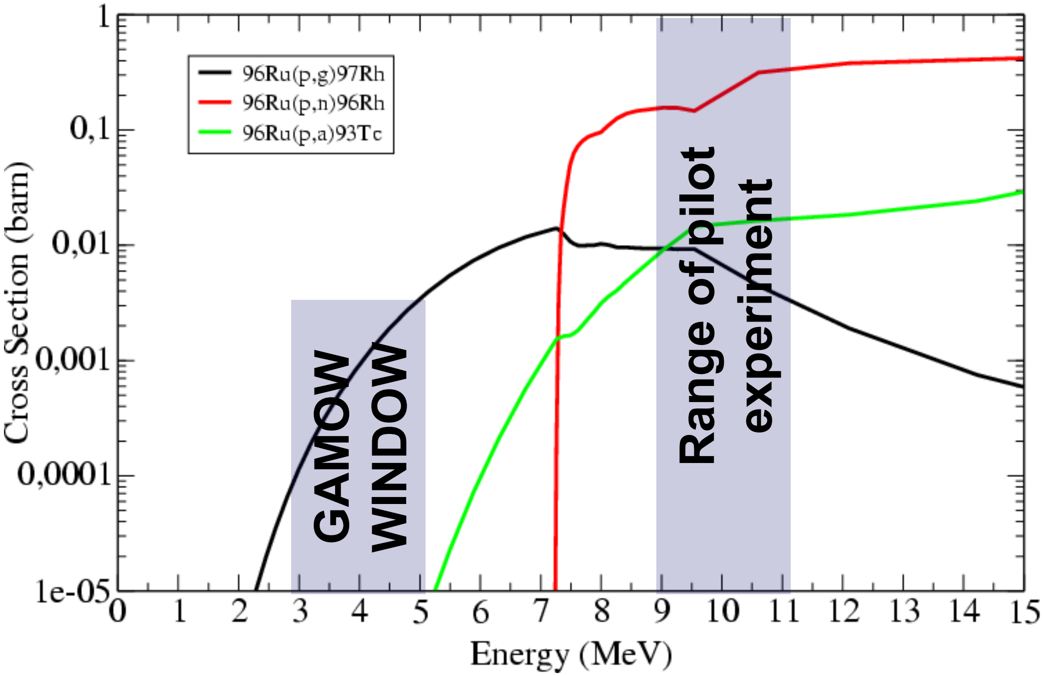
separated fragment beam

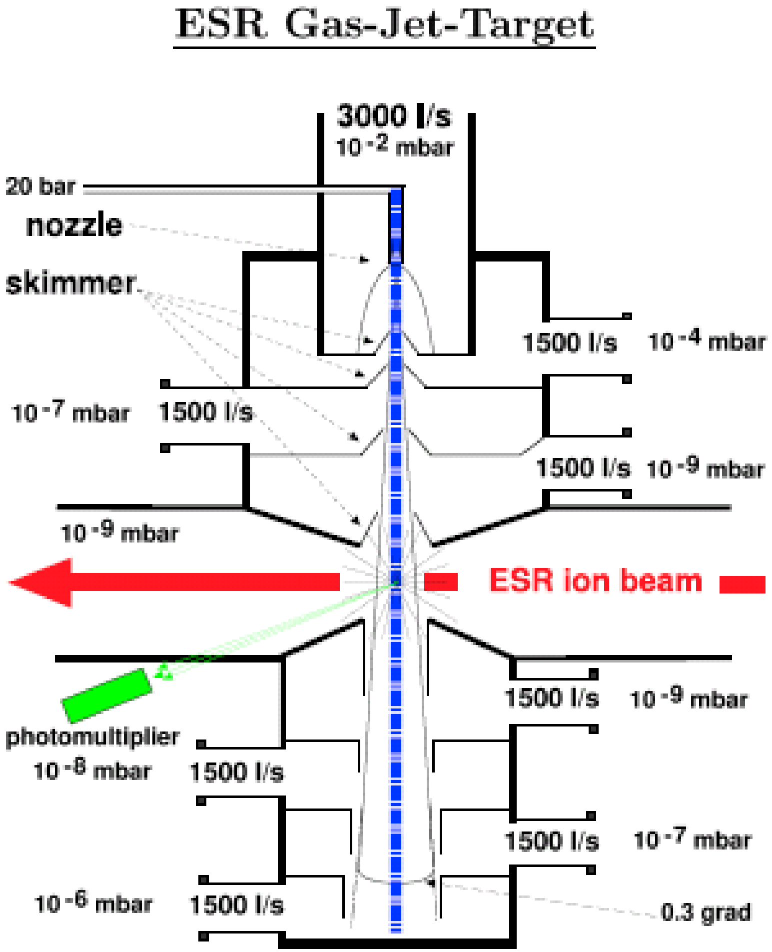
Stable beam from SIS

Reaction Studies at the ESR

First pilot experiment performed with stable beams: $^{96}Ru(p,\gamma)^{97}Rh$

- Measurements performed at 9, 10, 11 AMeV
- $5 \cdot 10^6$ particles per spill
- Target density $1 \cdot 10^{13}$ atoms/cm^2
- Luminosity $2.5 \cdot 10^{25}$
- Cross section 2 mbarn -> ~180 counts/h

