The Stellar neutron capture of ^{60}Fe

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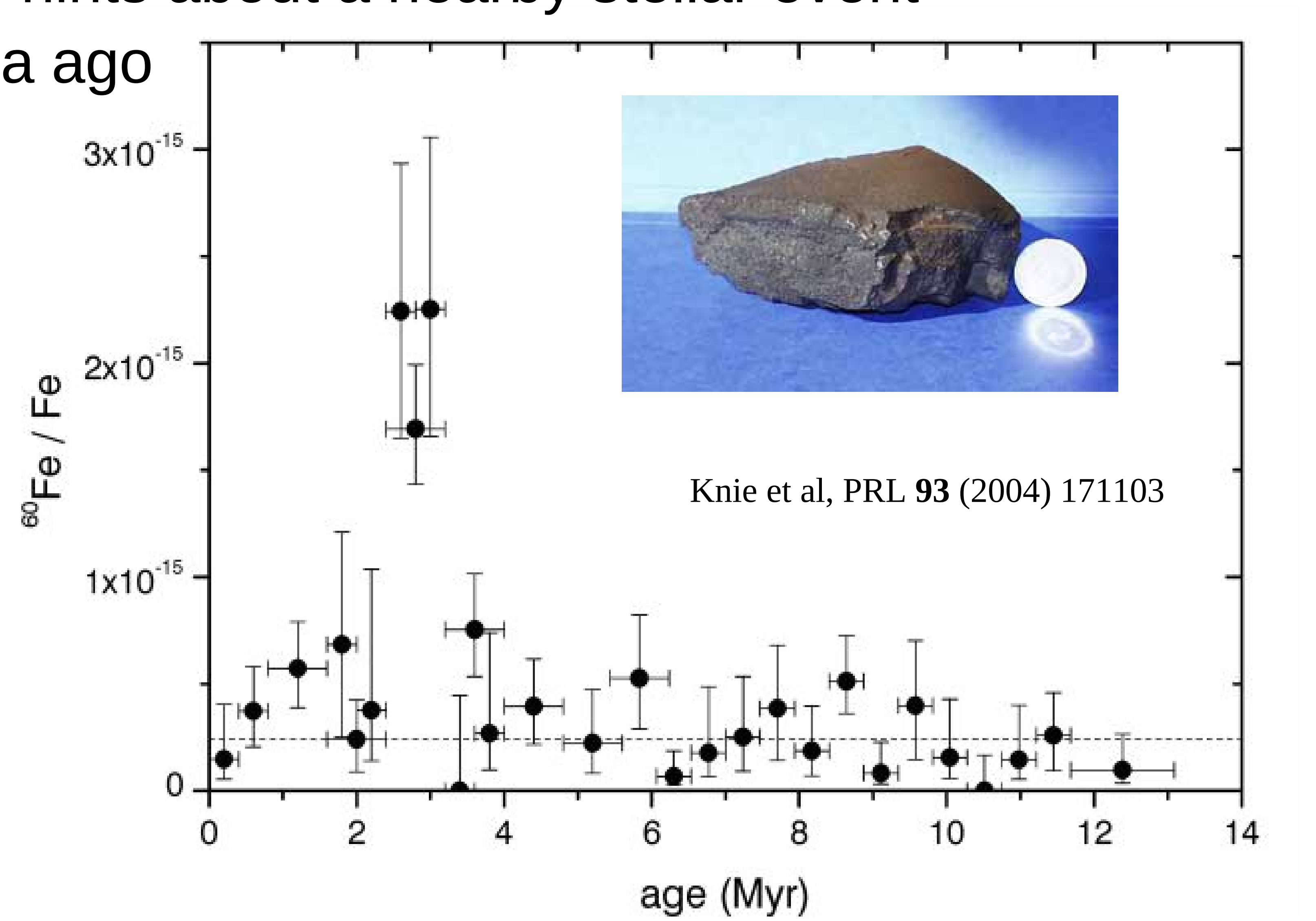
2nd workshop on
Exotic Radionuclides from Accelerator Waste
for Science and Technology
(ERAWAST II)
29.8.-2.9.2011 at Paul Scherrer Institute, Villigen, Switzerland

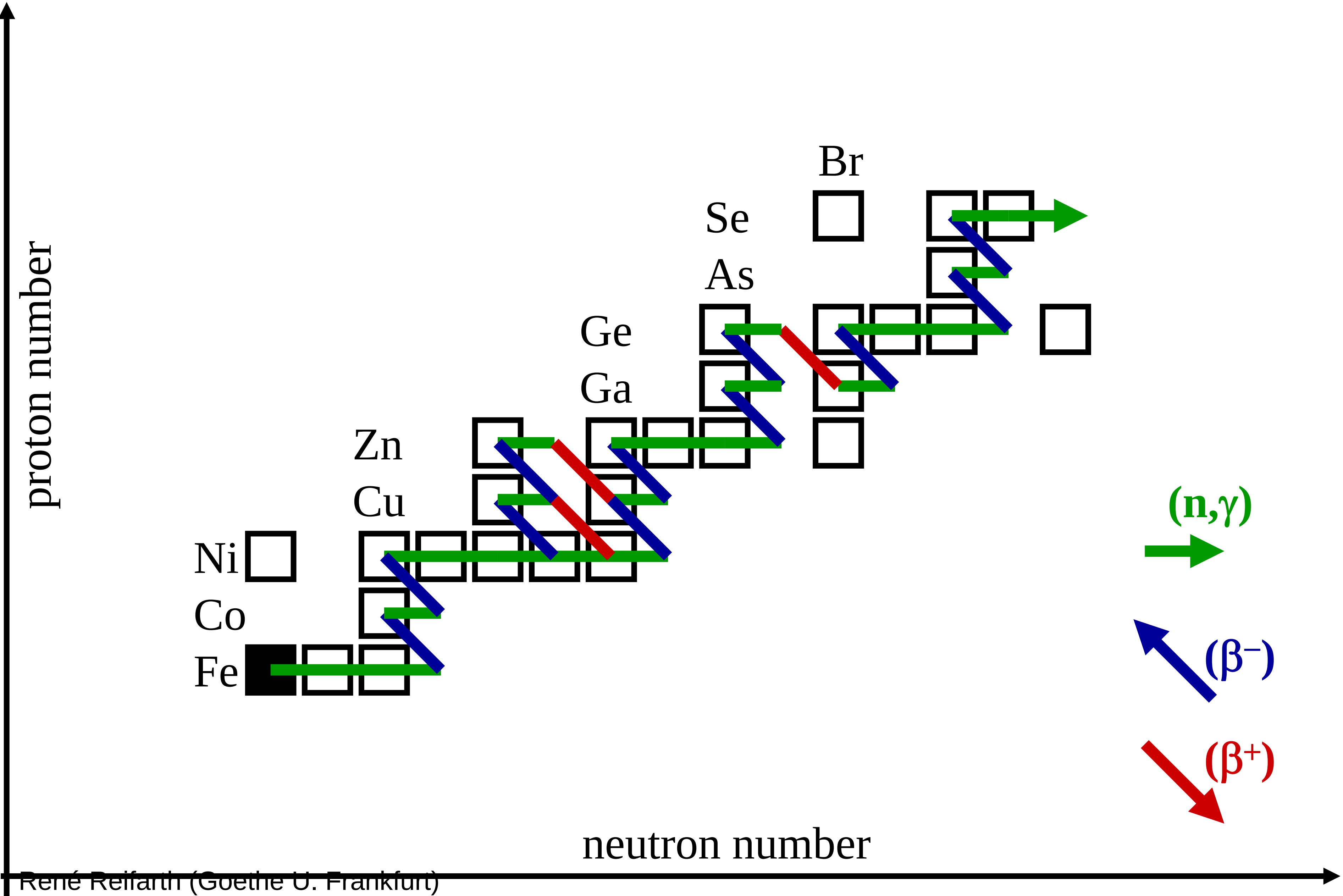
Motivation – ^{60}Fe on earth

- can be found in deep sea manganese crusts
- Gives hints about a nearby stellar event
- 2.8 Ma ago



Knie et al, PRL **93** (2004) 171103

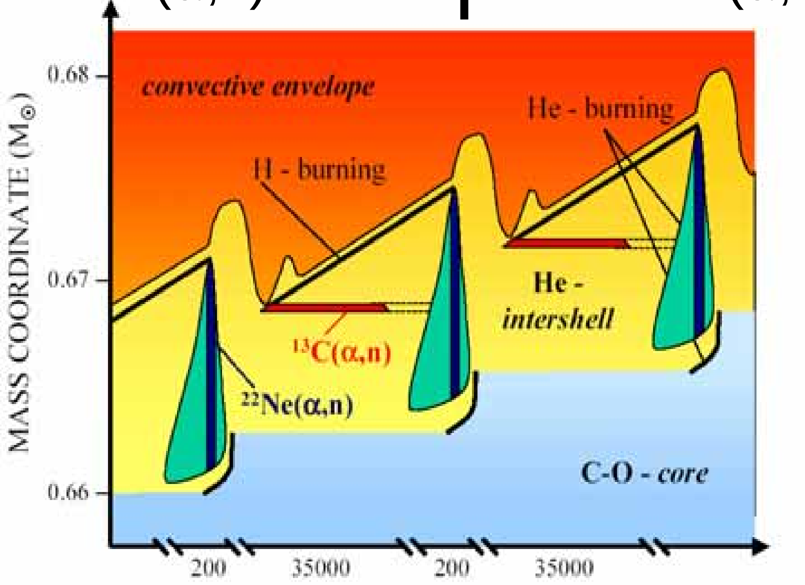
Motivation Astrophysics: the s-process

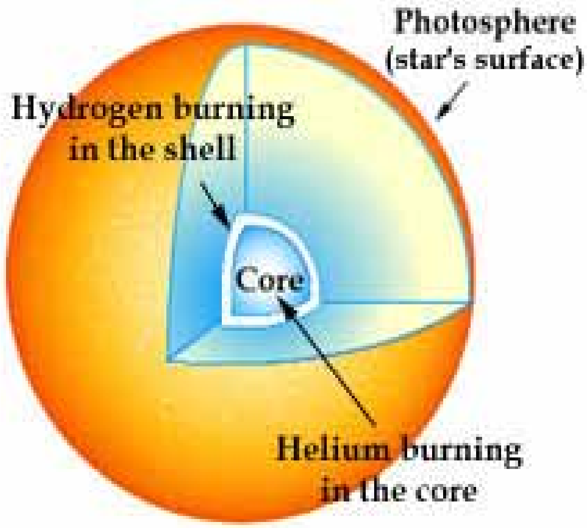


s-process nucleosynthesis

Two components were identified and connected to stellar sites:

Main s-process 90<A<210		**Weak s-process 60<A<90**	
TP-AGB stars 1-3 $M_\odot$		massive stars > 8 $M_\odot$	
shell H-burning	He-flash	core He-burning	shell C-burning
$0.9 \cdot 10^8$ K	$3\text{-}3.5 \cdot 10^8$ K	$3\text{-}3.5 \cdot 10^8$ K	$\sim 1 \cdot 10^9$ K
kT=8 keV	kT=25 keV	kT=25 keV	kT=90 keV
$10^7\text{-}10^8$ cm^{-3}	$10^{10}\text{-}10^{11}$ cm^{-3}	10^6 cm^{-3}	$10^{11}\text{-}10^{12}$ cm^{-3}
$^{13}C(\alpha,n)$	$^{22}Ne(\alpha,n)$	$^{22}Ne(\alpha,n)$	





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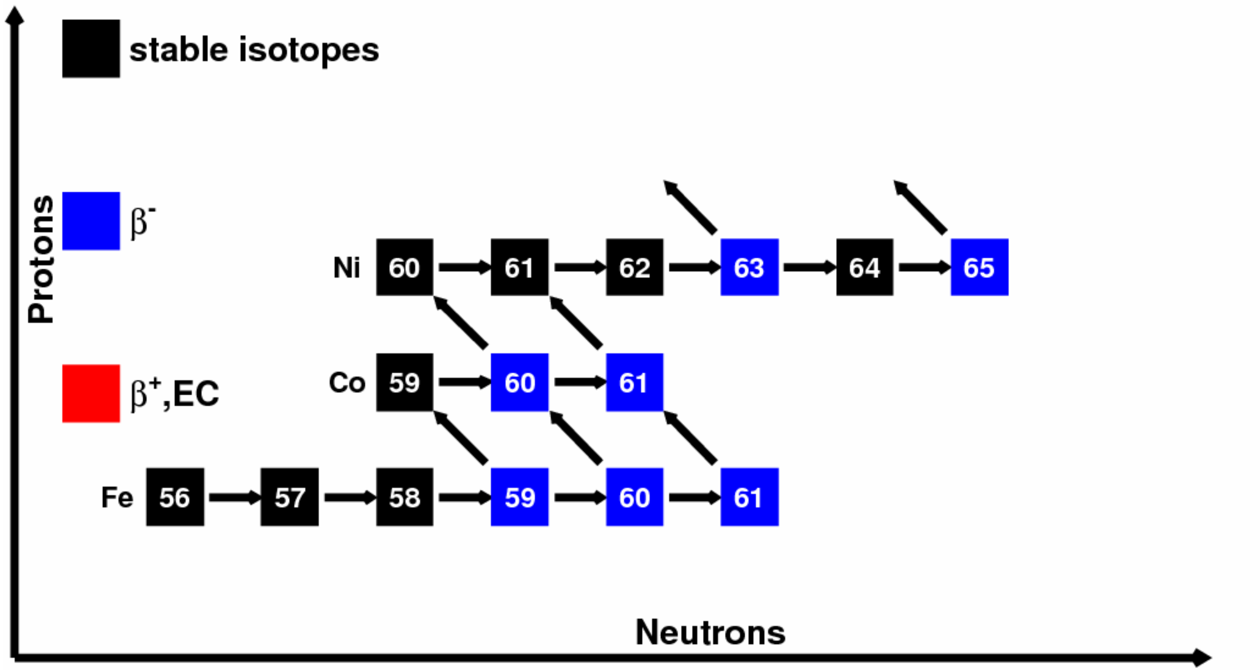
Production of ^{60}Fe

- Weak s-process component in massive stars
- C-shell burning
- ^{60}Fe(n,γ) cross section needed – ***no experimental data available yet (estimates: 1-10 mb)***



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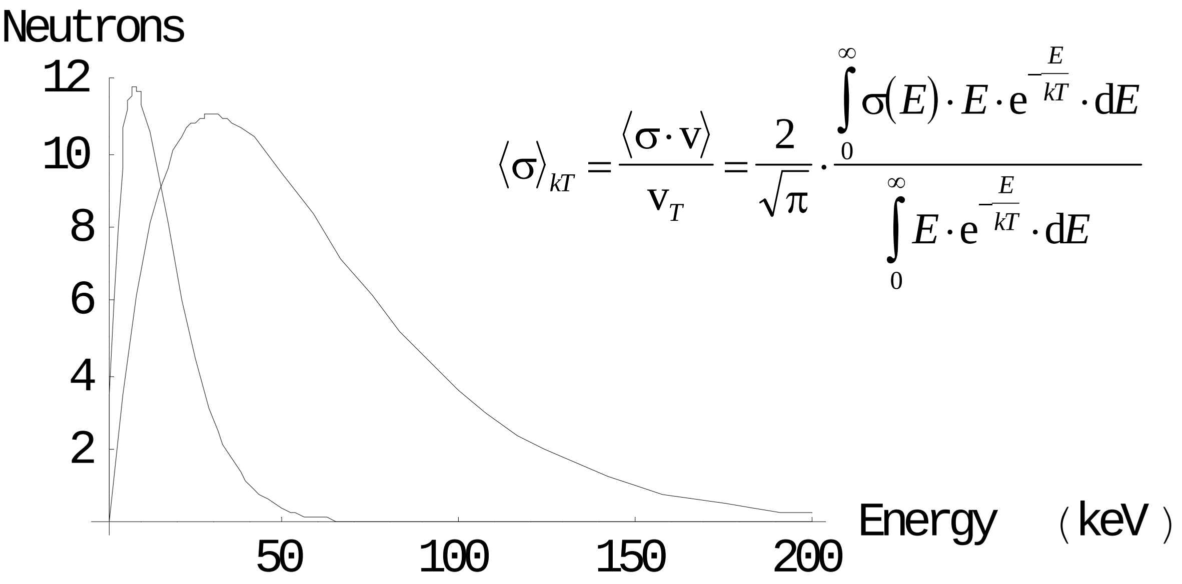
What nuclear physics input is needed?

- Ideally: differential (n,γ) cross sections for neutron energies of 1-300 keV



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

Sample

- 13.6 10^{15} atoms **^{60}Fe** (1.3 µg) ($t_{1/2}$ = 2.62 Ma)
- Retrieved from proton-irradiated copper beam stop (PSI) – ERAWAST!
- carrier: ^{nat}Fe, C
- active impurities:
  - ^{55}Fe ($t_{1/2}$ = 2.7 y)
  - ^{60}Co (ingrowth)
- 6 mm diameter

activation only (presently) feasible method

Activation Method

^{60}Fe(n,γ)^{61}Fe reaction detected via **^{61}Fe(β$^-$)^{61}Co** decay ($t_{1/2}$=6.0 min)

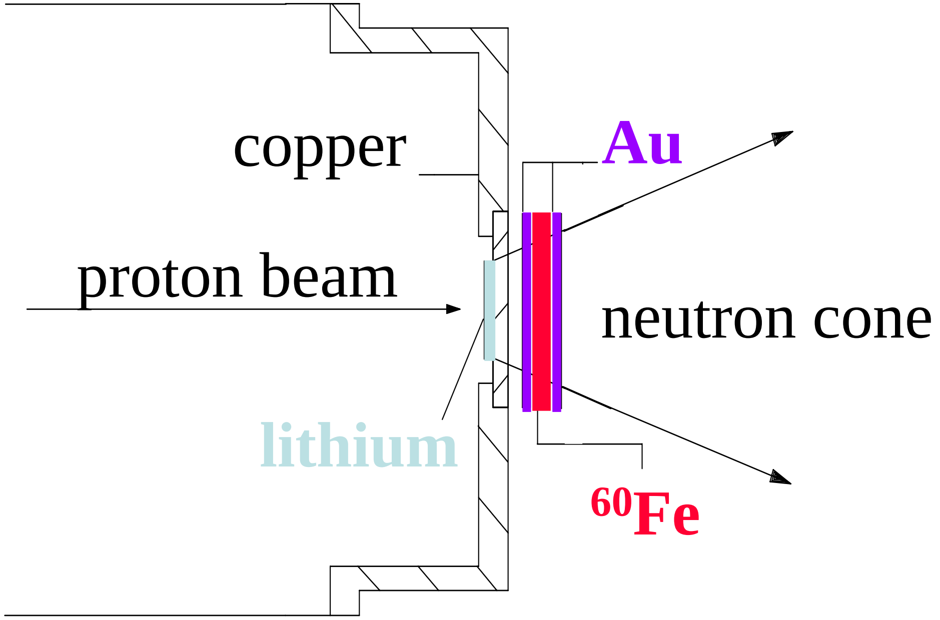
Determination of neutron flux via

^{197}Au(n,γ)^{198}Au

Neutron source:

^{7}Li(p,n)^{7}Be

^{60}Fe sample irradiated 40 times for 15 min, then activity counted for 10 min



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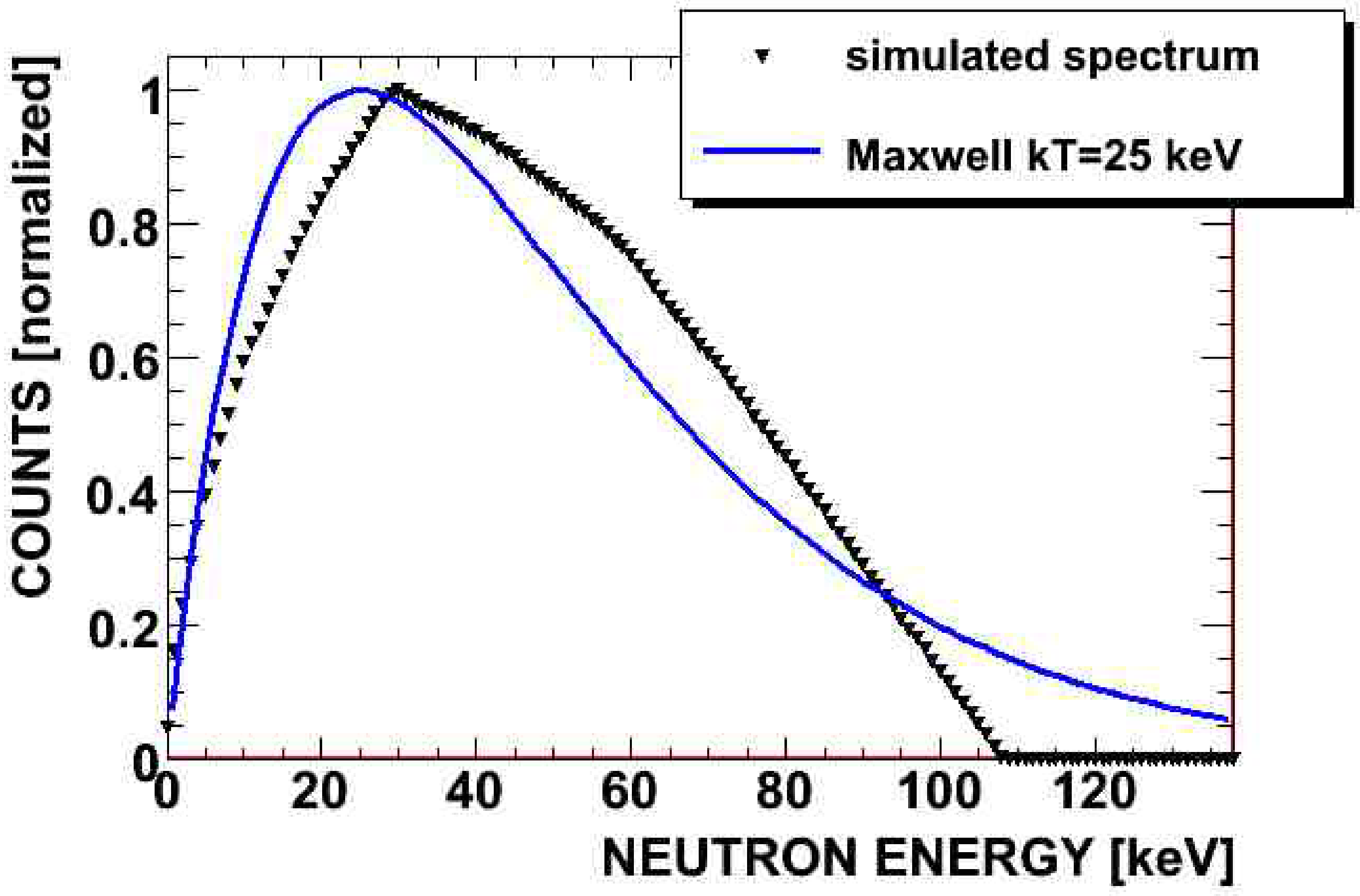
Neutron spectrum



Quasi-Maxwellian averaged distribution:

kT = **25 keV**

E_{max} = **110 keV**

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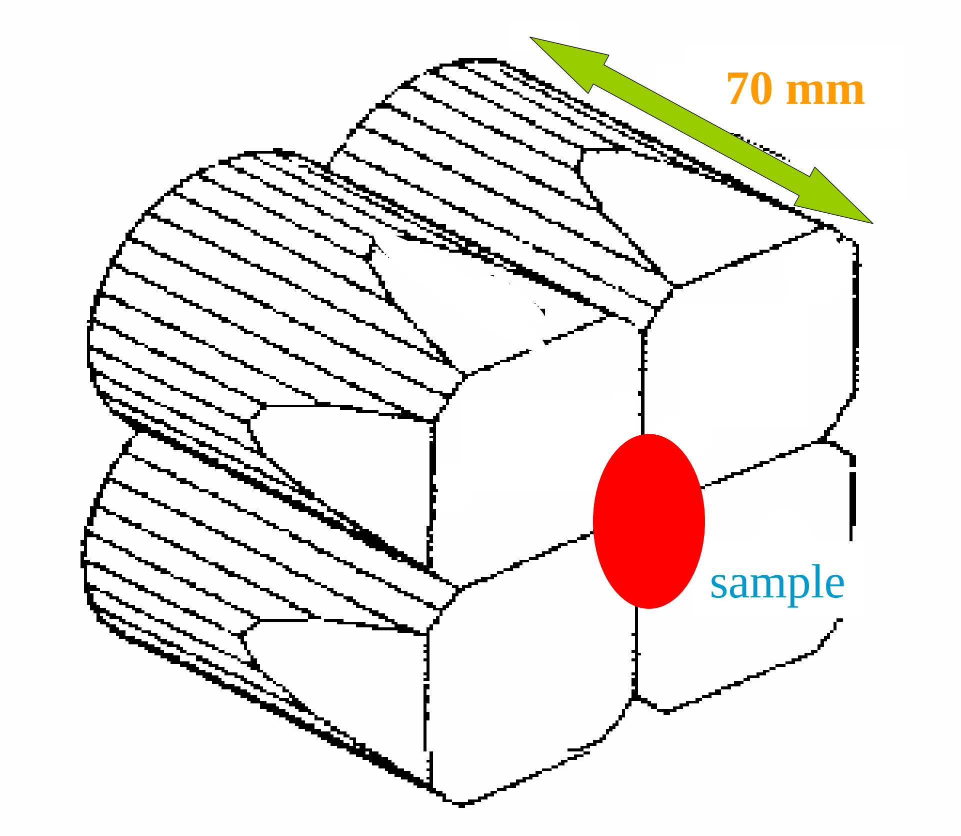
γ-detection



2 Ge-Clovers, face to face

Efficiency @ 1115 keV:

single crystal:

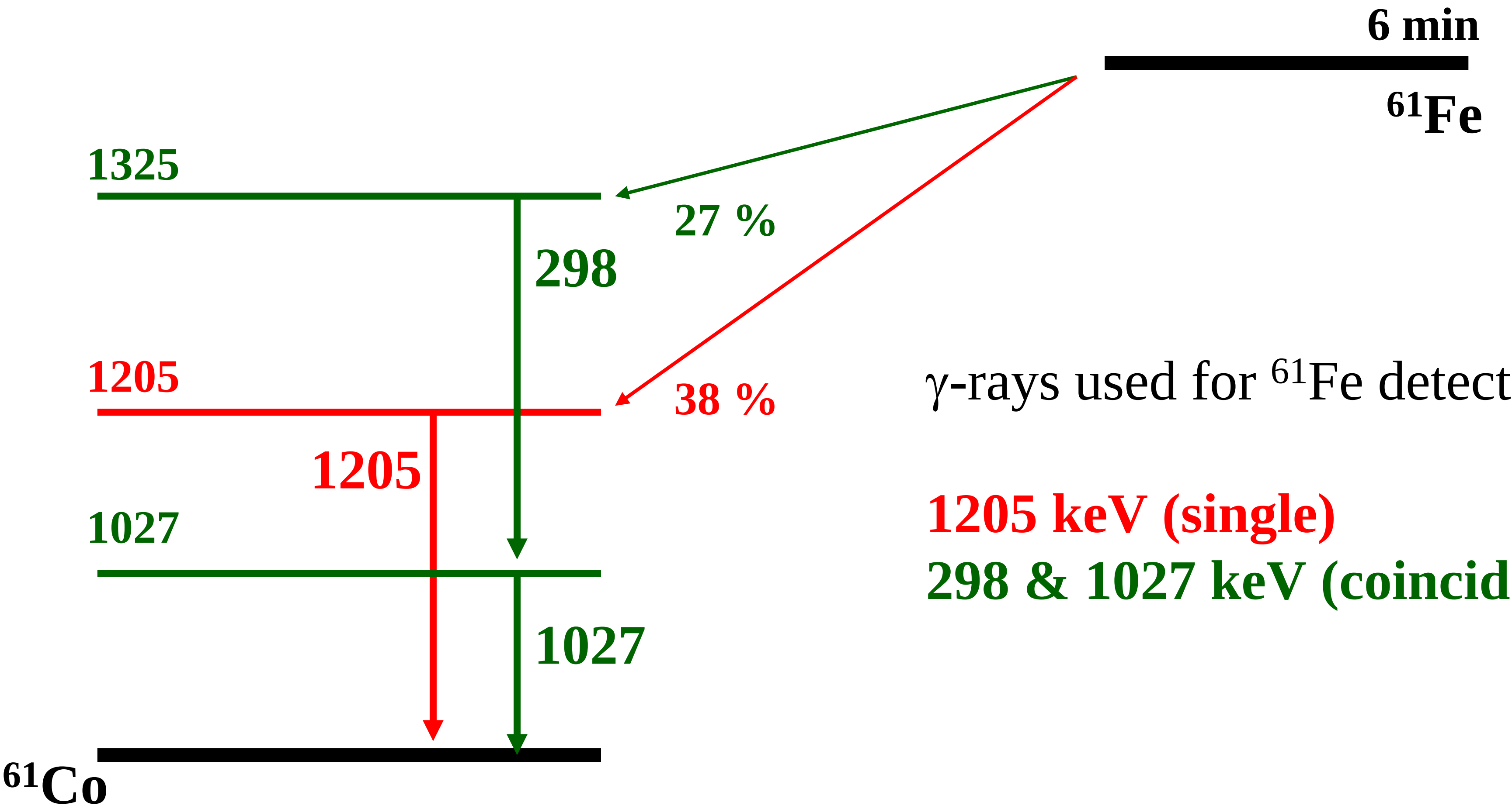
ε_{tot} = 11 %

ε_{peak} = 1.1 %

addback:

ε_{peak} = 15 %

^{61}Fe decay



γ-rays used for ^{61}Fe detection:

1205 keV (single)

298 & 1027 keV (coincidence)

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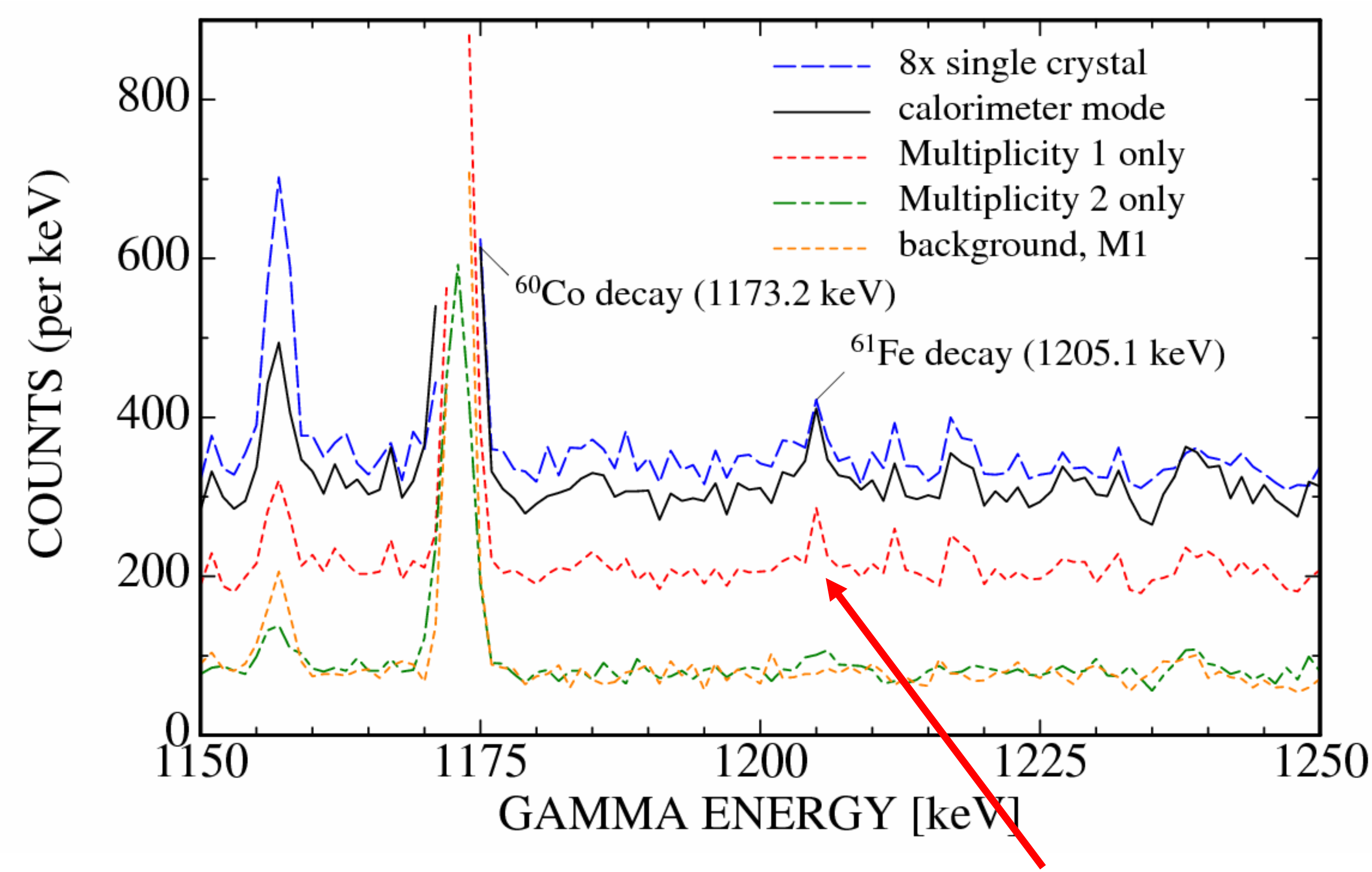
Single spectra

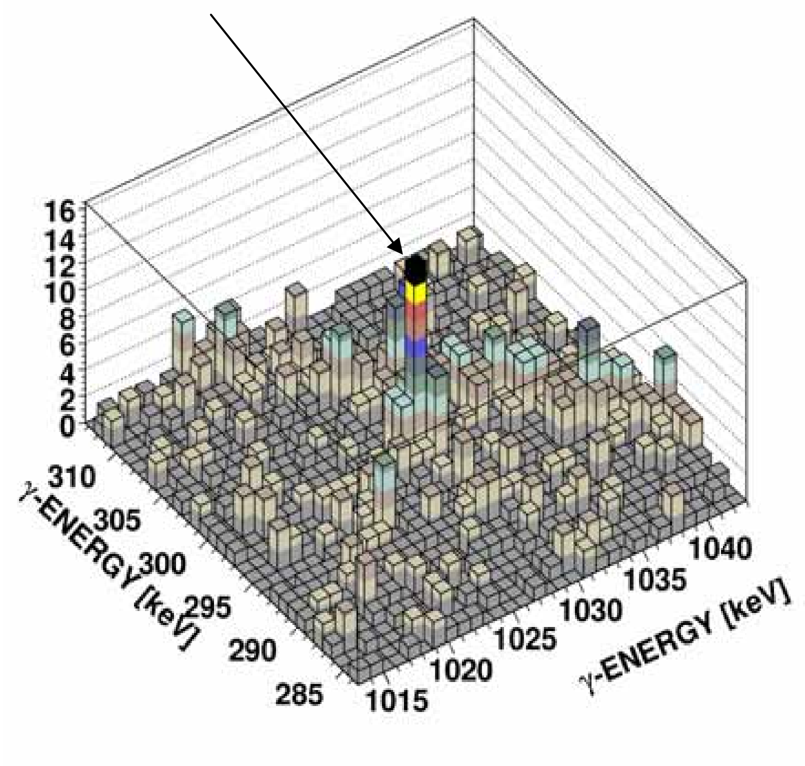


1205 keV (single)

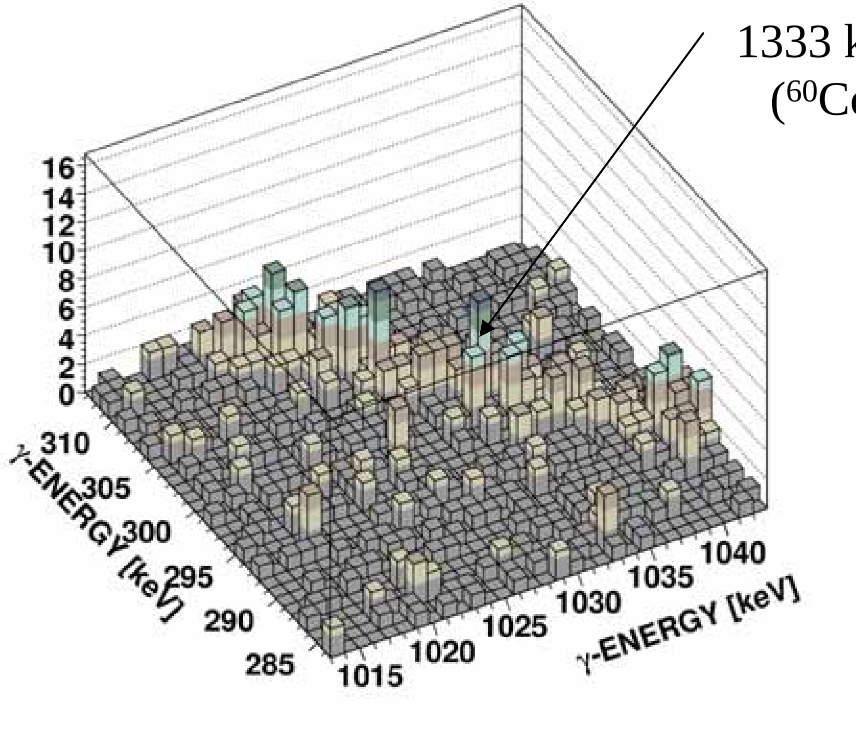
Coincidences: 298 & 1027 keV

- almost no background
- significantly reduced counts

^{61}Fe



Sample background only



1333 keV
(^{60}Co)

