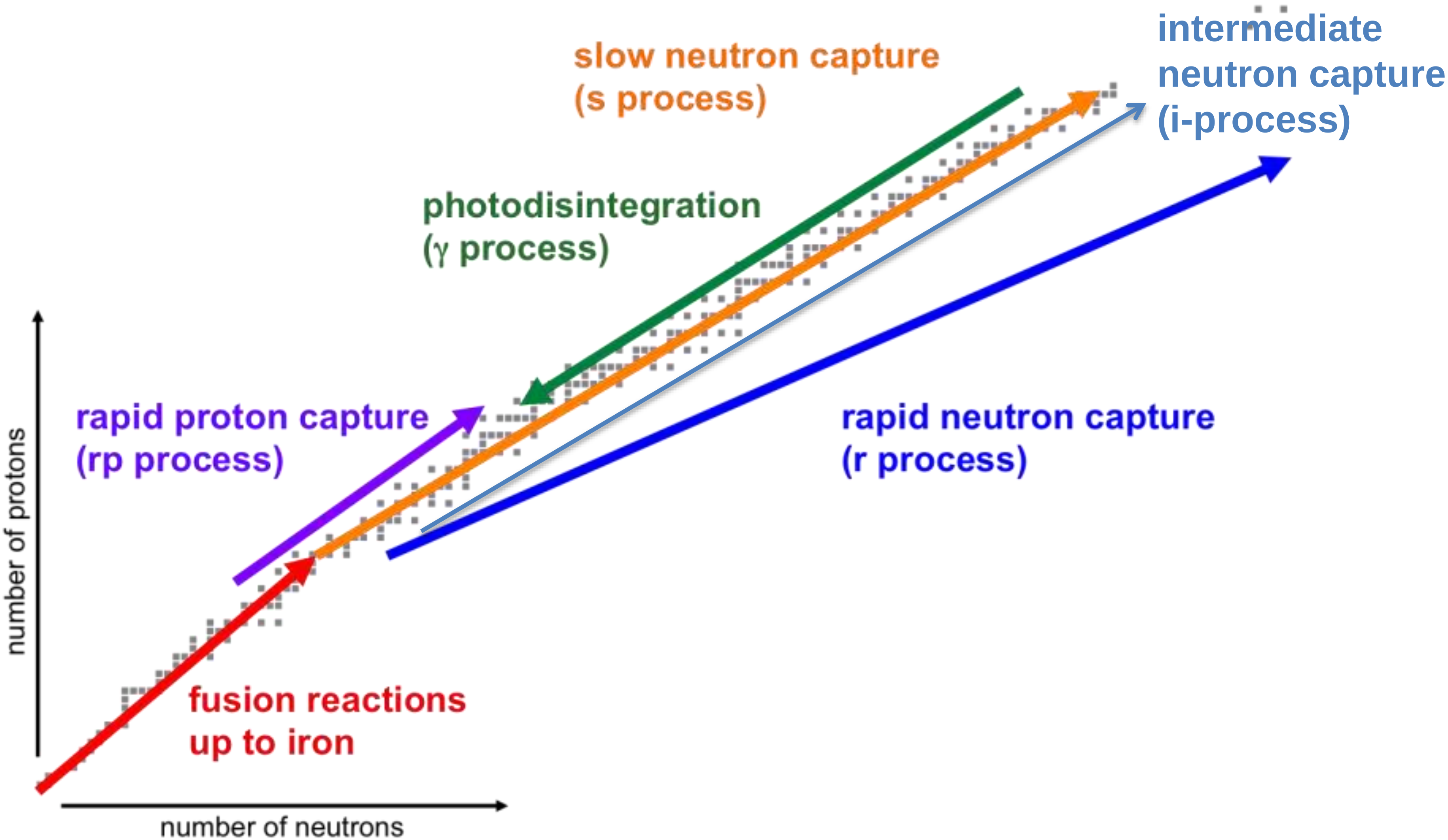
The s-, i- and r-process in the laboratory

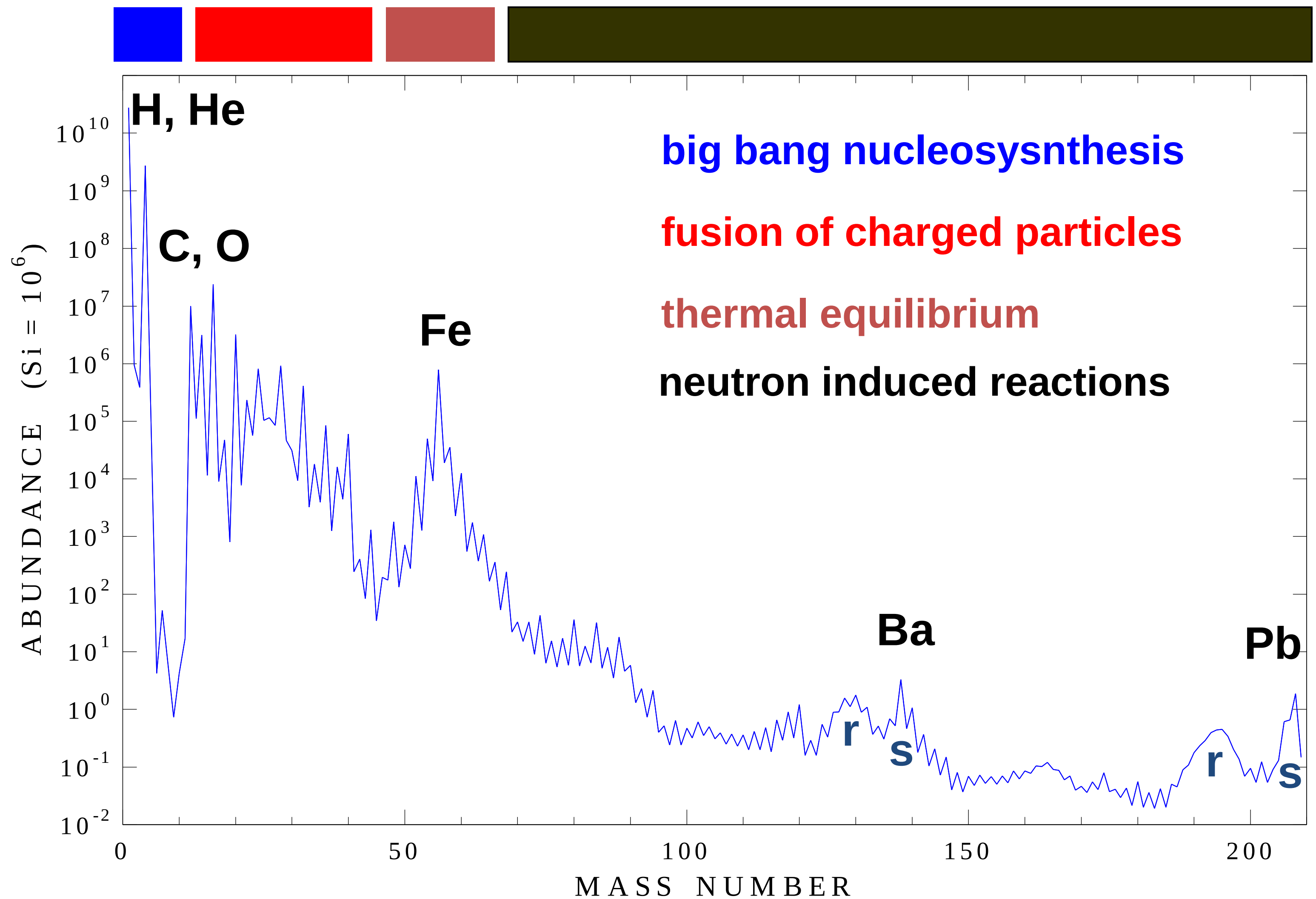
René Reifarth
Goethe-University Frankfurt

10th Russbach School on Nuclear Astrophysics
10.-15 March 2013
Russbach – Austria