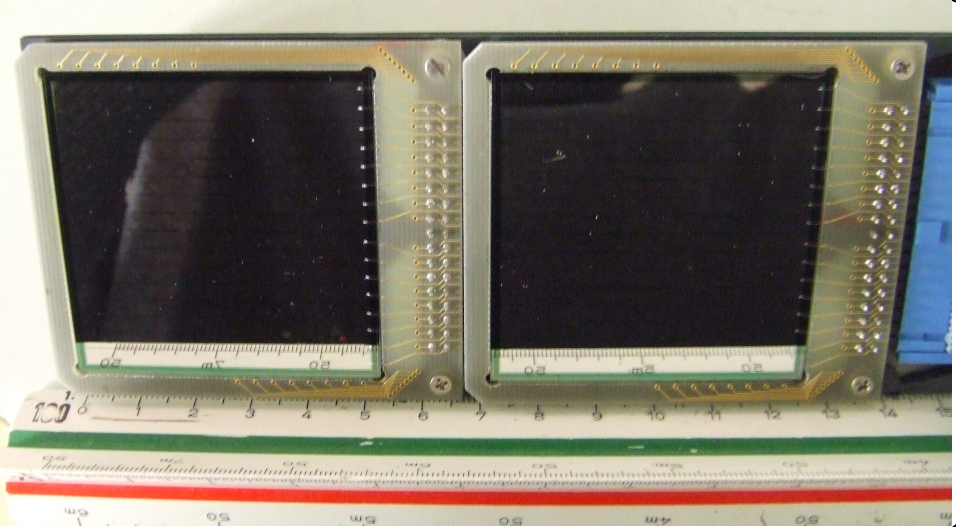


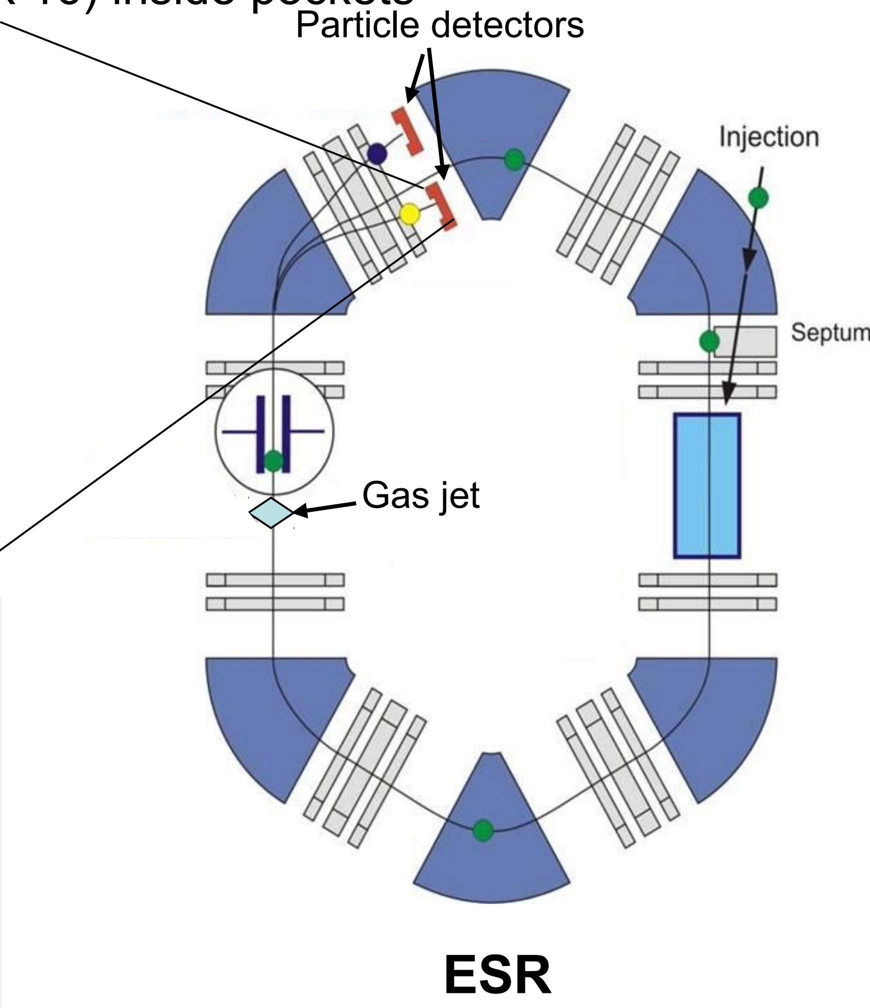


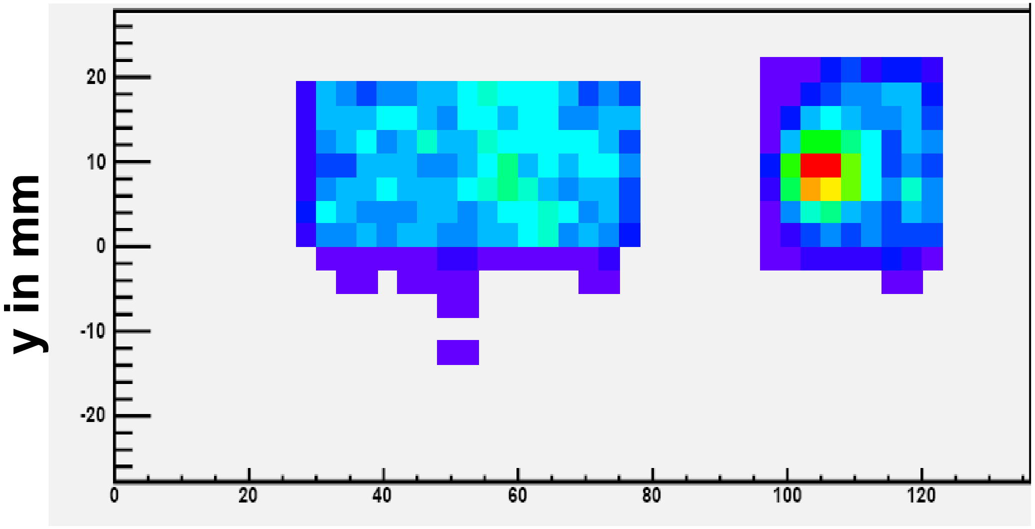
Q. Zhong et al., Journal of Physics: Conference Series, Volume 202, Issue 1, pp. 012011 (2010)