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Results

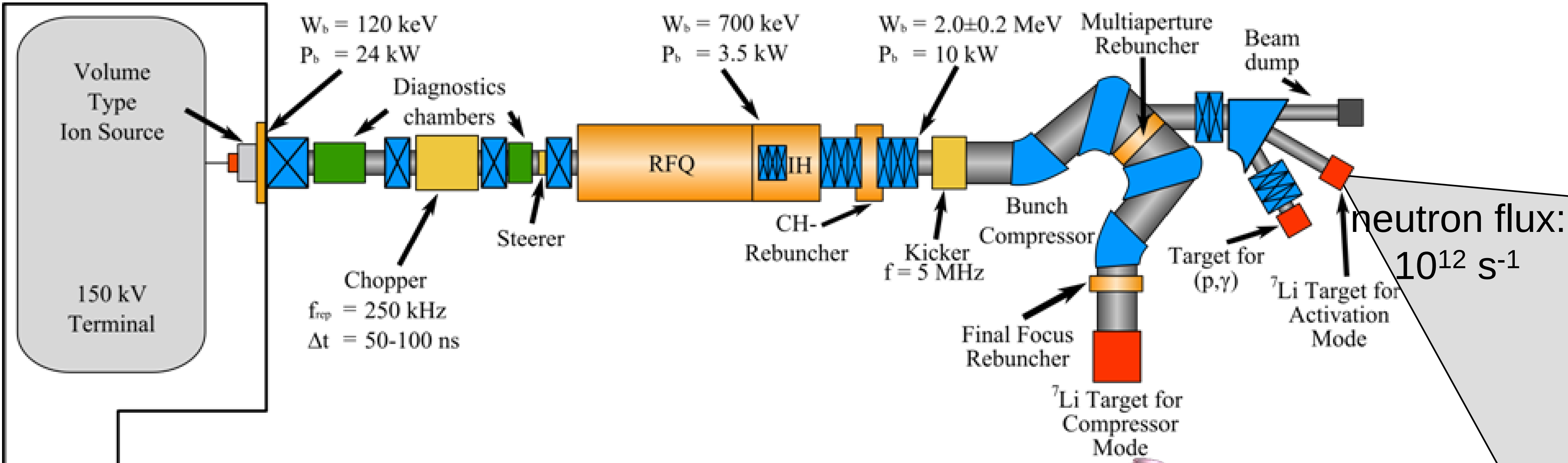
- **5.84 (1.1^{sys}) (0.8^{stat}) mb for experimental spectrum**
- **Extrapolation to Maxwellian spectra necessarily based on theoretical energy dependence**

Future developments - neutrons

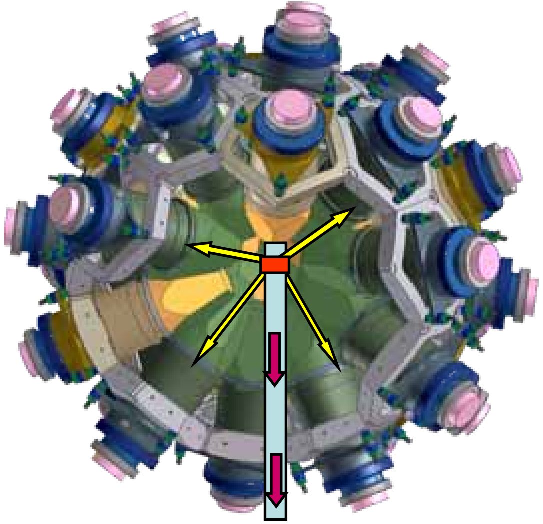
- if $t_{1/2}$ goes down: Activity ~ atoms/ $t_{1/2}$ goes up
- hence: number of atoms needs to go down
- since: captures ~ atoms * neutrons

- **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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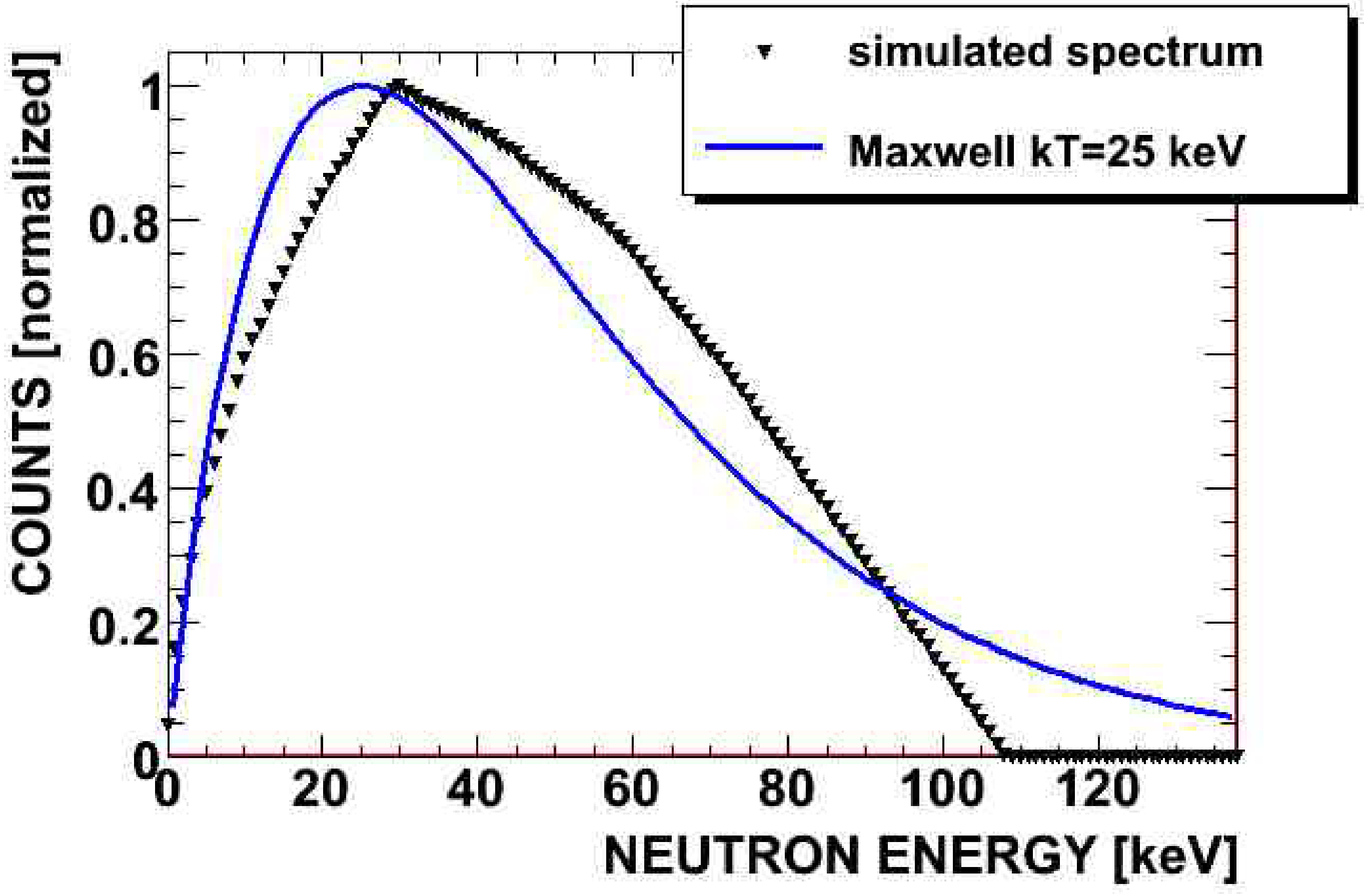
Neutron spectrum