The nucleosynthesis of the elements

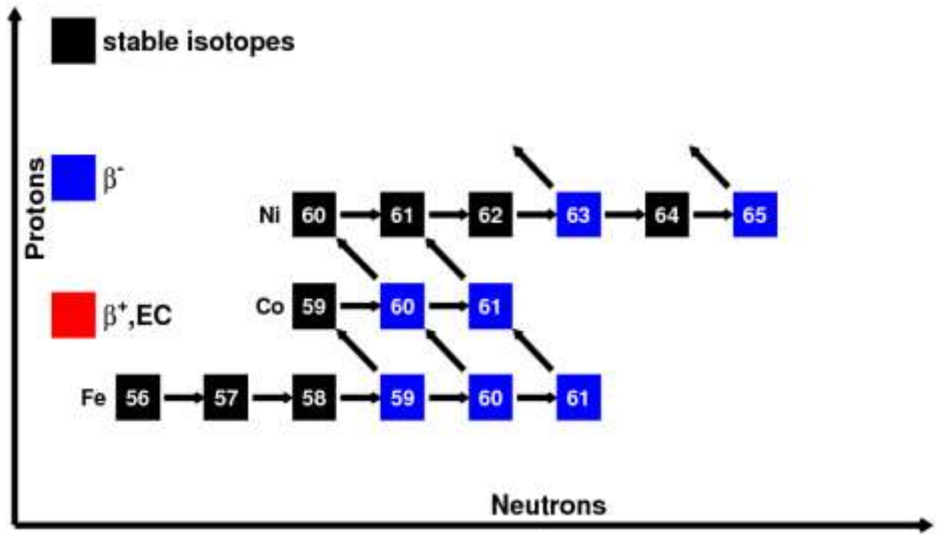


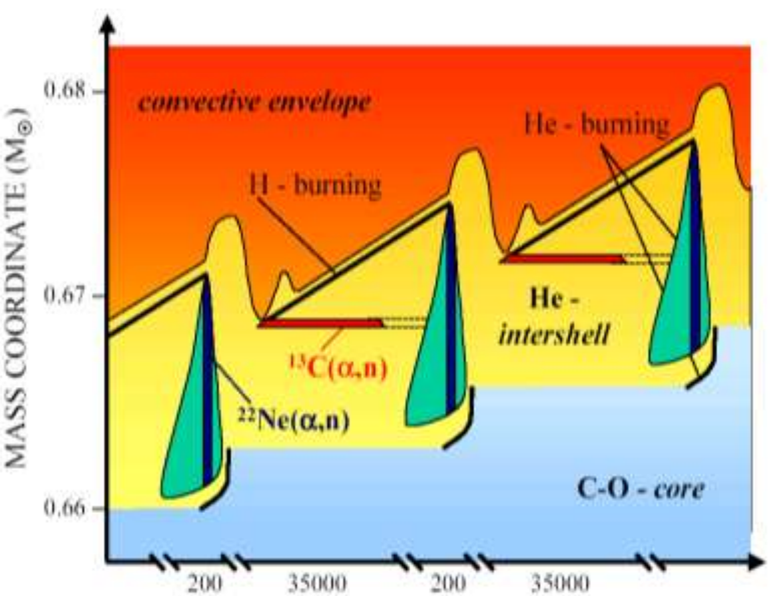
solar abundance distribution

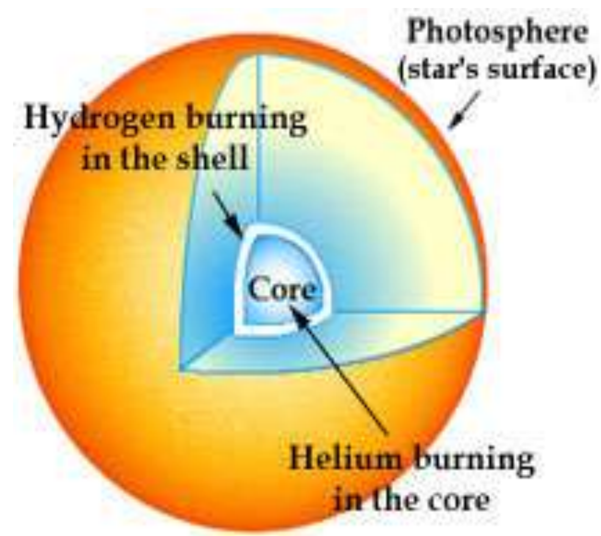


(n,γ) reactions and the s process

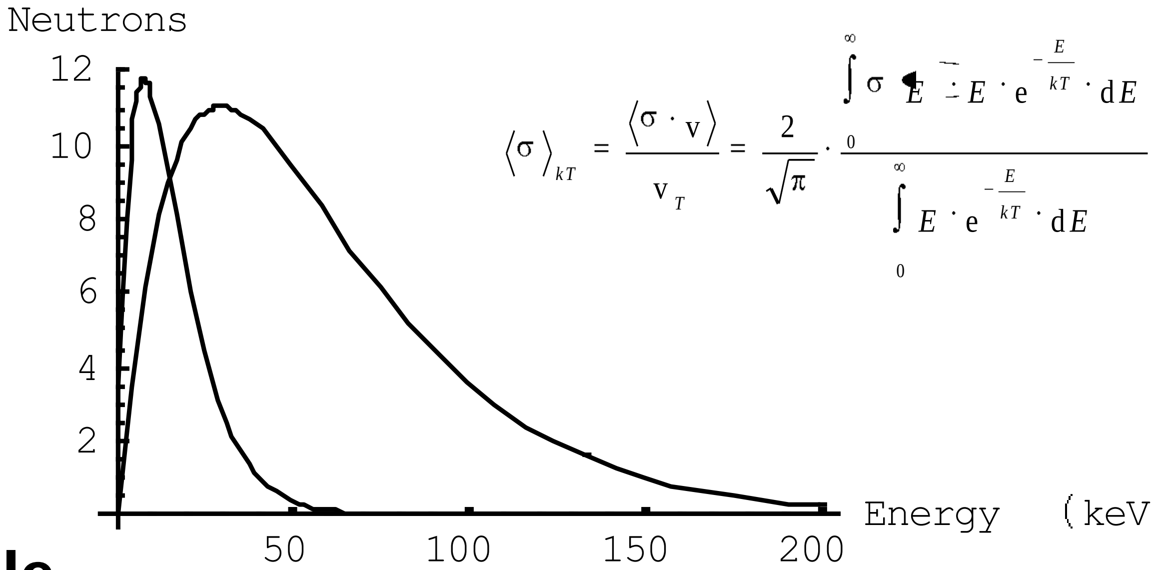
s process:
- occurs in TP-AGB and massive stars
- neutron capture & beta-decays
- branch points allow conclusions on stellar paramters







Neutrons - what is needed?

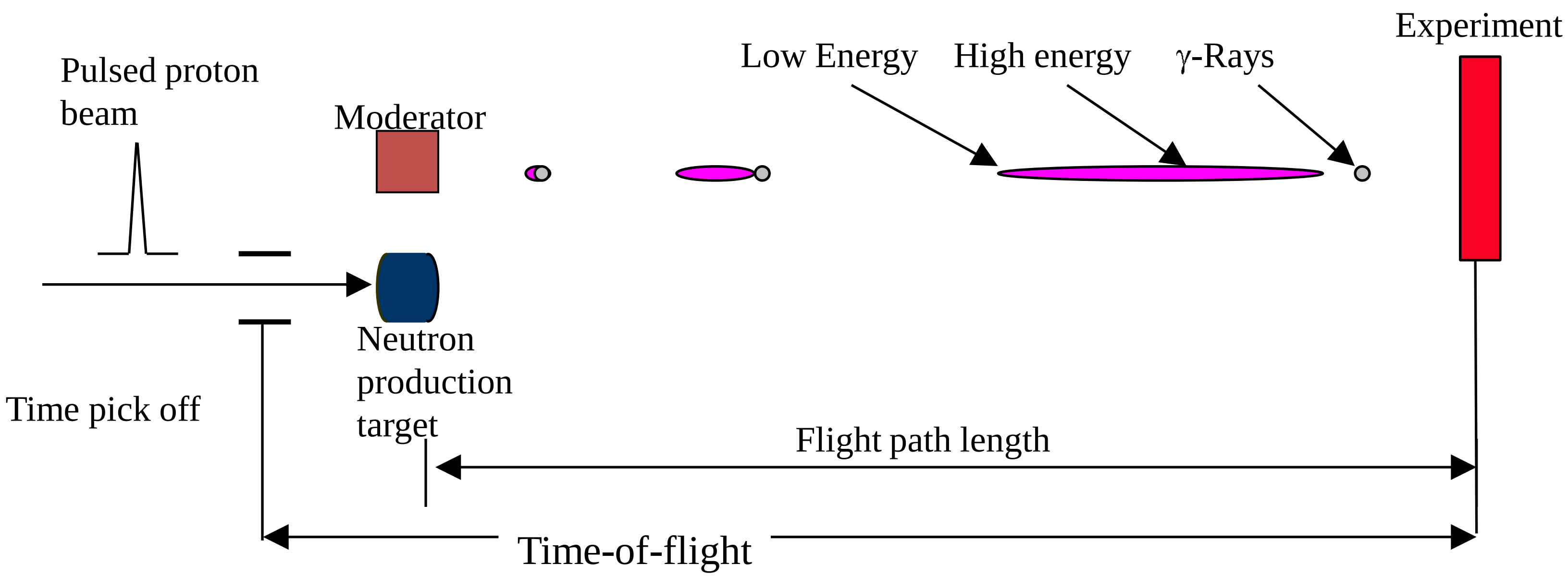


$$\langle\sigma\rangle_{kT} = \frac{\langle\sigma\cdot v\rangle}{v_T} = \frac{2}{\sqrt{\pi}}\cdot\frac{\int_0^\infty \sigma(E)\cdot E\cdot e^{-\frac{E}{kT}}\cdot dE}{\int_0^\infty E\cdot e^{-\frac{E}{kT}}\cdot dE}$$

Challenges

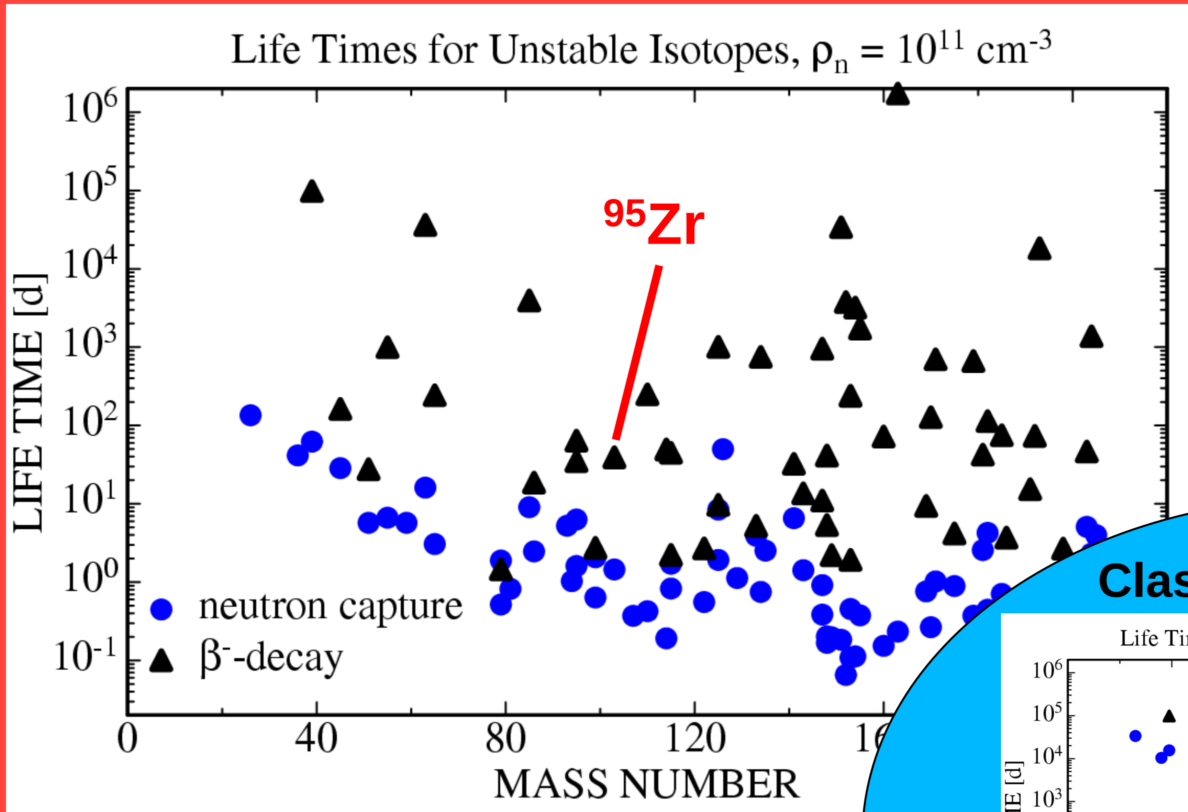
- **Neutrons are not stable**
  - Inverse kinematics not possible
  - Neutrons are difficult to produce
- **Neutrons are neutral**
  - Acceleration not possible
  - Guidance not possible

Neutron Captures – time-of-flight technique



- the TOF-technique is the only generally applicable method the determine energy-dependent neutron capture cross sections
- beam pulsing & distance to the neutron production site significantly reduce the number of neutrons available on the sample

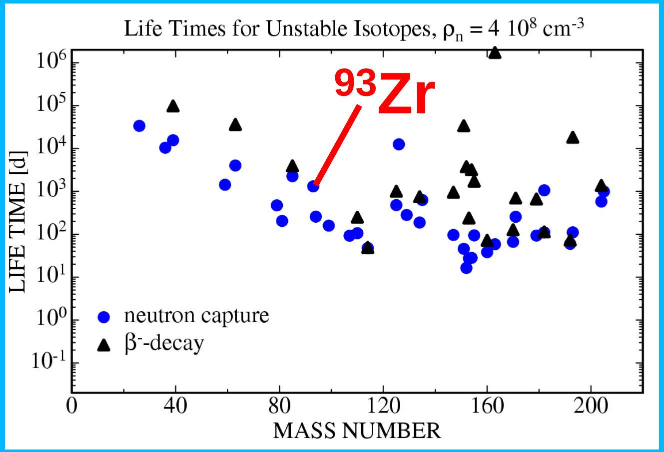
Stellar model vs. experiment



Modern s-process models (AGB stars)