Reaction Studies at the ESR

Particle detectors: Double sided silicon strip (16 x 16) inside pockets







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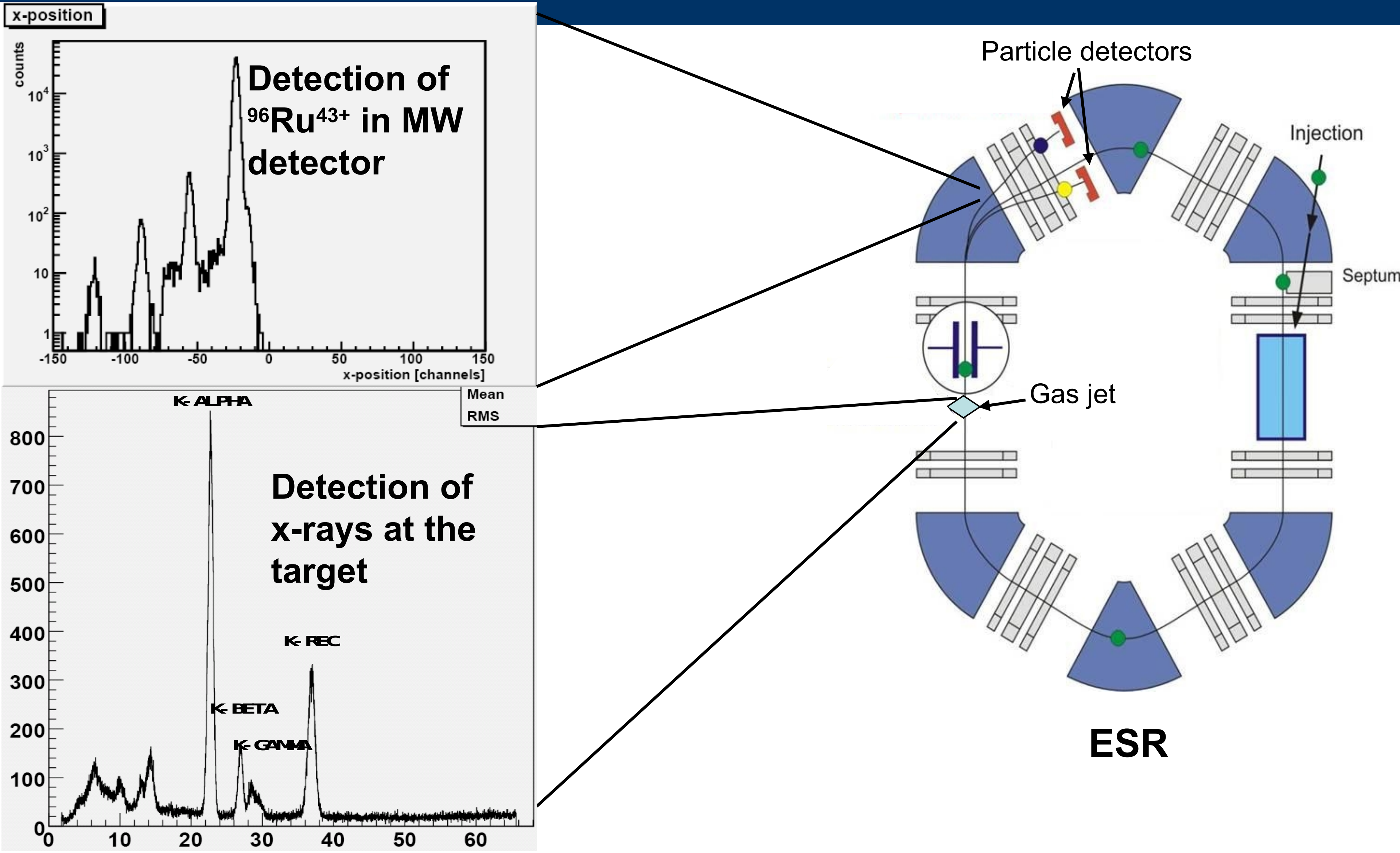
Normalization of the cross section

Detection of atomic electron pick-up in the gas target ($^{96}\mathrm{Ru}^{44+}+e^{-} \rightarrow {}^{96}\mathrm{Ru}^{43+}$):