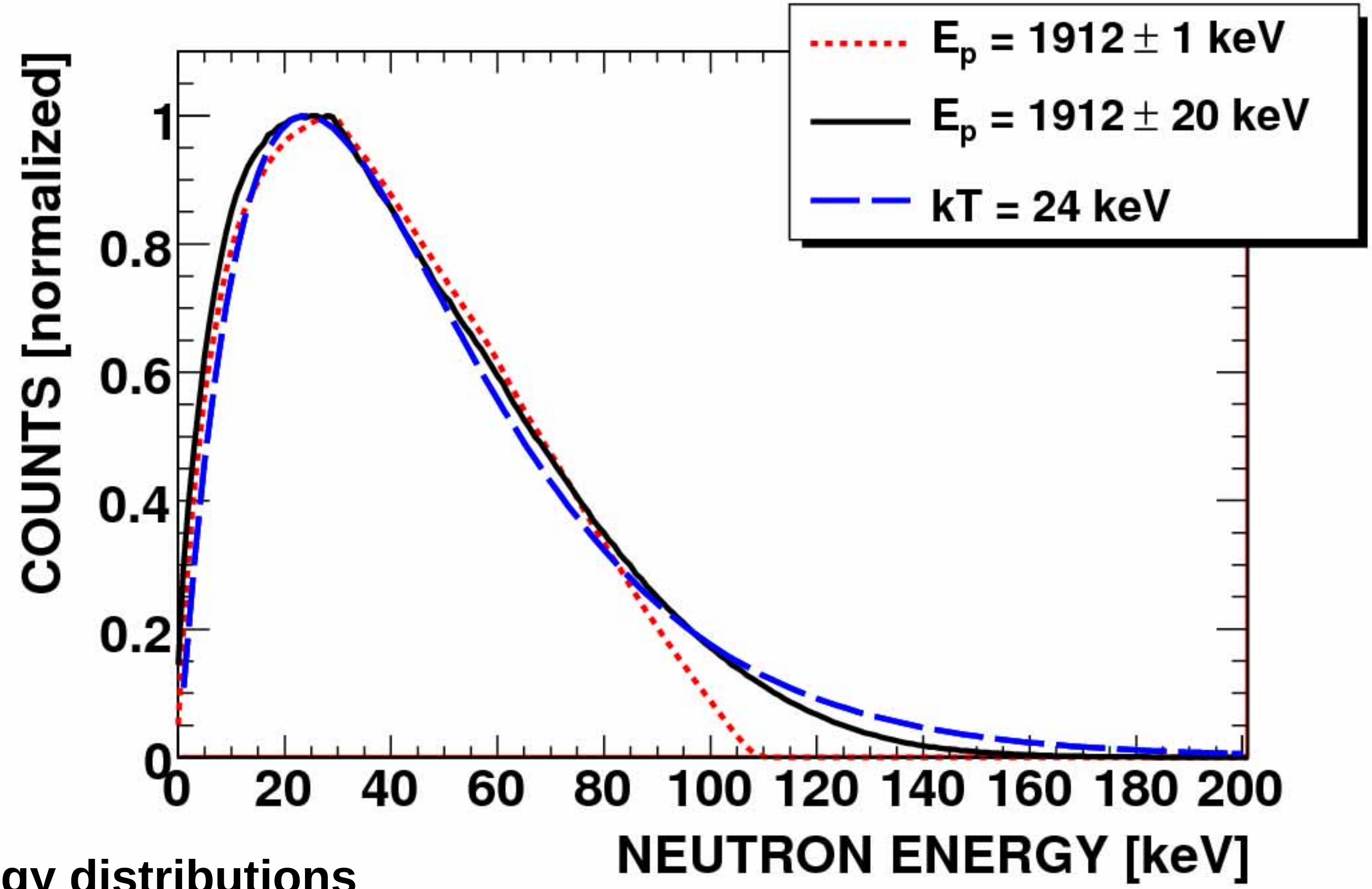


Quasi-Maxwellian averaged distribution:

$$kT = 25\ \mathrm{keV}$$

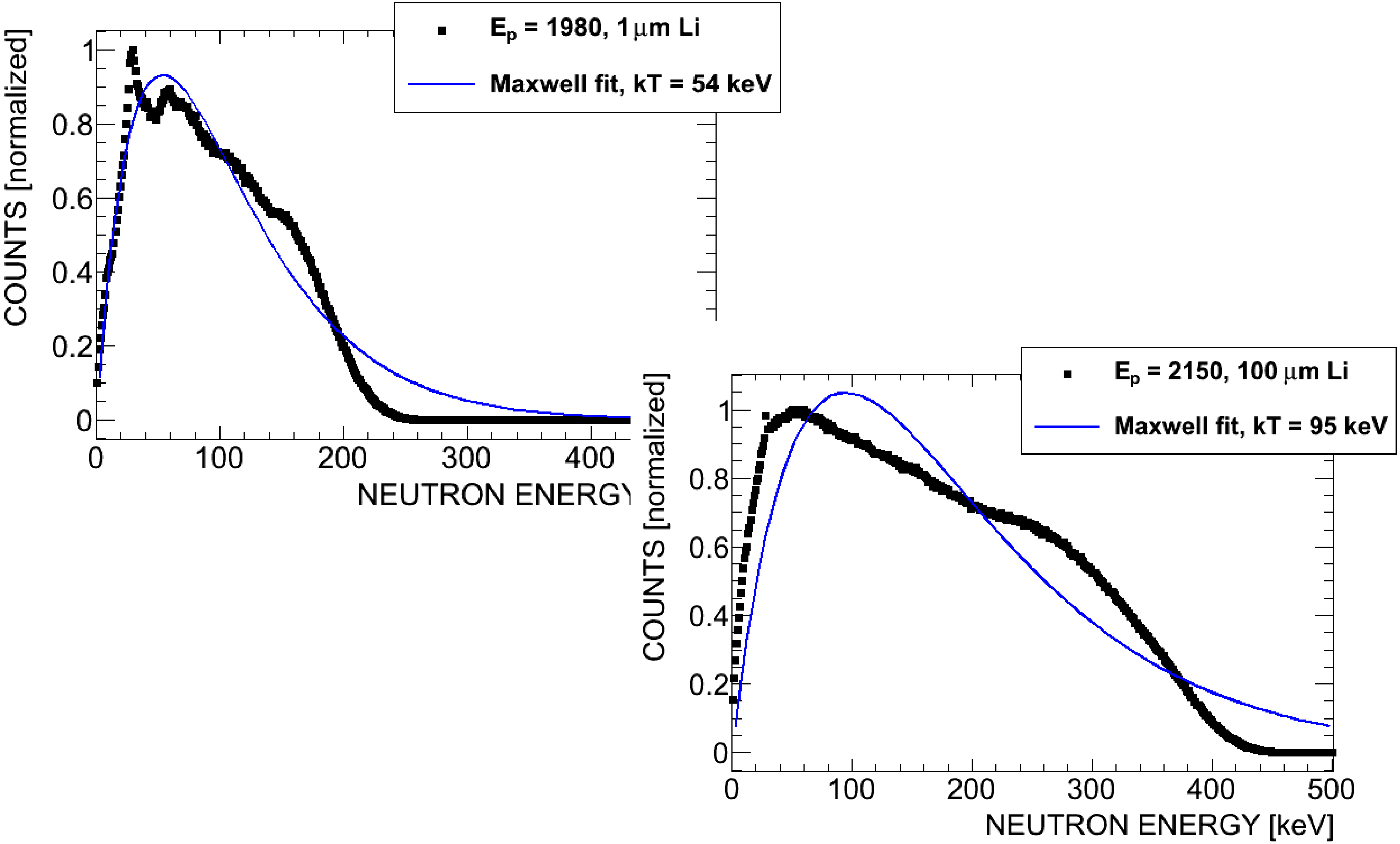
$$E_{max} = 110\ \mathrm{keV}$$

Effect of proton energy uncertainty

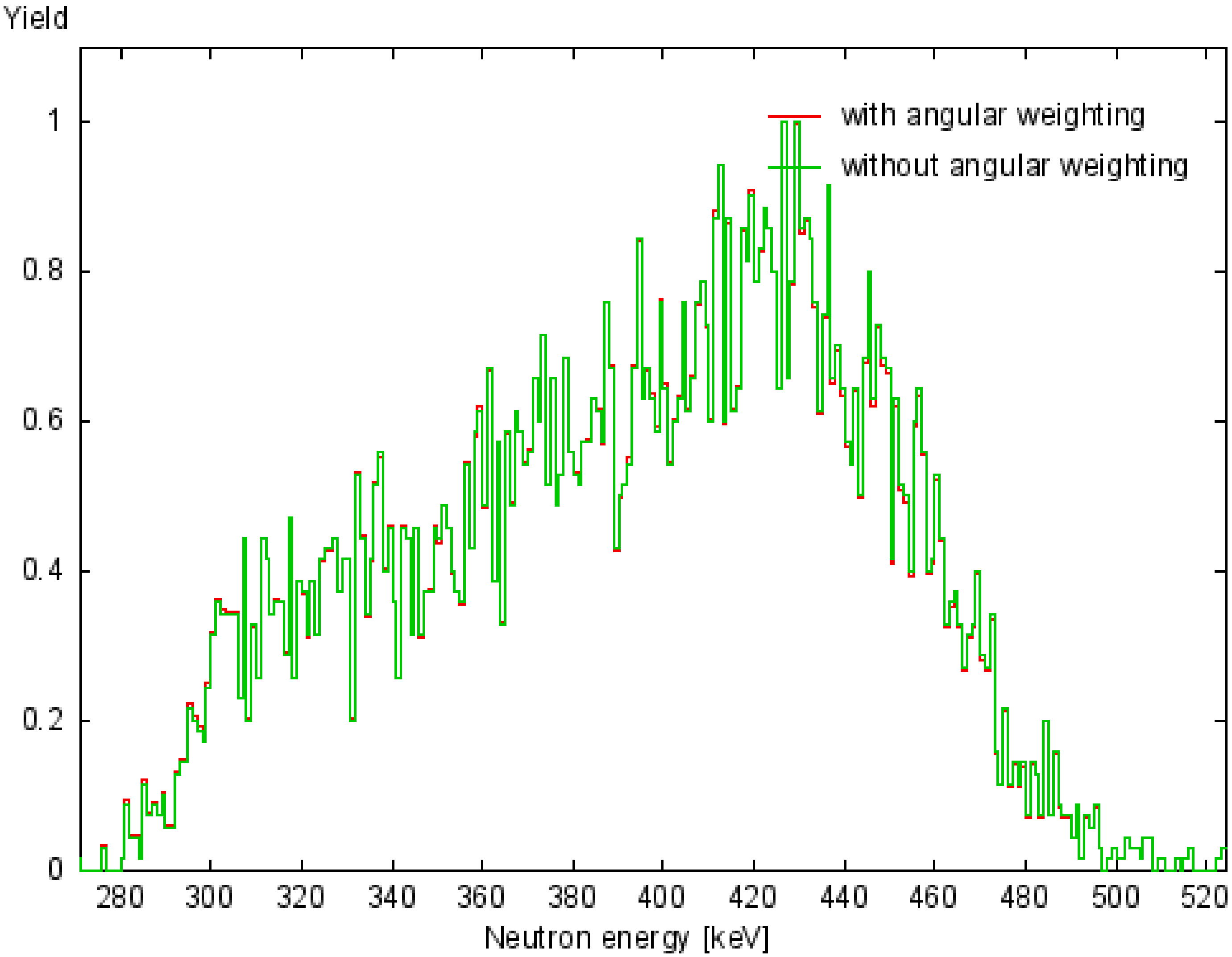


- E_p = 1912 keV
- different proton energy distributions
- 30 µm lithium
- 10 mm diameter gold foils
- weighting of sample thickness for different neutron angles considered