A. Couture, ADNT 93 (2007) 807

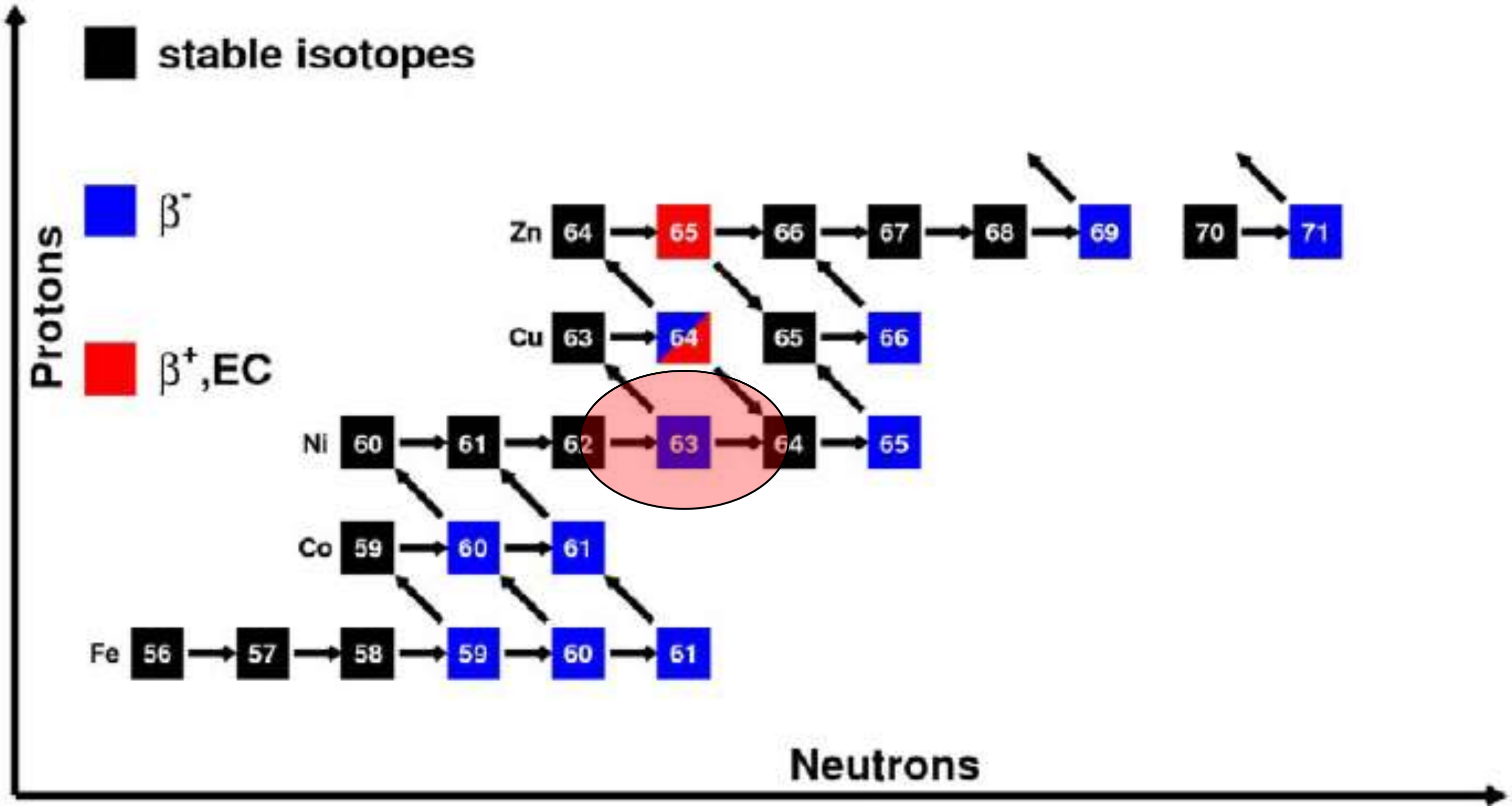
Classical s-process



DANCE, n_TOF

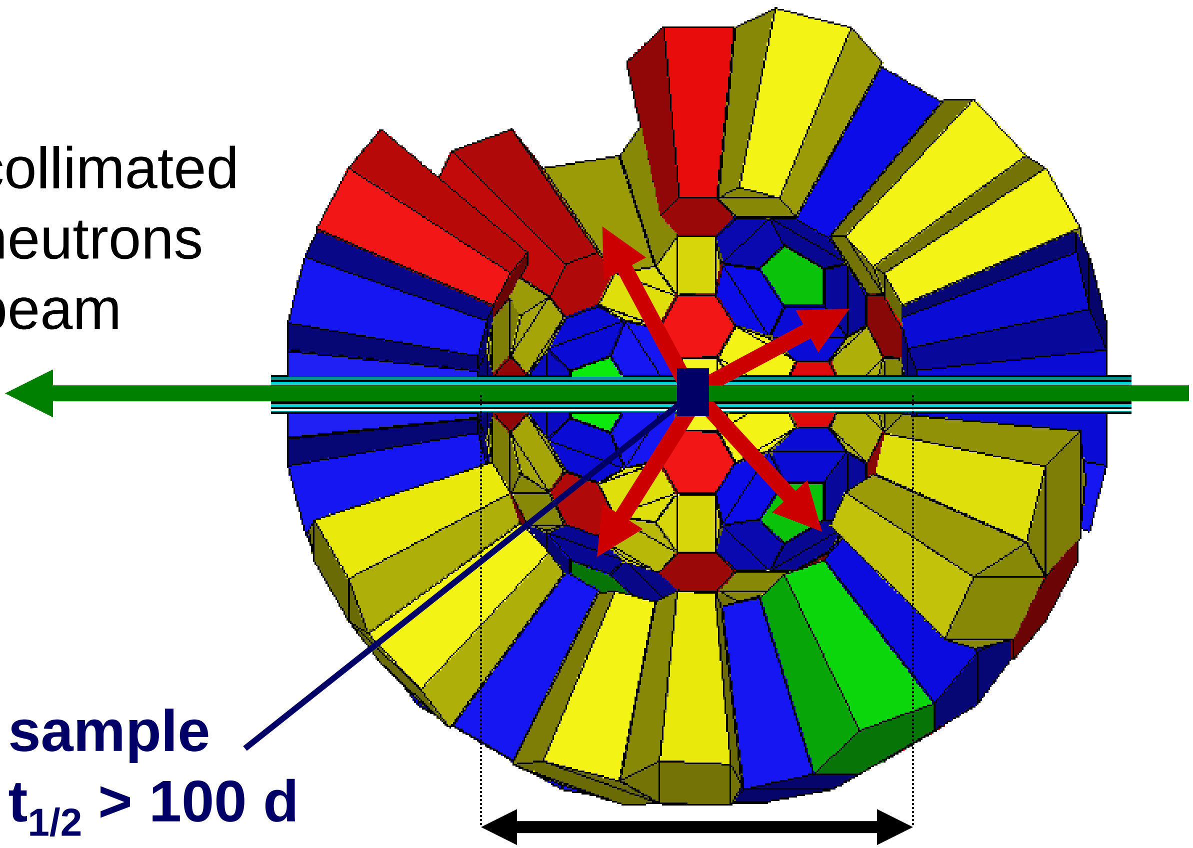
new n-facilities (FRANZ,SARAF)

The s-process around ^{63}Ni



s-process nucleosynthesis in the region between iron and tin with the important branching at ^{63}Ni

Detector for Advanced Neutron Capture Experiments



neutrons:

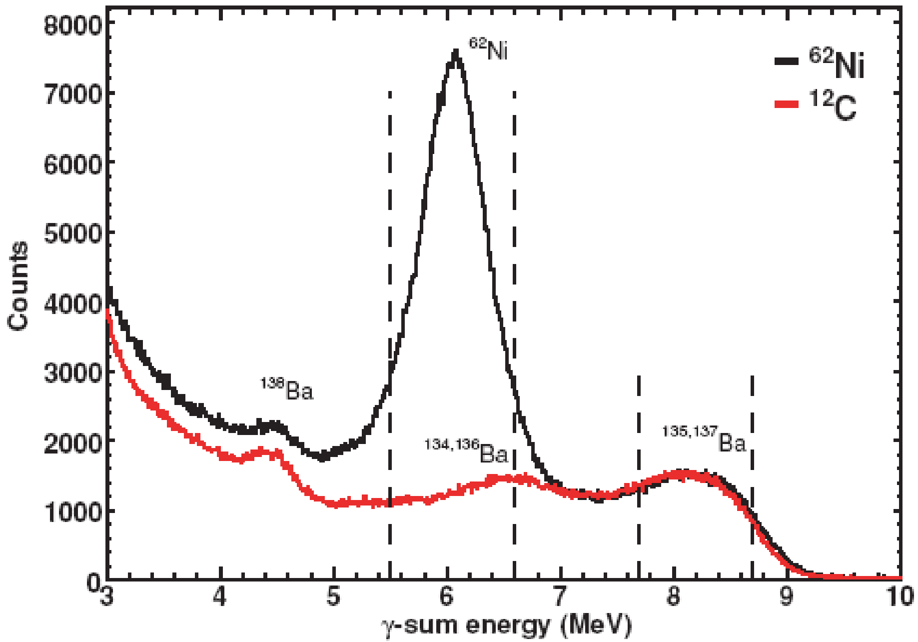
- **spallation source**
- **thermal .. 500 keV**
- **20 m flight path**
- **3 10^5 n/s/cm^2/decade**

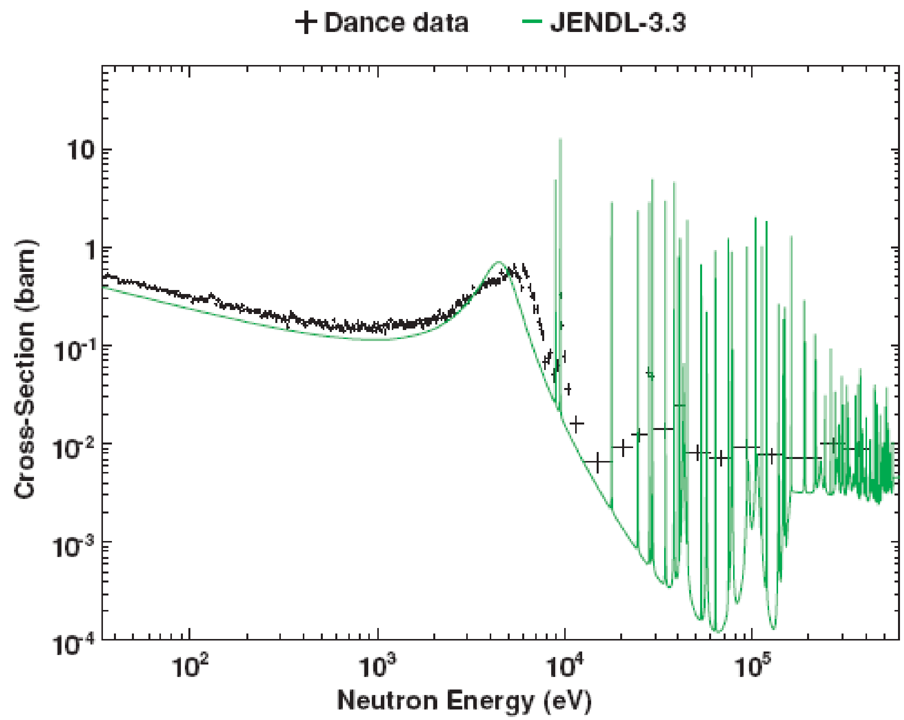
γ-Detector:

- **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 %**

R. Reifarth, NIM A 531 (2004) 530

^{62}Ni(n,γ) at DANCE





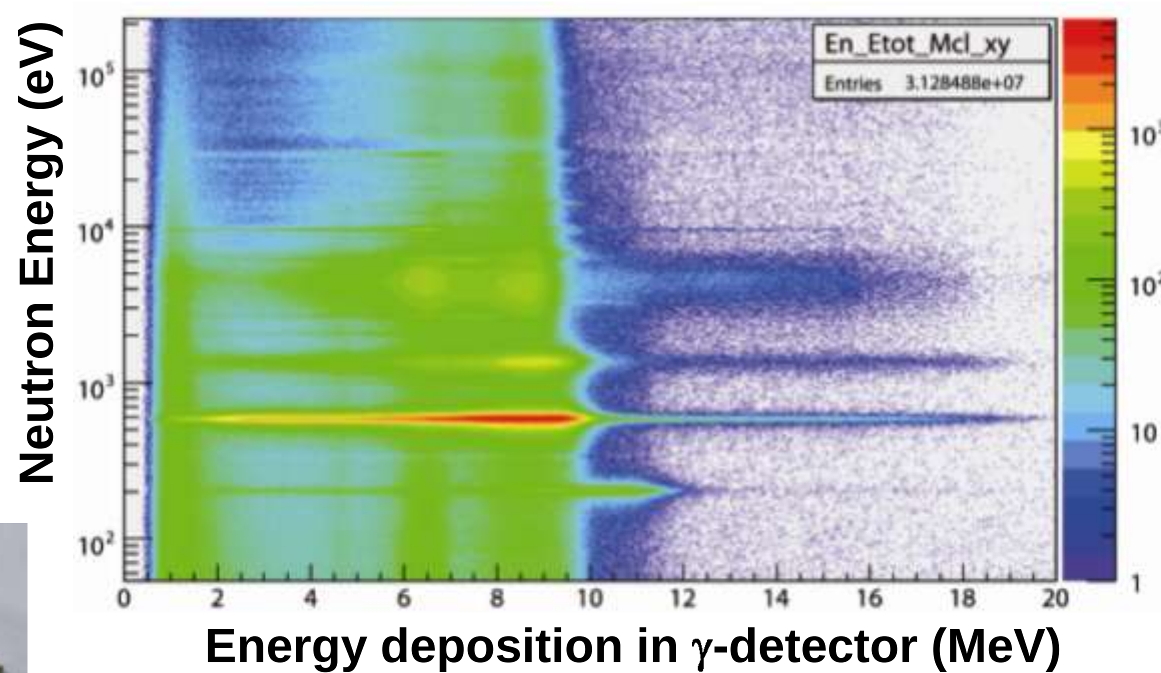
A.M. ALPIZAR-VICENTE PRC 77 (2008) 015806