Detection of $^{96}\mathrm{Ru}^{43+}$ in MW detector

Detection of x-rays at the target

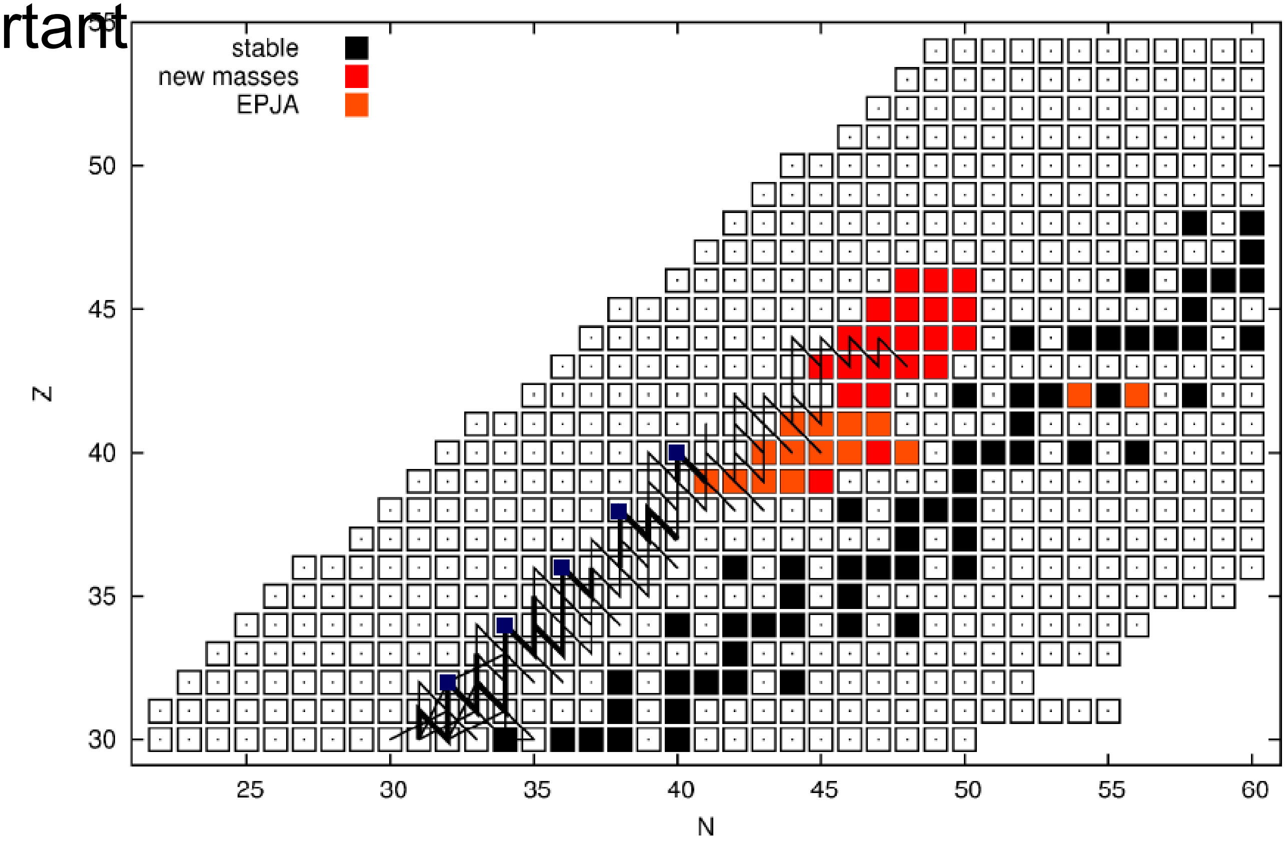
ESR

Neutron-induced via detailed balance

(small (p,γ) cross section, long EC/β^+ half-lives)

- can be overcome with small amount of neutrons coming from $\nu + p \rightarrow n + \beta^+$ reactions, the νp-process
- ^{64}Ge(n,p)^{64}Ga important

Possibly measurable via ^{64}Ga(p,n)^{64}Ge at the ESR



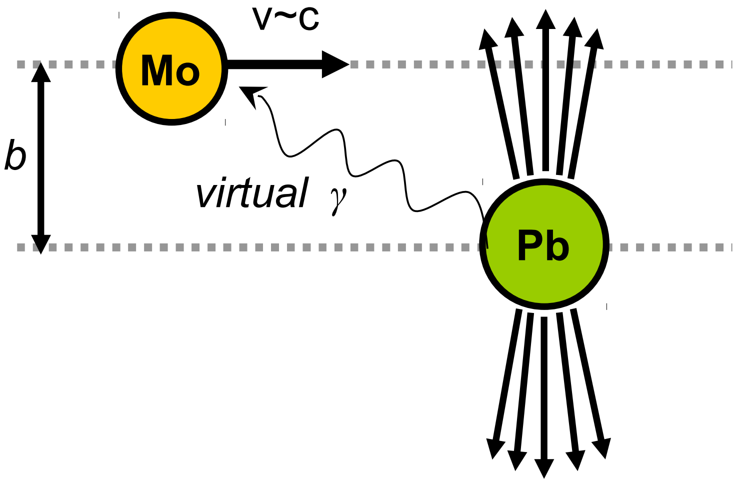
Thielemann et al, Journal of Physics: Conference Series **202** (2010) 012006

Experimental method

~ 1 MeV

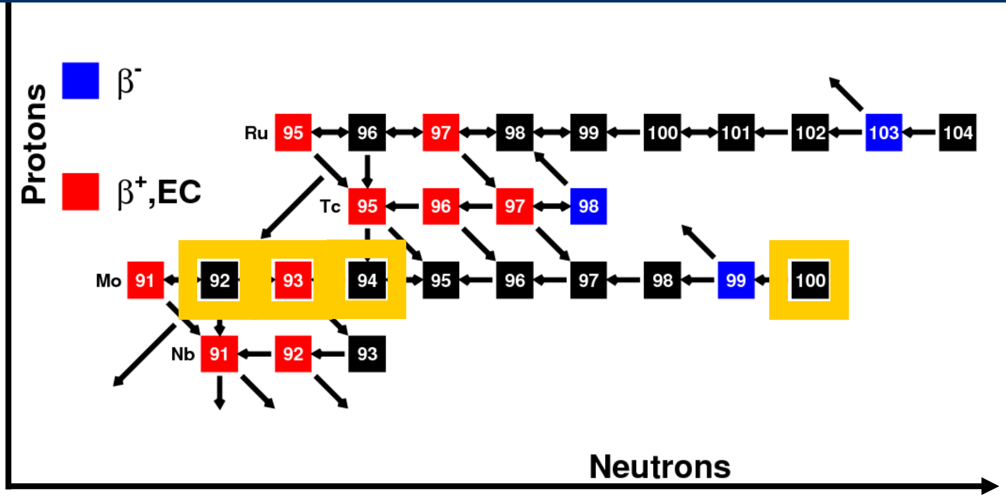
Coulomb dissociation in inverse kinematics:

- Virtual photons produced by a high-Z target (Pb)
- Projectile at ~500 MeV/u
- Large impact parameter *b*
- E_{max} of the virtual photon spectrum ~ 20 MeV
- C and empty target measurements (to subtract nuclear contribution and background)



Important: results for the stable isotopes can be compared with measurements with real photons on ELBE (FZD) and S-DALINAC (TUD).

(γ,n) reaction on Mo isotopes - why?



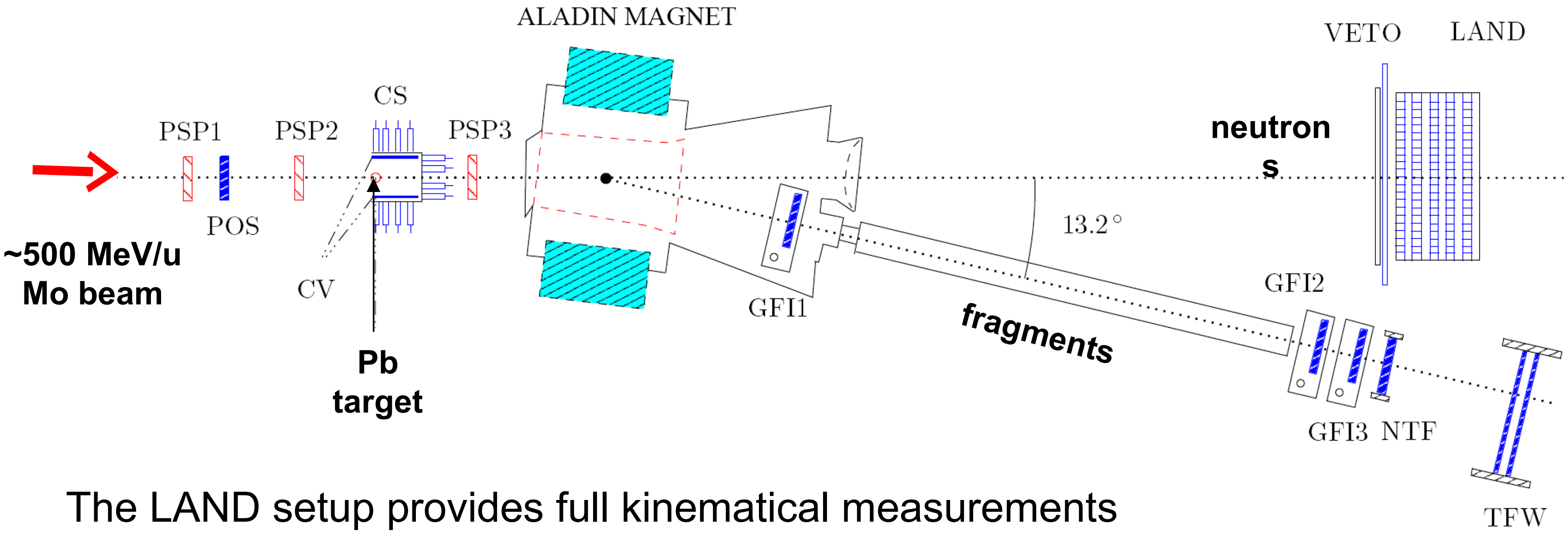
calculations:

- Large networks
- Most of the reaction rates from the statistical model

- ^{92}**Mo** has one of the highest cosmic abundances of all p-nuclei
- Ru and Mo isotopes are **significantly underproduced** in all existing network calculations
- Studied isotopes:
  - ^{92}**Mo,** ^{94}**Mo,** ^{100}**Mo** (stable) – to verify the method;
  - ^{93}**Mo** ($t_{1/2}$ = 4*10^3 y) – reaction rate not measured before

O. Ershowa et. al, DPG Spring Meeting 2010 (Bonn)

LAND/ALADiN setup

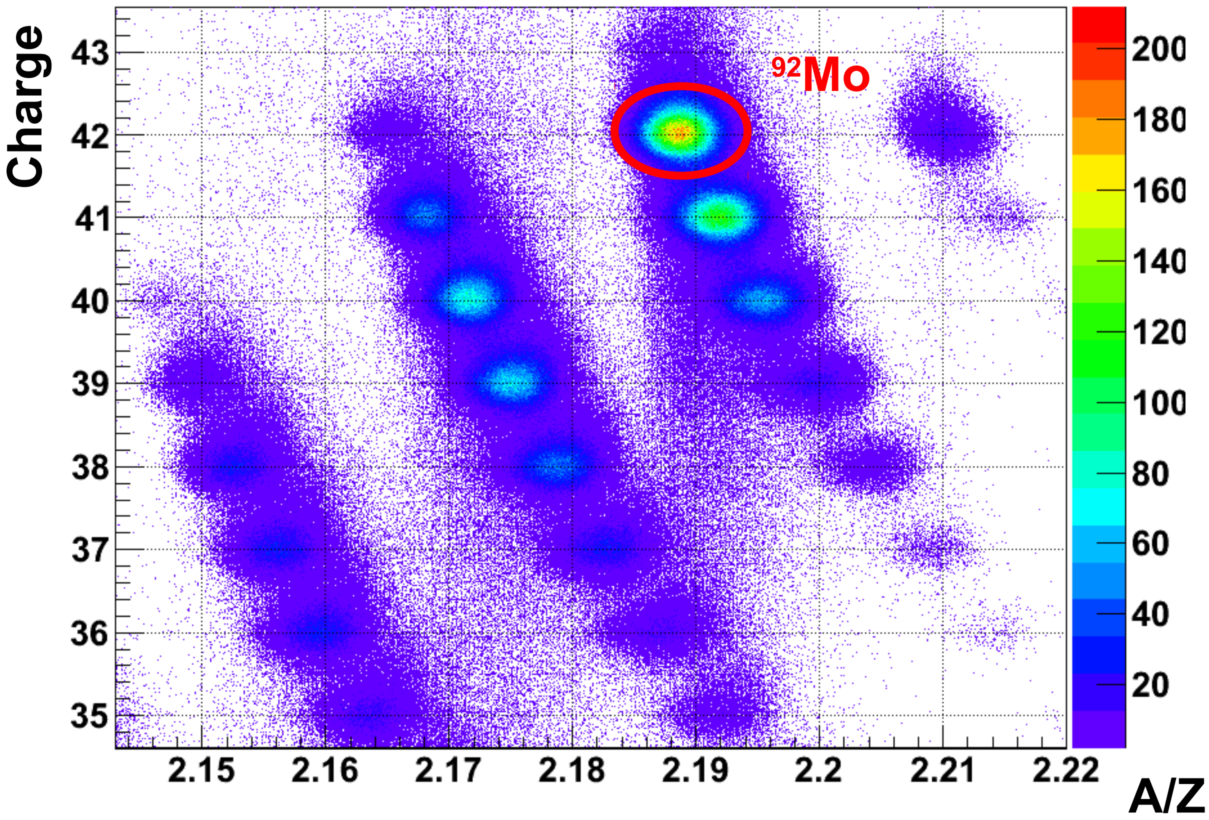


The LAND setup provides full kinematical measurements

PSP1, 2, 3: **dE, x, y**
POS: **t**
CS: **dE, θ, φ (gammas)**
GFI1, 2, 3: **x**
TFW: **dE, t**
LAND: **dE, t, x, y, z (neutrons)**