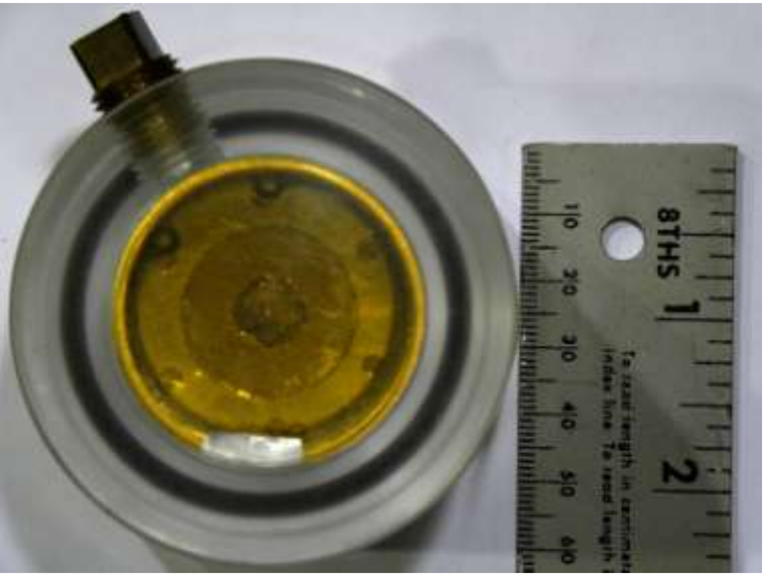
New high-resolution campaign been performed at n_TOF/CERN

^{63}Ni(n,γ) - $t_{1/2}$ = 100 yr

^{63}**Ni Sample:**

- **347 mg**
- **~11% ^{63}Ni**
- **Aktivität ~2.2 Ci**
- **Via reactor irradiation of ^{62}Ni (20-25 yr ago)**

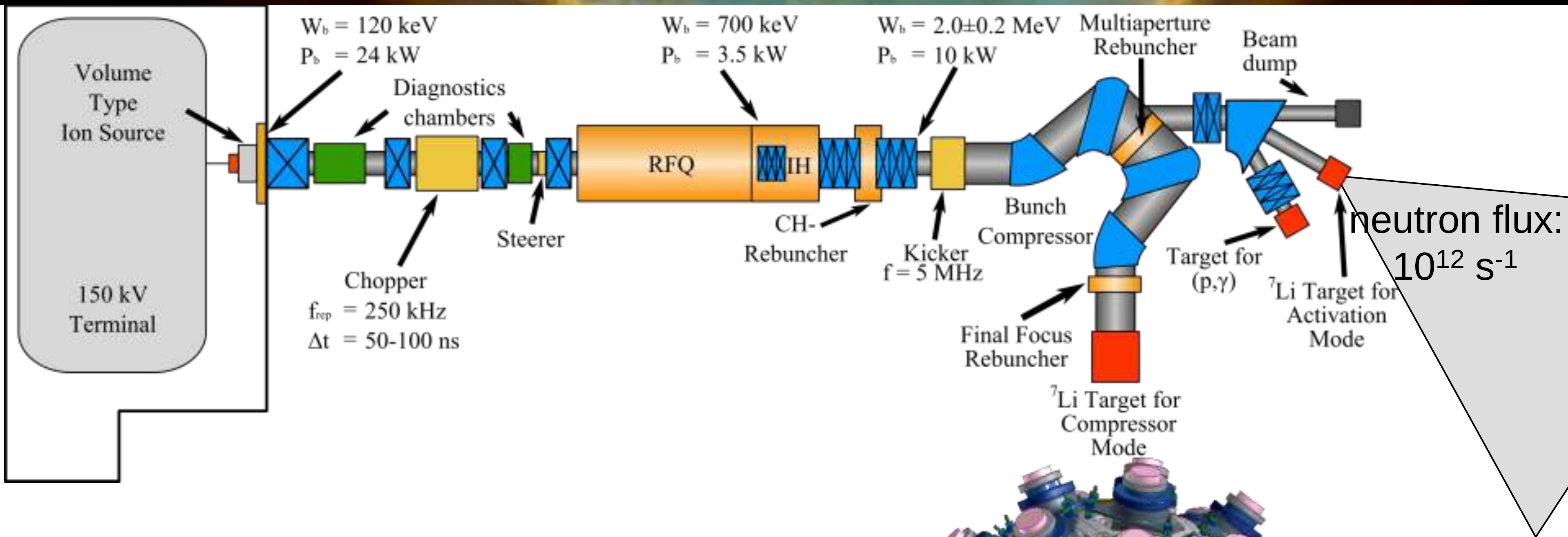


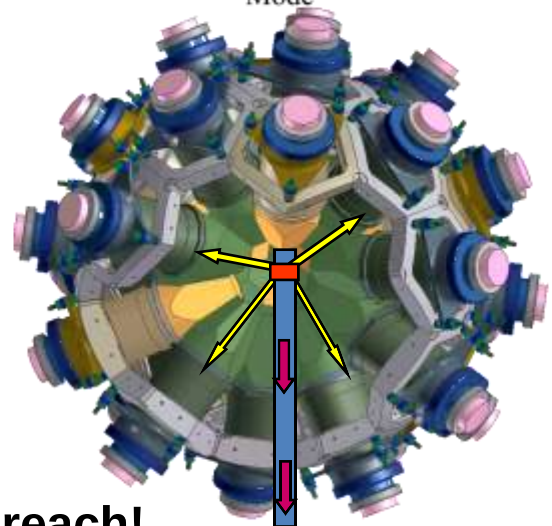


DANCE: M. Weigand, POS (NIC XII) 184
n-TOF: C. Lederer, PRL 110 (2013) 022501

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

GOETHE UNIVERSITÄT FRANKFURT AM MAIN



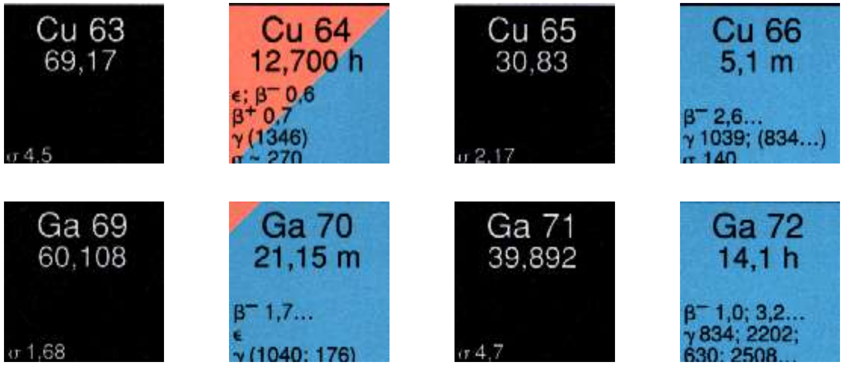


2 mA proton beam (8 A peak current)
250 kHz
< 1ns pulse width
neutron flux at 1 m: 10^7 s^{-1} cm^{-2}
neutron flux at 0.1m: 10^9 s^{-1} cm^{-2}

Isotopes with half-lives down to months are in reach!

R. Reifarth, PASA, 26 (2009) 255

Activation of natural samples at IRMM



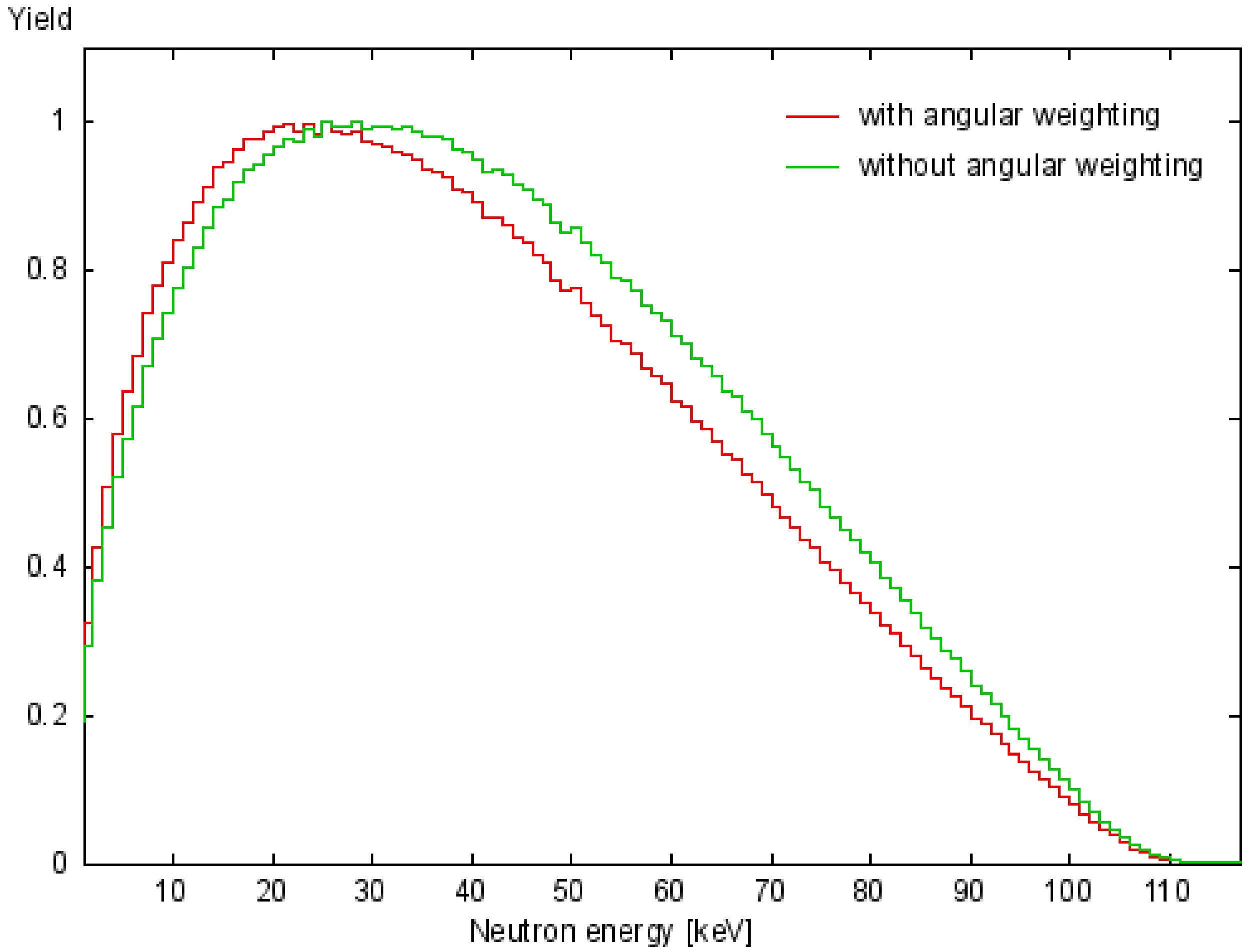
- **samples:**
  - Natural cupper
  - Natural gallium
- **Reference: ^{197}Au**
- **Lithium targets:**
  - Metallic
  - 1.1 and 27 µm

Master thesis: C. Beinrucker

- **Purpose:**
  - Invesitigate dicrepancies in previous data at 30 keV MACS
    - Factor 1.5 for ^{63}Cu between TOF and activation
    - Factor 1.3 for ^{65}Cu between TOF and activation
    - Factor 1.3 for ^{71}Ga between 2 activations
  - Determine activation cross section for 90 keV neutrons
  - Weak s-process

Neutron spectrum: kT = 25 keV

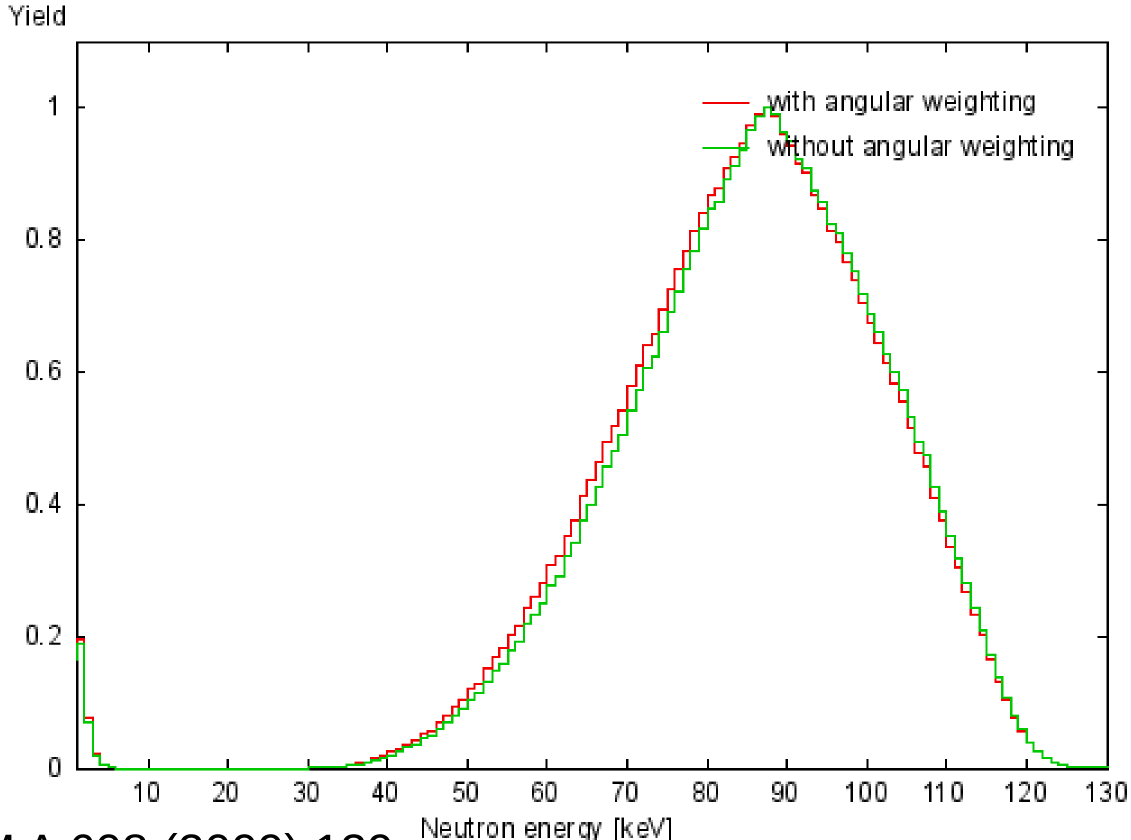
- **E_p=1912 keV, 27 µm Lithium, 2 mm distance**



R. Reifarth, NIM A 608 (2009) 139

Neutron spectrum: <E> = 90 keV

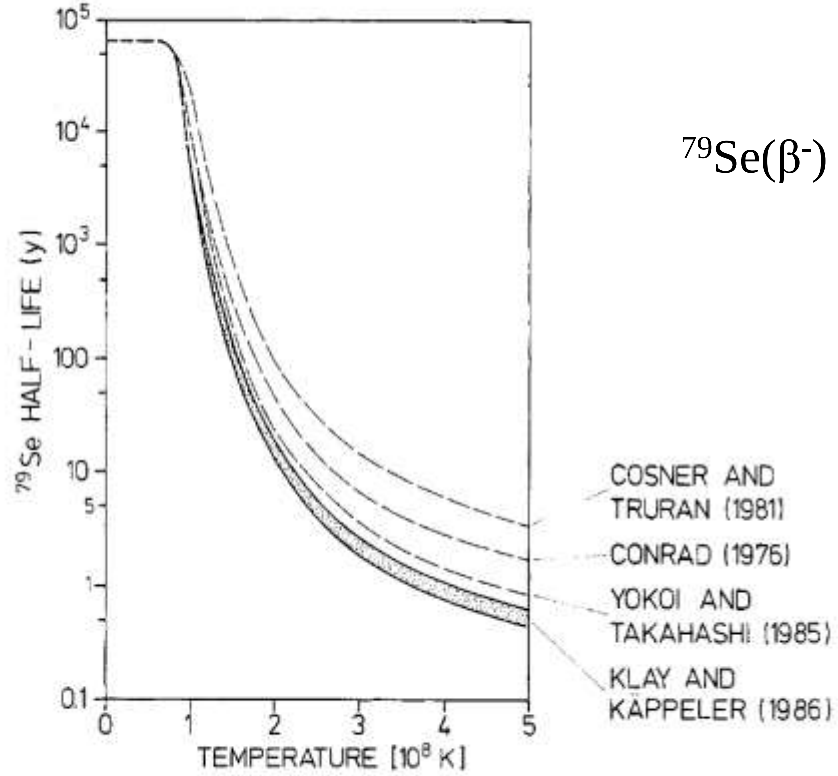
- **E_p=1920 keV, 1.15 µm Lithium, 10 mm distance**
- **Never done before for Cu, Ga**



R. Reifarth, NIM A 608 (2009) 139

Stellar half lives

- **stellar β-decay times 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)

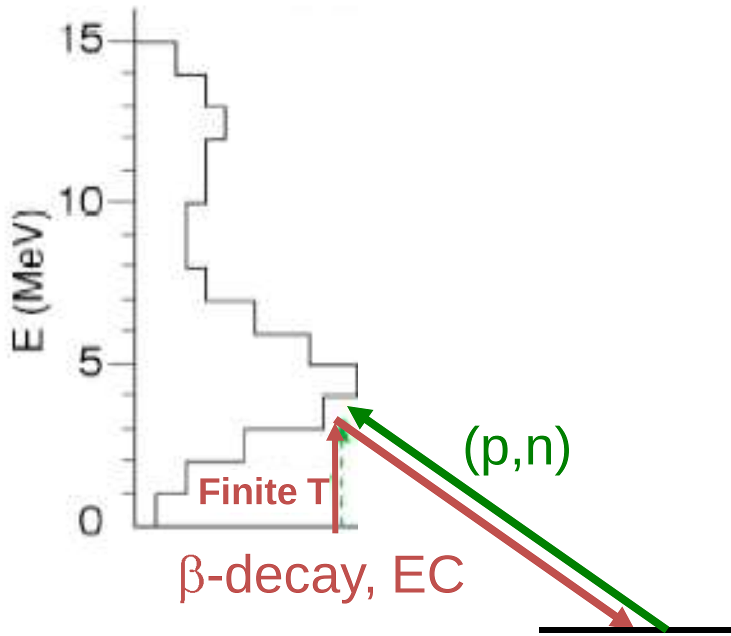
- **(β^-), (EC) with storage rings via Schottky analysis**
- **(β^+) from (p,n) reactions @ R^{3}B or storage rings**
- **(β^-) from (d,^{2}He) reactions @ R^{3}B or storage rings**

Experimental method: Charge exchange reactions

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

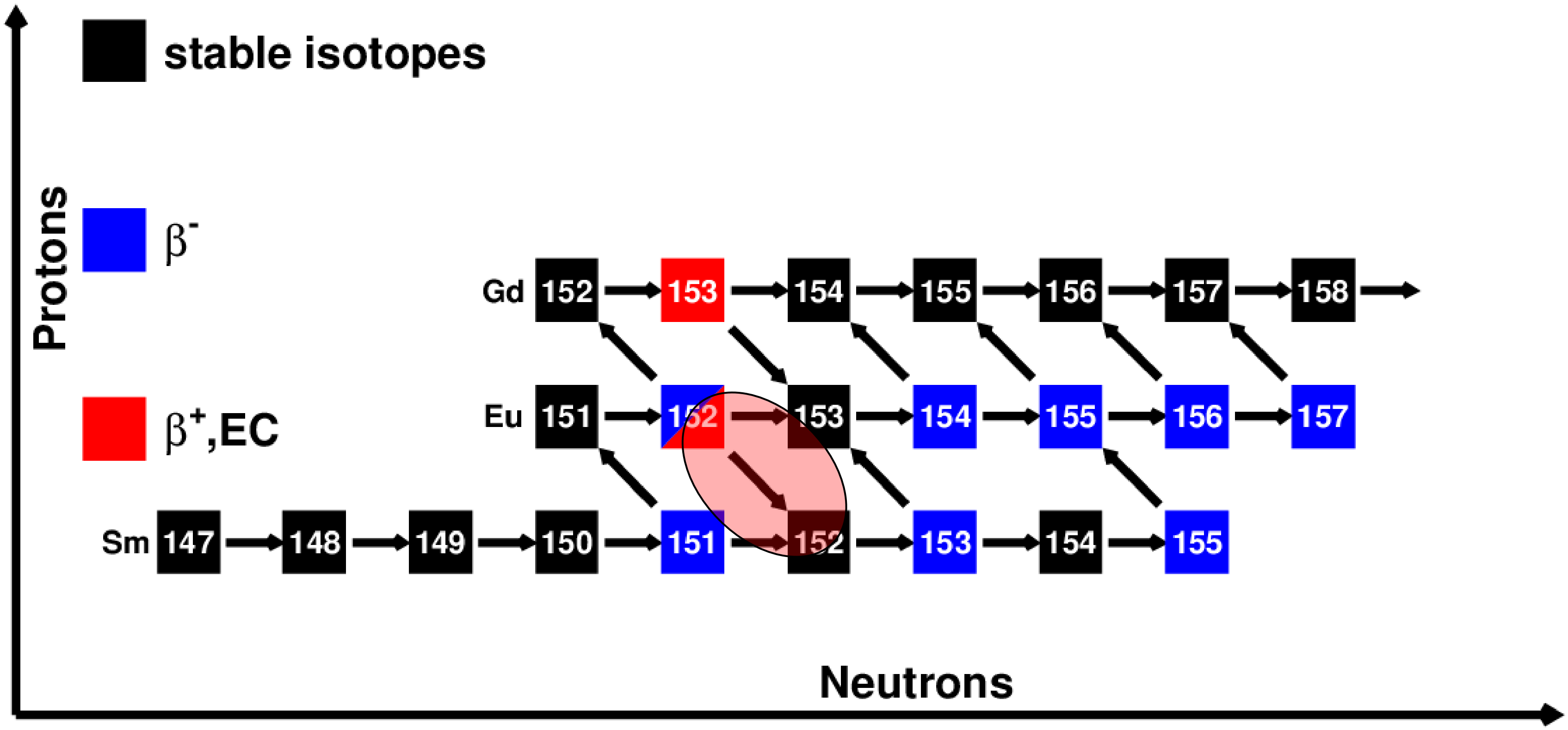
This **can not be measured** in the laboratory. **Theory is needed**!