Incoming beam ID

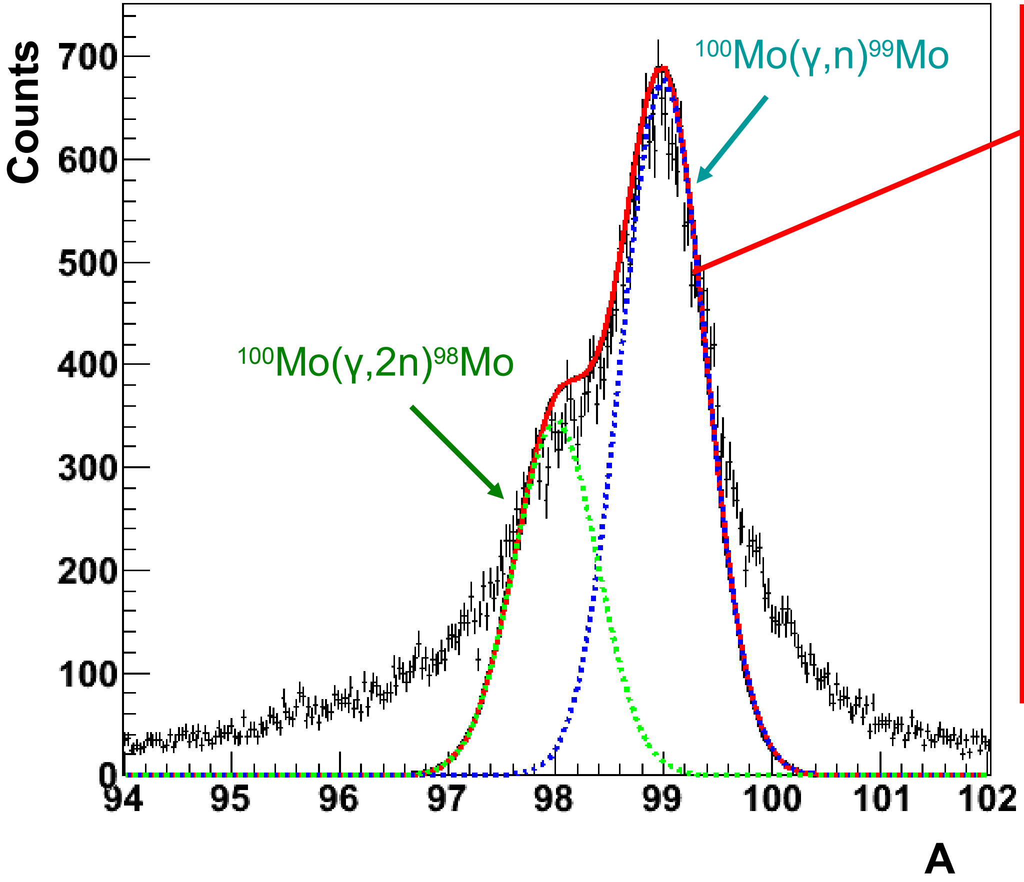
$$Z \propto f(\beta)\sqrt{-\frac{dE}{dx}}$$



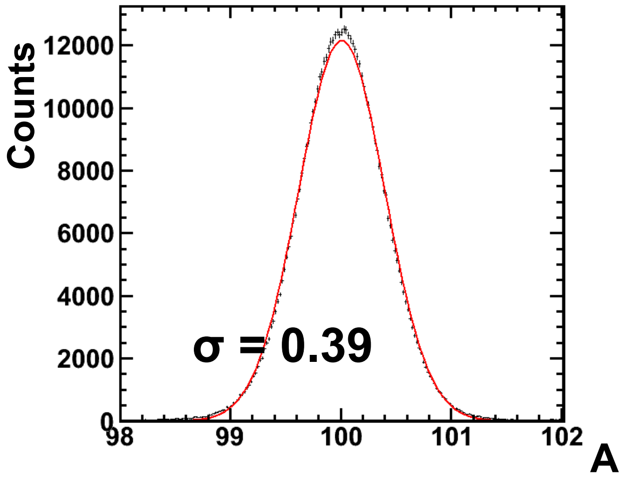
$$\frac{A}{Z}=\frac{e}{uc}\frac{B\rho}{\beta\gamma}$$

Outgoing beam ID: mass

(with cuts on incoming **^{100}Mo**, outgoing **Z=42** (Mo)
and **neutron multiplicity in LAND =1**)



Fixed σ, determined from the non-reacting beam:



Summary

- the s-process as a nucleosynthesis process is well understood and established
- In particular the weak component still lacks accurate nuclear data
- Data on radioactive nuclei are needed to enhance the reliability stellar model predictions
- Current facilities can measure some, upcoming facilities will investigate a suite of radioactive isotopes
- There will always be the need for other than TOF methods (half lives!)

Thank you!