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



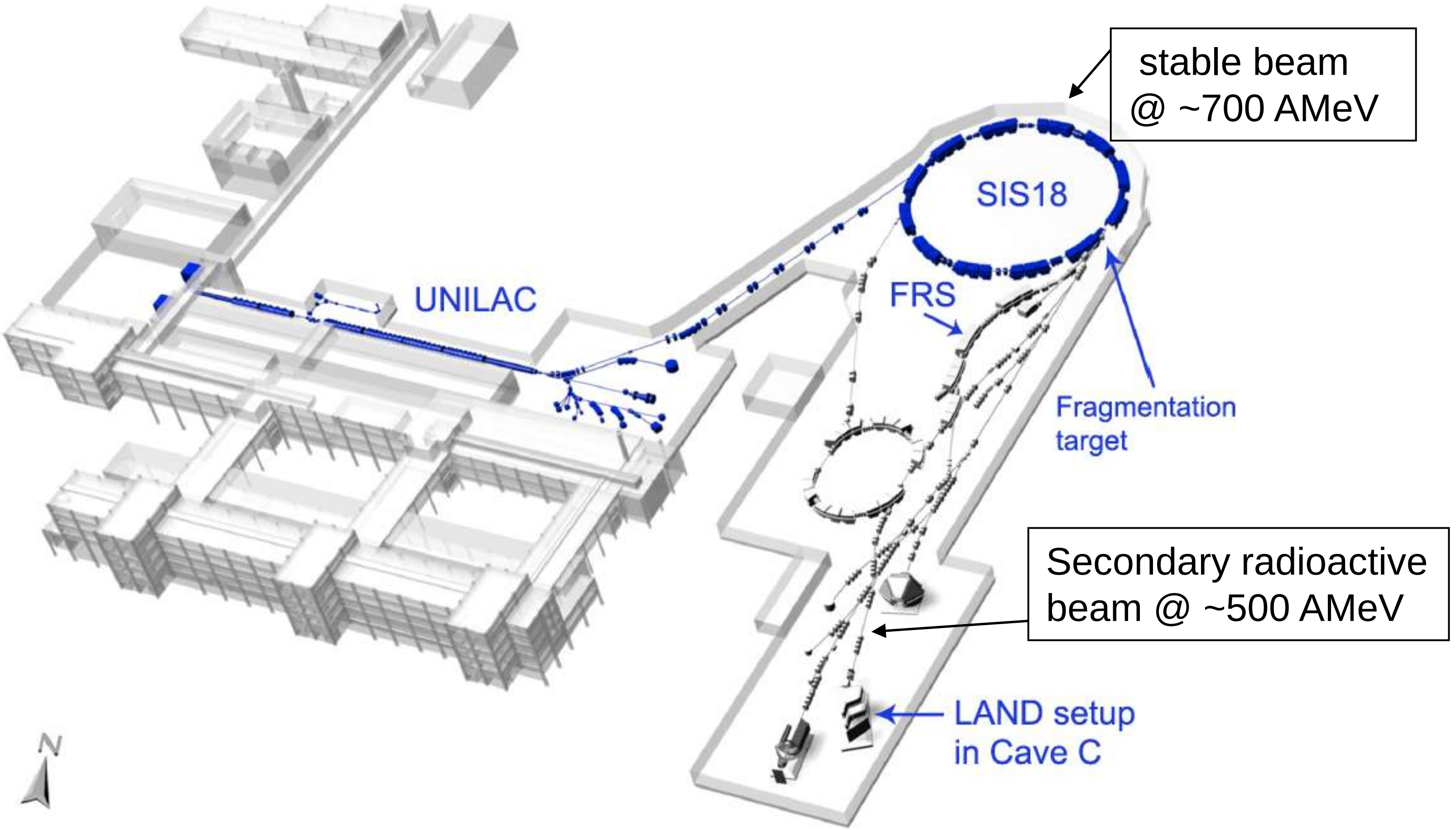
$$\frac{d\sigma^{CE}}{d\Omega}(q=0) = \hat{\sigma}_{GT}(q=0)B(GT)$$

The s-process around ^{152}Eu

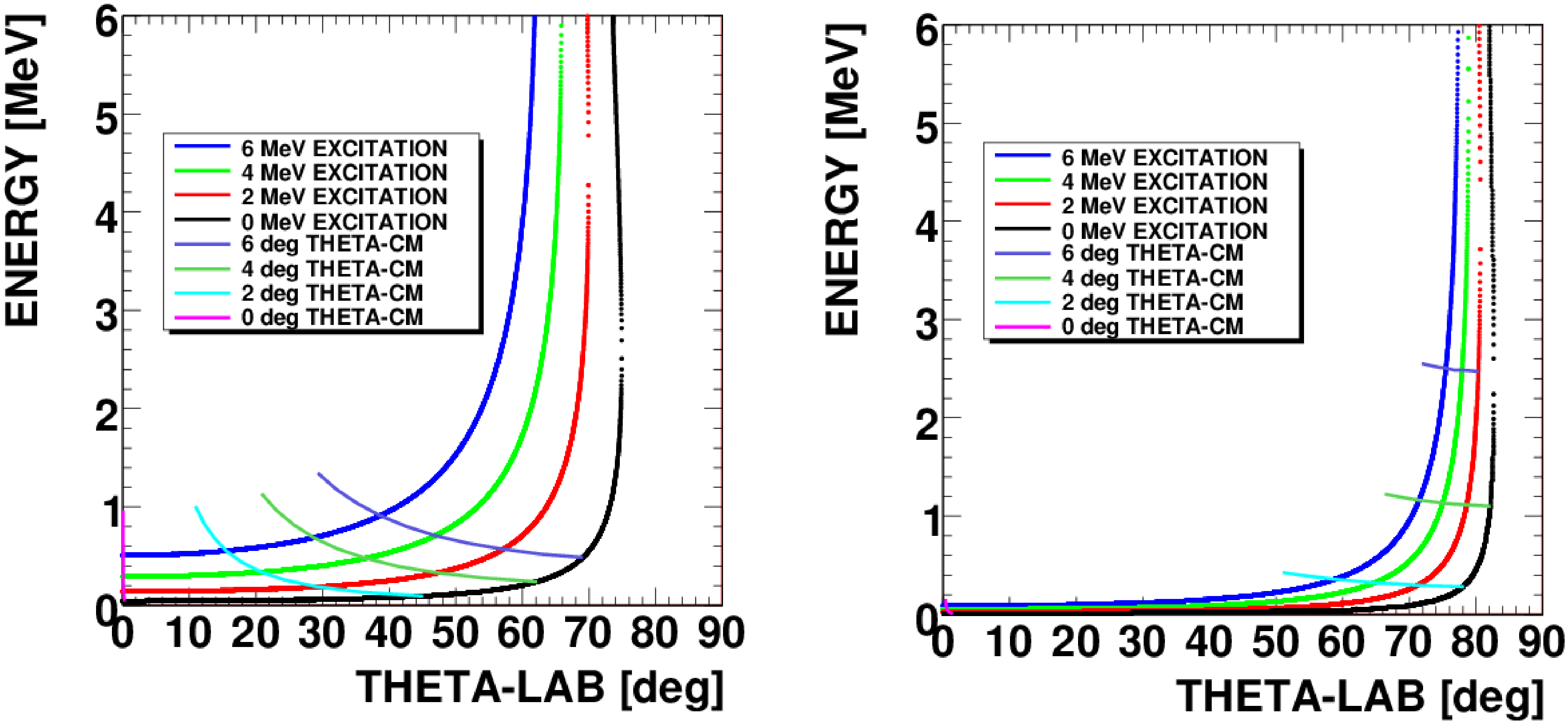


s-process nucleosynthesis in the region between iron and tin with the important branchings at ^{151}Sm and ^{152}Eu

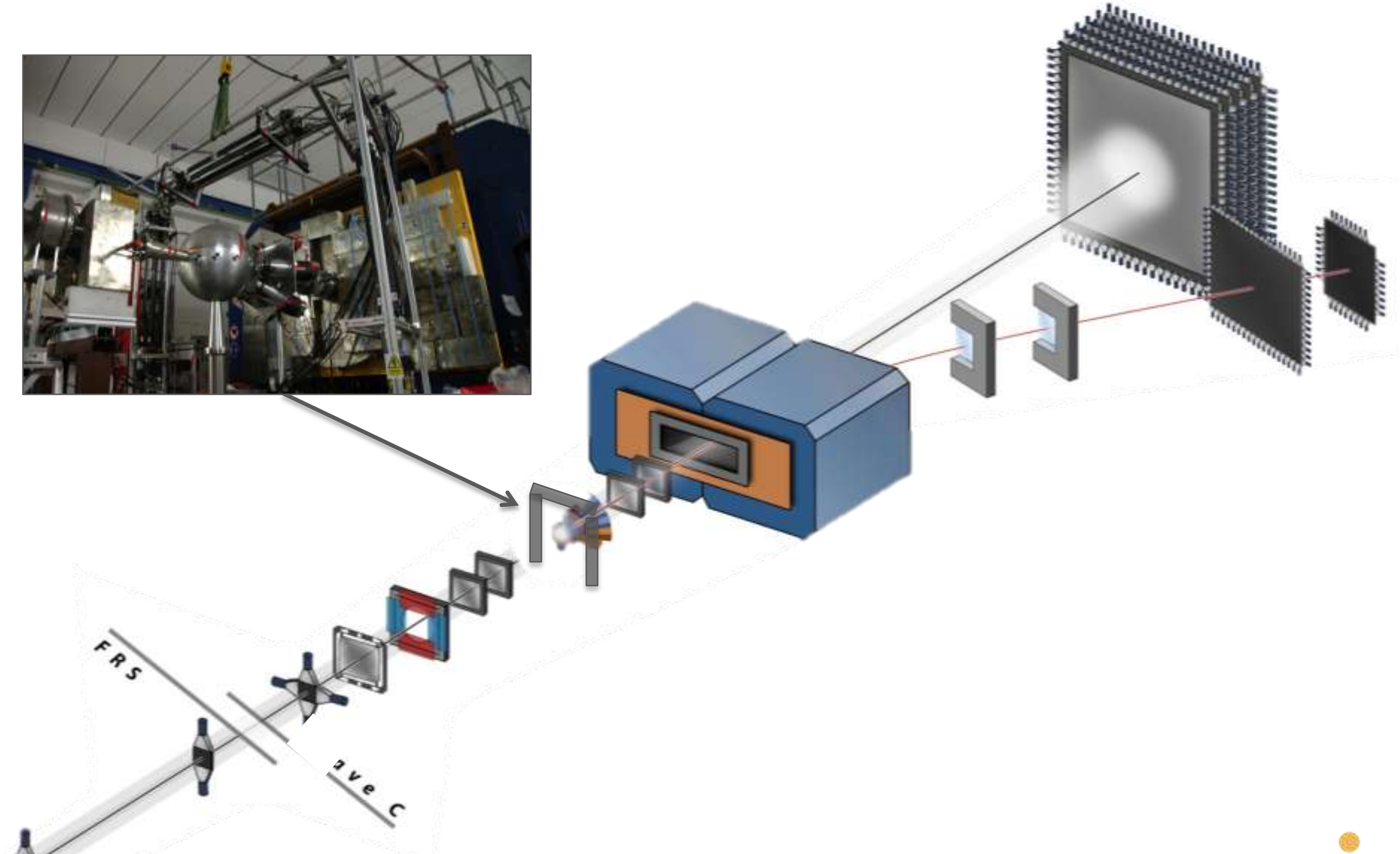
R^3B – unique environment to investigate reactions on exoctic isotopes @ GSI



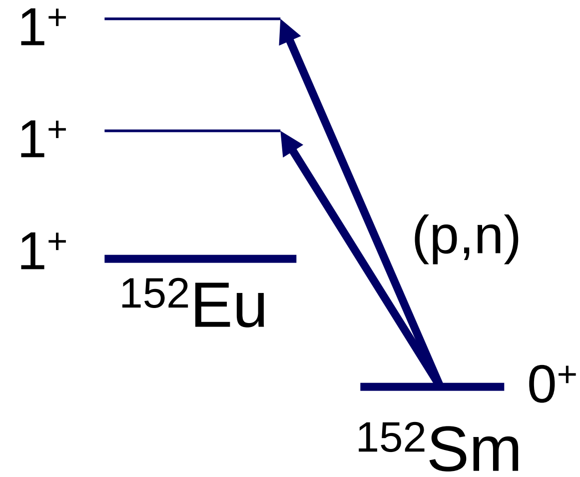
Energy vs. laboratory angle for the emitted neutrons



Charge exchange on ^{152}Sm



Charge exchange on ^{152}Sm



- test experiment performed last fall
- analysis in progress
- if successful - applicable to shorter half-lives

PhD thesis: M. Pohl

The i-process: p+^{12}C combustion

... this is not a new idea, just a bit forgotten ...

PRODUCTION OF ^{14}C AND NEUTRONS IN RED GIANTS

John J. Cowan and William K. Rose
Astronomy Program, University of Maryland, College Park

Received 1976 June 28

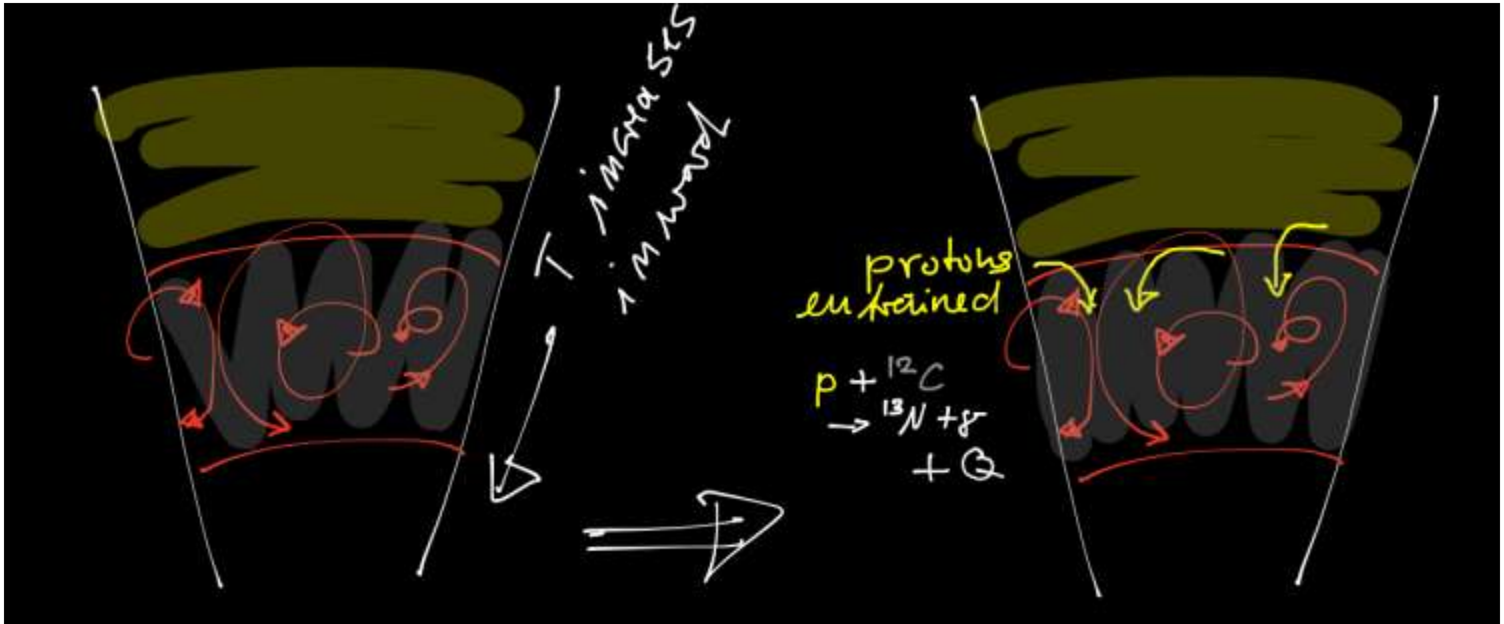
ABSTRACT

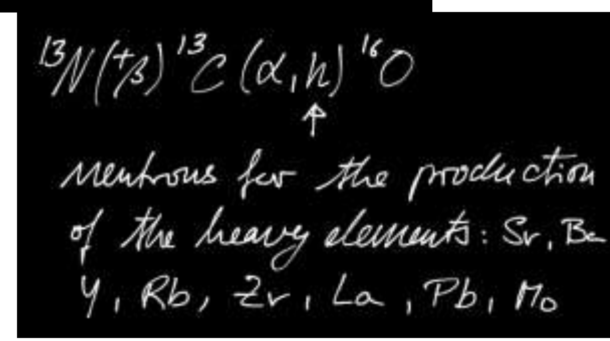
We have examined the effects of mixing various amounts of hydrogen-rich material into the intershell convective region of red giants undergoing helium shell flashes. We find that significant amounts of ^{14}C can be produced via the ^{14}N$(n, p)^{14}$C reaction. If substantial portions of this intershell region are mixed out into the envelopes of red giants, then ^{14}C may be detectable in evolved stars.

We find a neutron number density in the intershell region of $\sim 10^{15}$–10^{17} cm^{-3} and a flux of $\sim 10^{23}$–10^{25} cm^{-2} s^{-1}. This neutron flux is many orders of magnitude above the flux required for the classical *s*-process, and thus an intermediate neutron process (*i*-process) may operate in evolved red giants. The neutrons are principally produced by the ^{13}C$(\alpha, n)^{16}$O reaction.

In all cases studied we find substantial enhancements of ^{17}O. These mixing models offer a plausible explanation of the observations of enhanced ^{17}O in the carbon star IRC 10216. For certain physical conditions we find significant enhancements of ^{15}N in the intershell region.

H-entrainment into He-shell flash convection zone



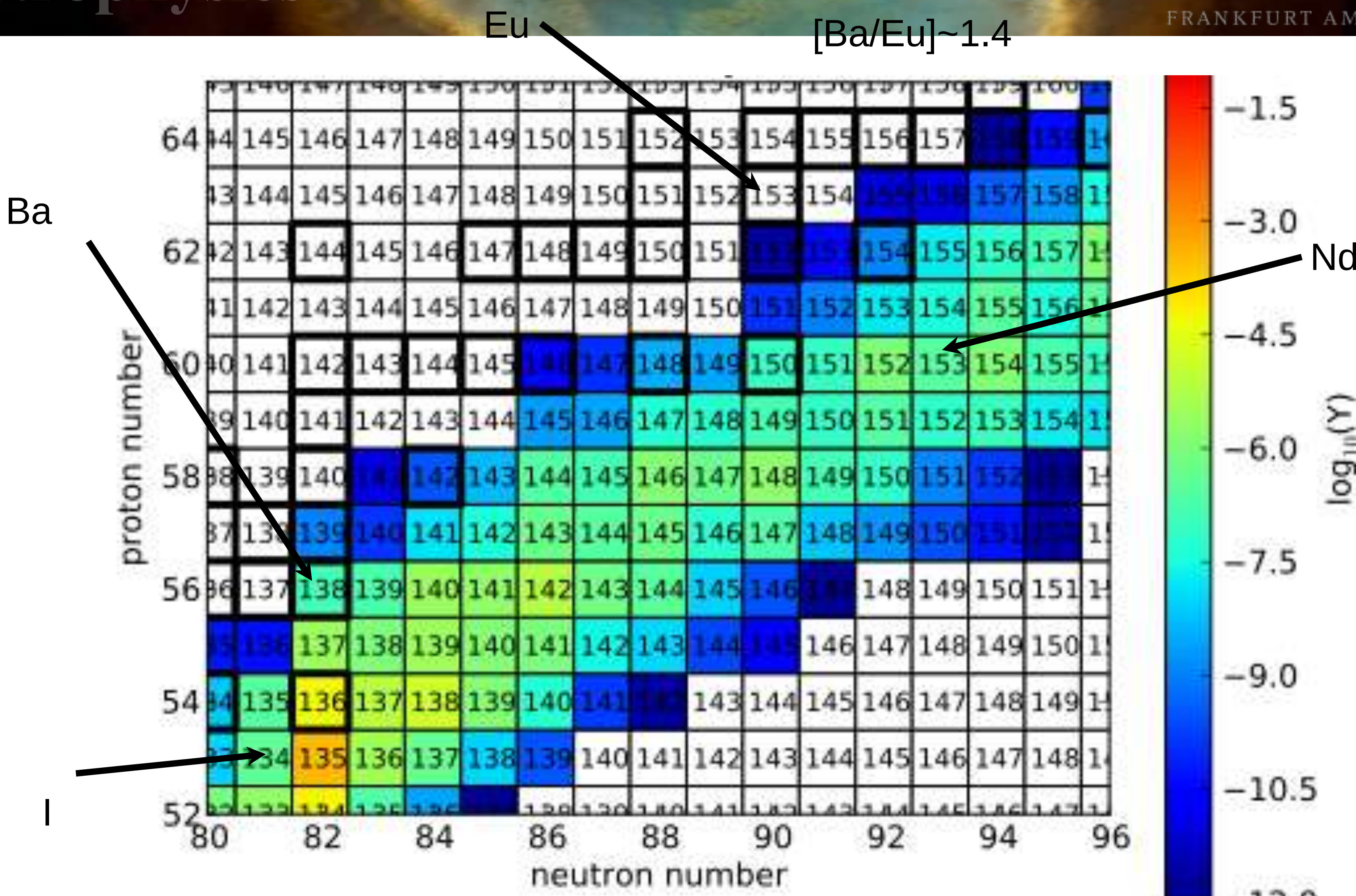


- **in AGB stars of very low metallicity, massive SN progenitor stars, post-AGB stars: *convective mixing entrains protons from stable layer above***
- **prototype of *convective-reactive combustion regime* increasingly believed to be an important regime especially in stars that formed in the early Universe (from F. Herwig – lecture)**

s. also R. Stancliff

F. Herwig, The Astrophysical Journal 727 (2011) 89

The i-process path

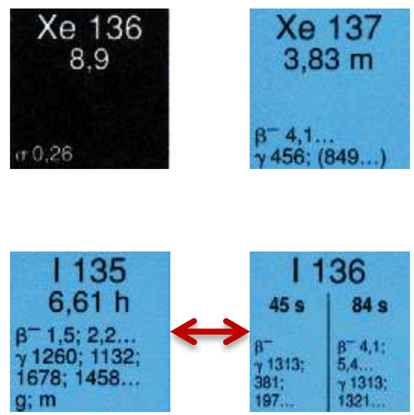


F. Herwig, The Astrophysical Journal 727 (2011) 89

(n,γ) from (γ,n)

Time-inversed method advantageous if:

- **Product of neutron capture is ALSO radioactive**
- **Half life is short**
- **Example: ^{135}I(n,γ)^{136}I via ^{136}I(CD)^{135}I (during the i-process)**



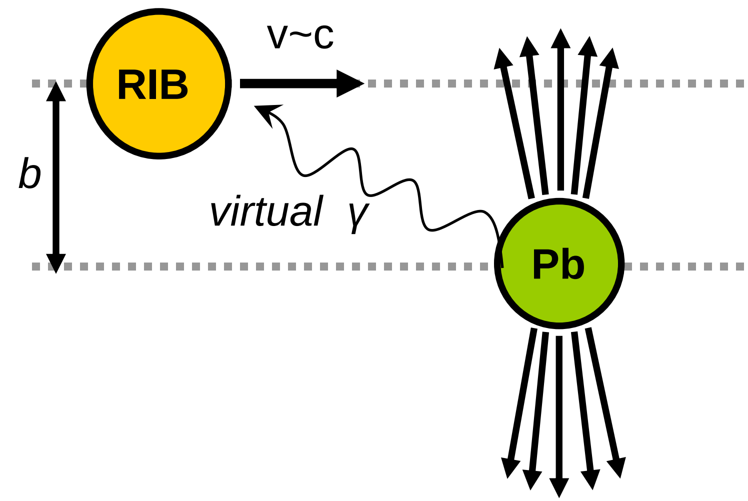
- **Setup: R^{3}B or potentially rings –** Y. Litvinow on Friday

Experimental method

Astrophysically relevant energy window: $E_\gamma \approx S_n + kT/2$ = 8-12 MeV, width ~ 1 MeV

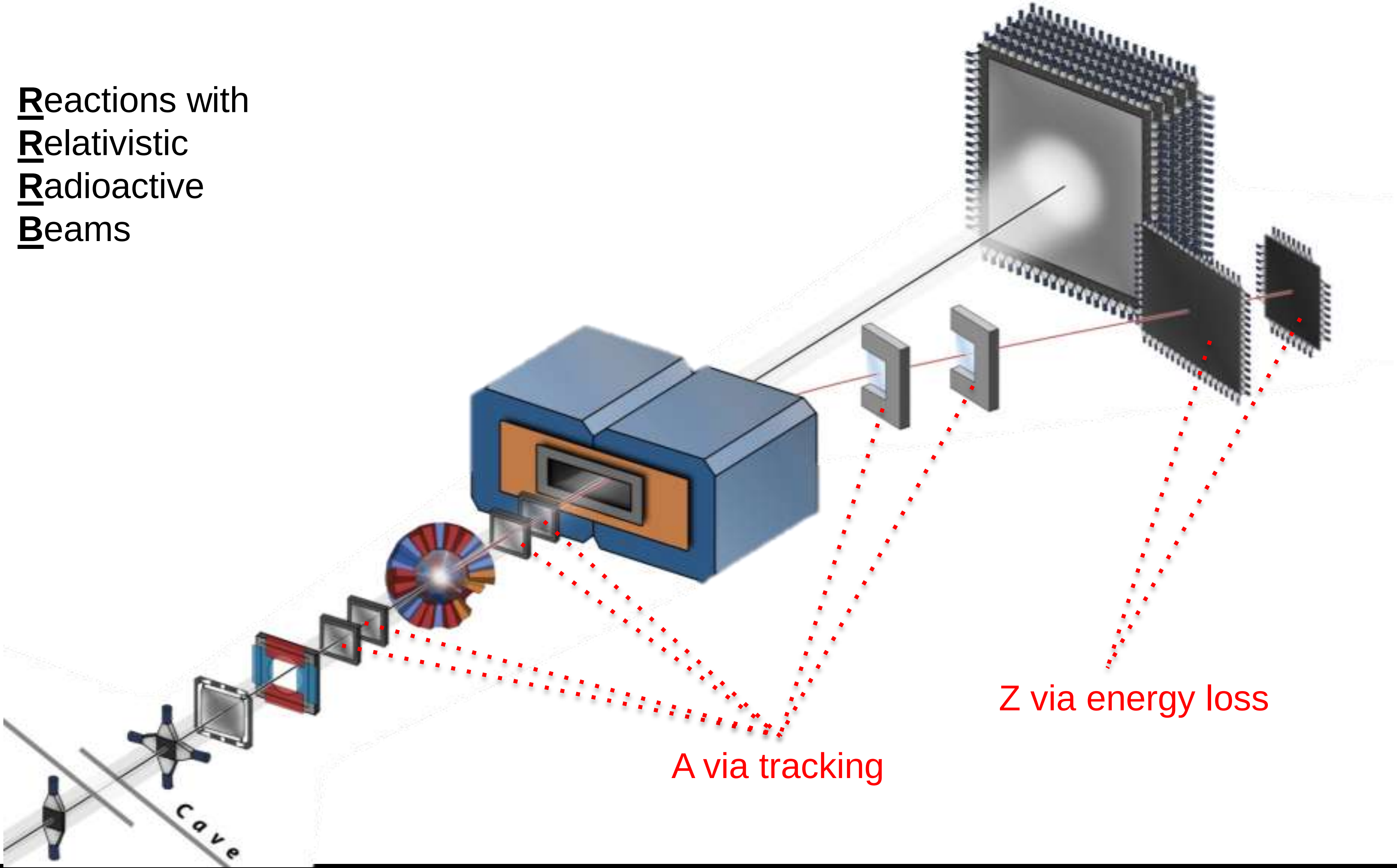
Coulomb dissociation in inverse kinematics:

- 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)

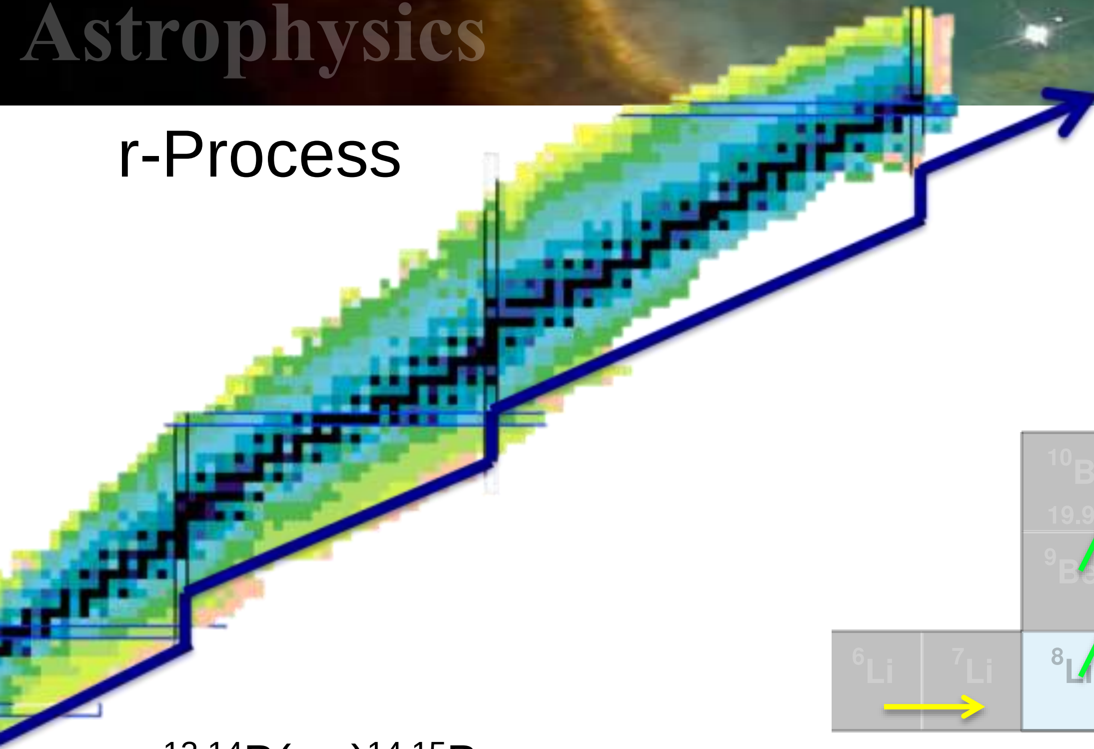


R³B @ GSI/FAIR

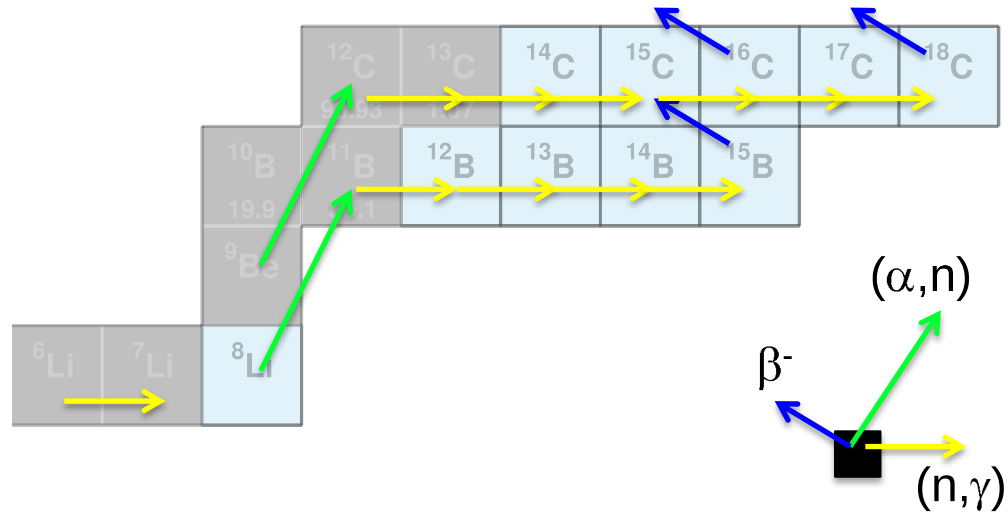
Reactions with
Relativistic
Radioactive
Beams



r-Process



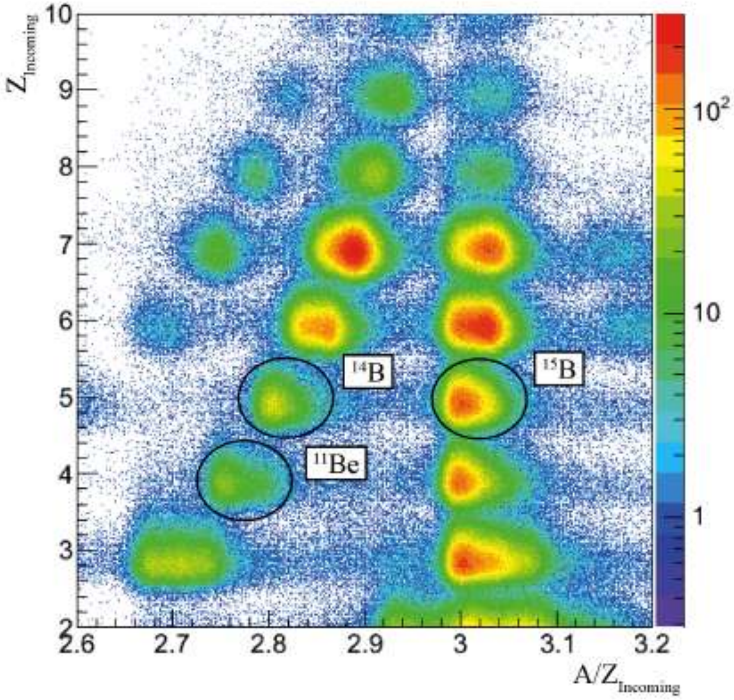
$^{13,14}B(n,\gamma)^{14,15}B$
Proc. of ND 2013
Sebastian Altstadt



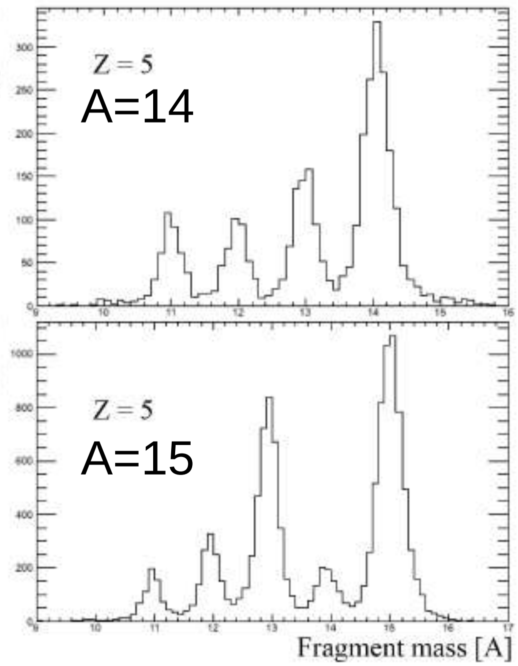
- $(n,\gamma) \longleftrightarrow \beta^-$
- time between 2 neutron captures ≈ ms
  ⇒ synthesize very neutron rich isotopes
- production ≈ 50% of the heavy elements

r-process and light isotopes

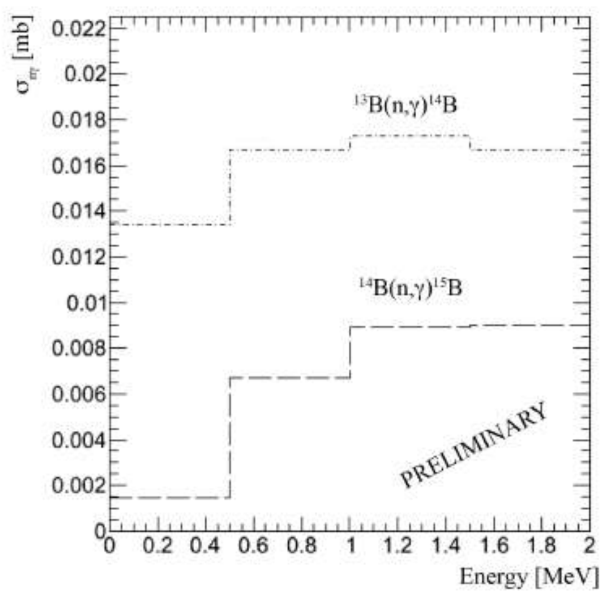
Incoming



Outgoing



(n,g) cross sections



Sebastian Altstadt, Proc. of Nuclear Data Conf. 2013

Summary

- **Nuclear data on radioactive isotopes are extremely important for modern astrophysics (reactions and masses)**
- **Direct investigations are very difficult**
- **Indirect methods for neutron-induced reactions cover the entire range from s- via i- to r-process**