Producing spectra similar to stellar environments



E_p=2200 keV, 5 µmx3mm Li, 3mm sample



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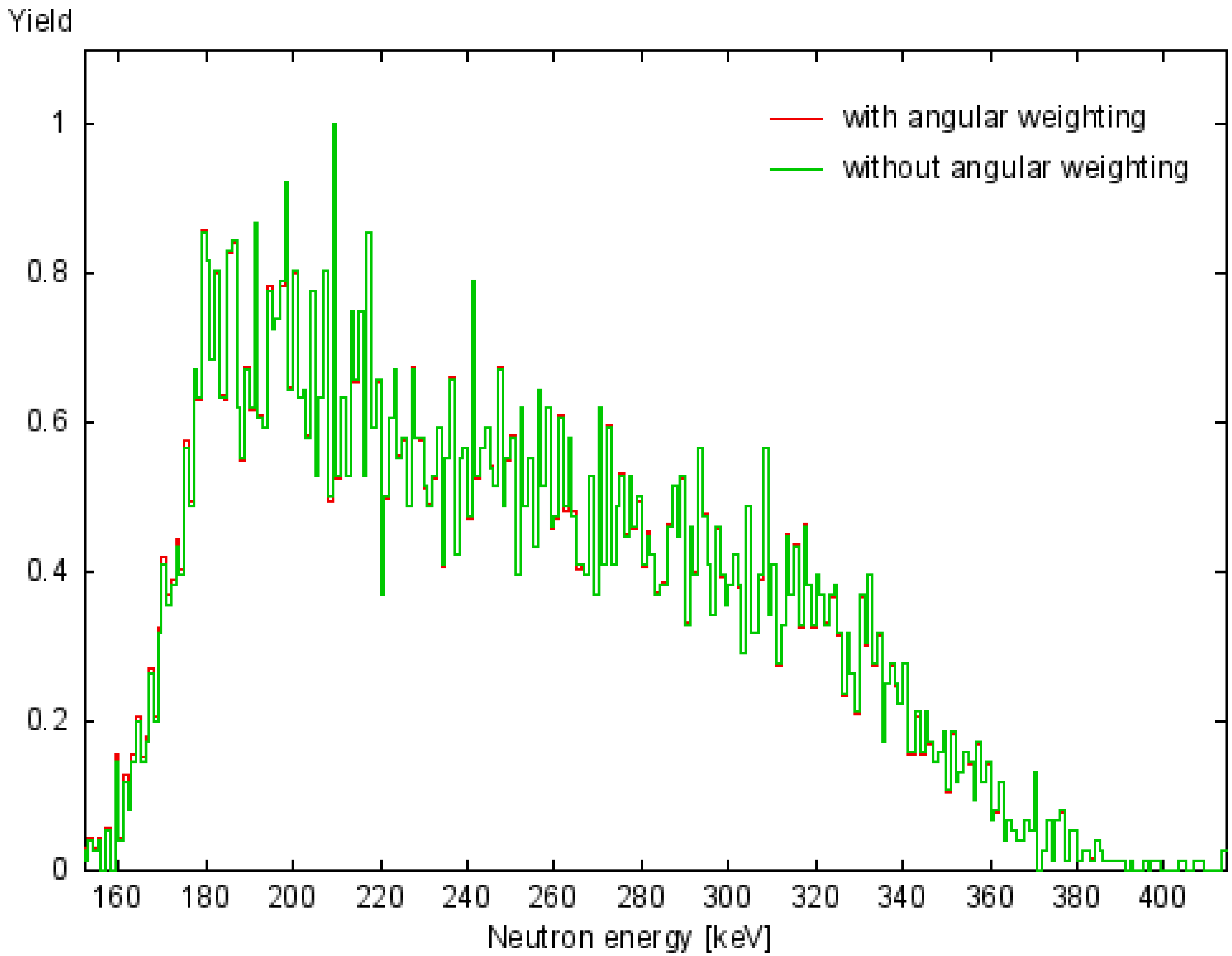
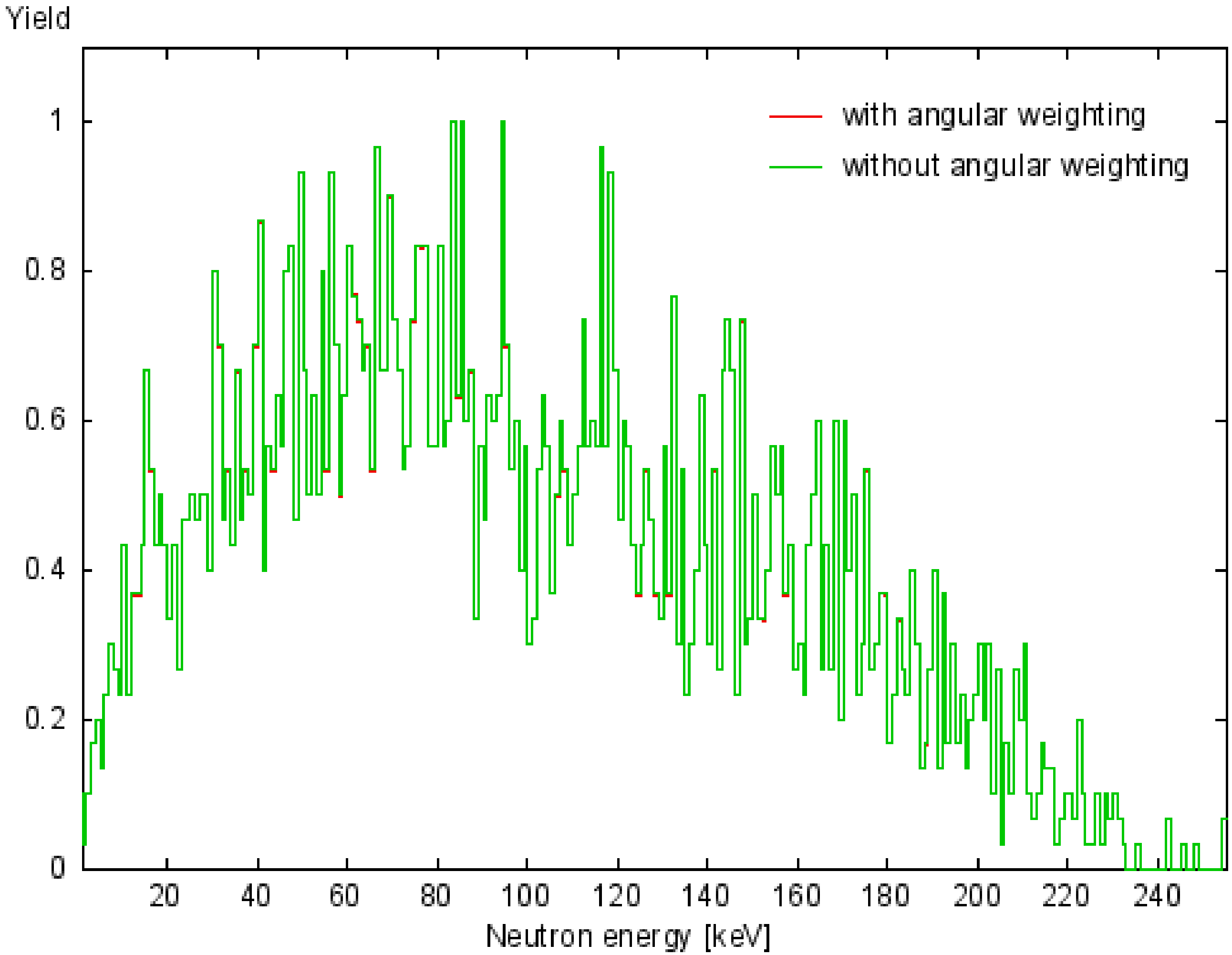
E_p=2100 keV, 5 µmx3mm Li, 3mm sample



E_p=1980 keV, 1 µmx3mm Li, 3mm sample



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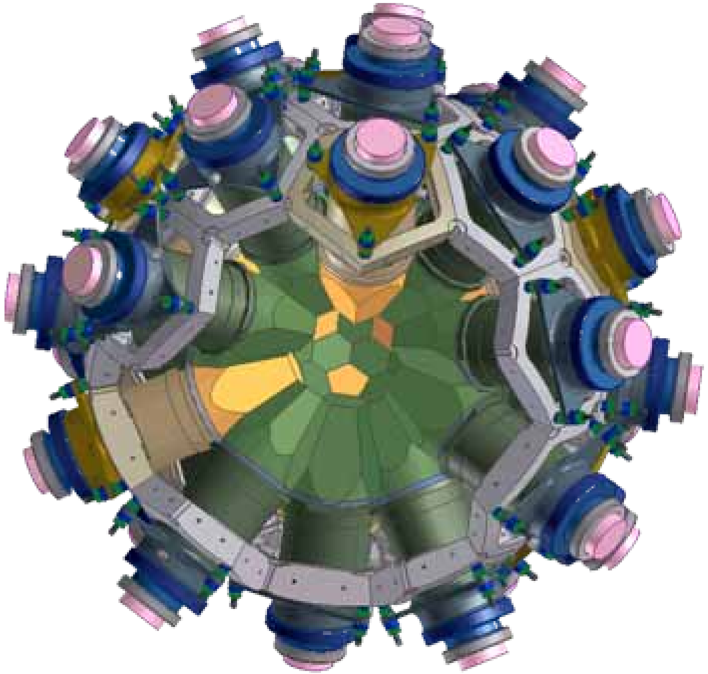
The 4π BaF_2 array for TOF measurements

Hardware:

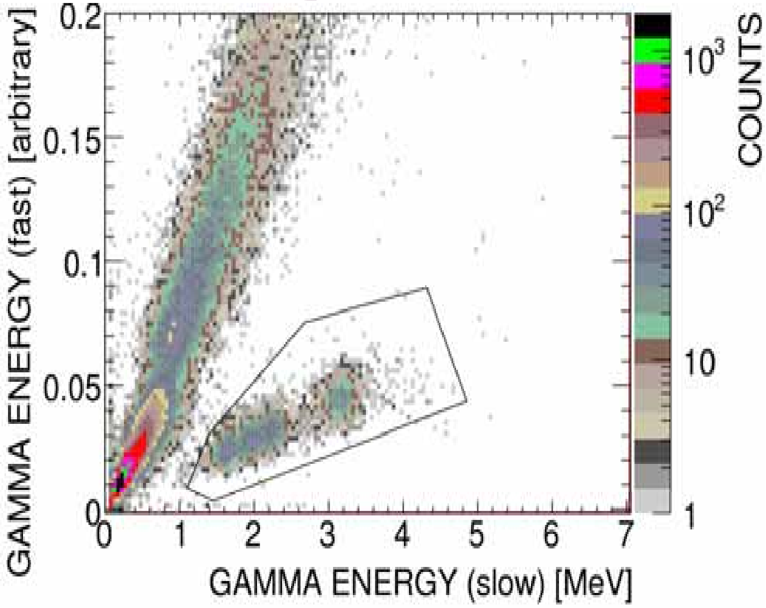
- γ-calorimeter
  - 15 cm thick
  - $\varepsilon_{\gamma,\text{ total}}$ ~ 90 %
  - $\varepsilon_{\text{casc, total}}$ ~ 98 %
  - $\varepsilon_{\text{casc, peak}}$ ~ 50 %

- 96 channels 1GS/s FADC + FPGA
- 30 TB RAID array

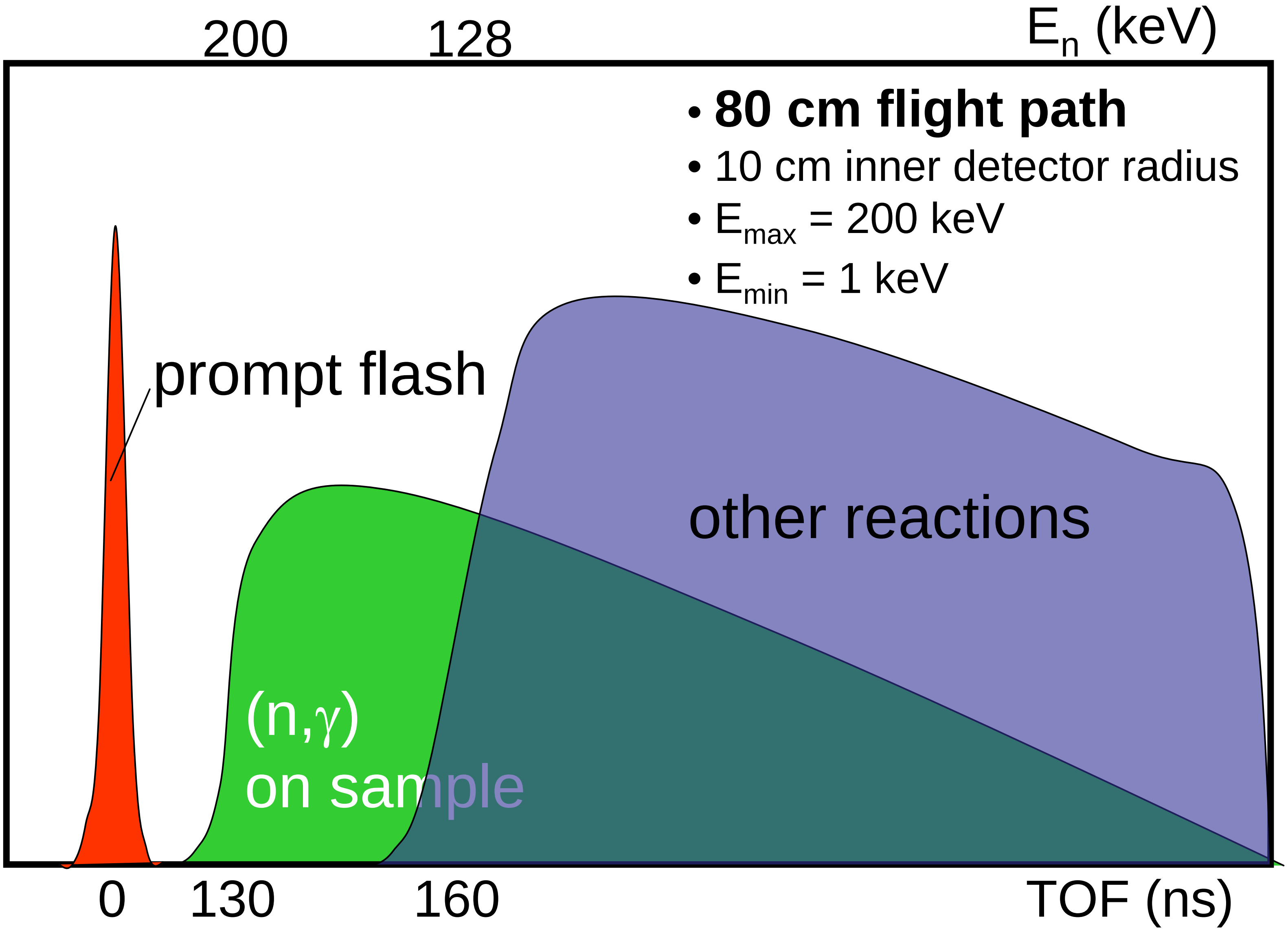


Allows:

- Particle identification
- deadtime-less DAQ
- pile-up correction
- fast data reduction



Schematic TOF spectrum



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

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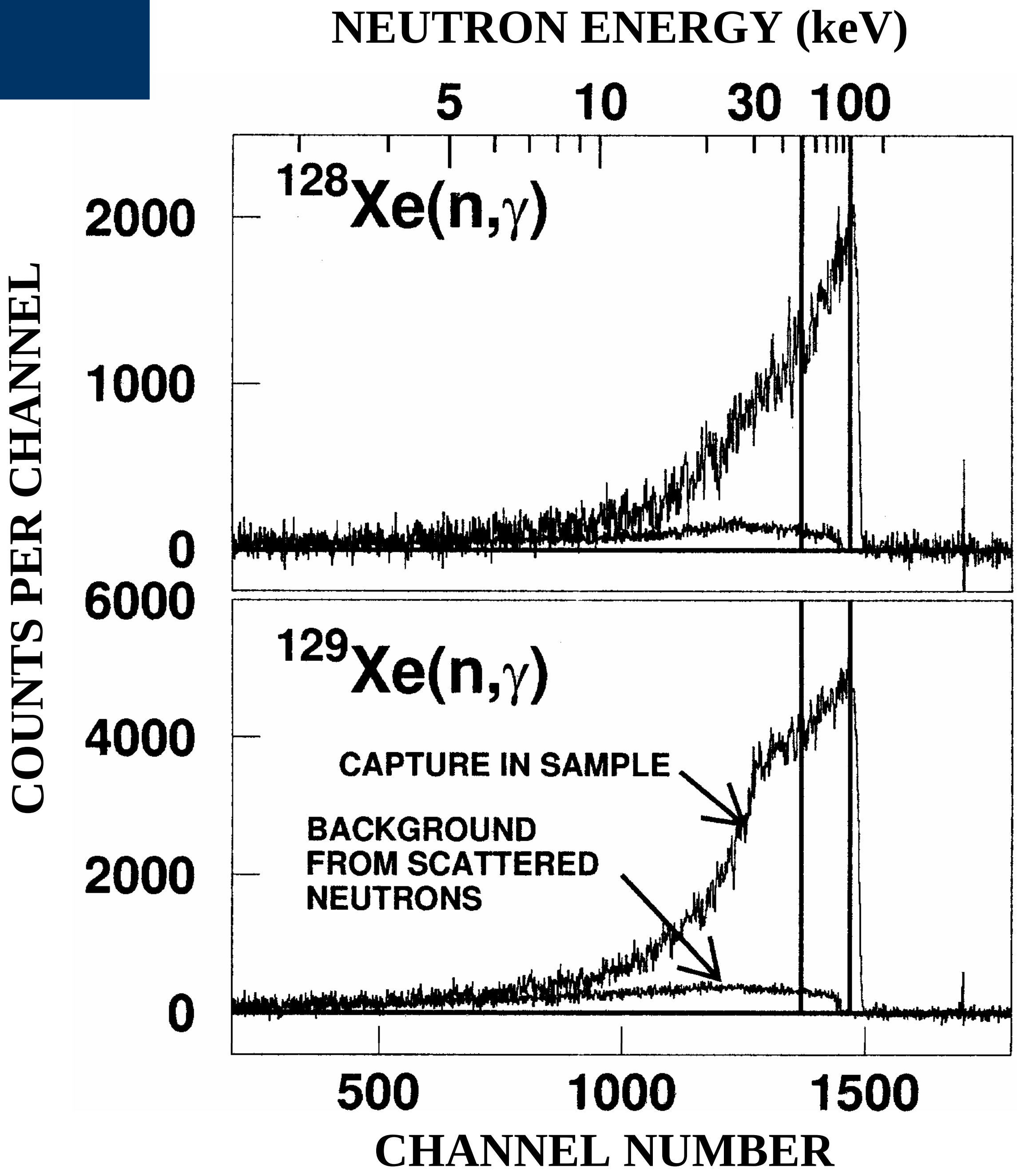
Time of flight

- delayed background from scattered neutrons
- $\sigma_{tot}/\sigma_{\gamma}(^{128}Xe) = 25.$



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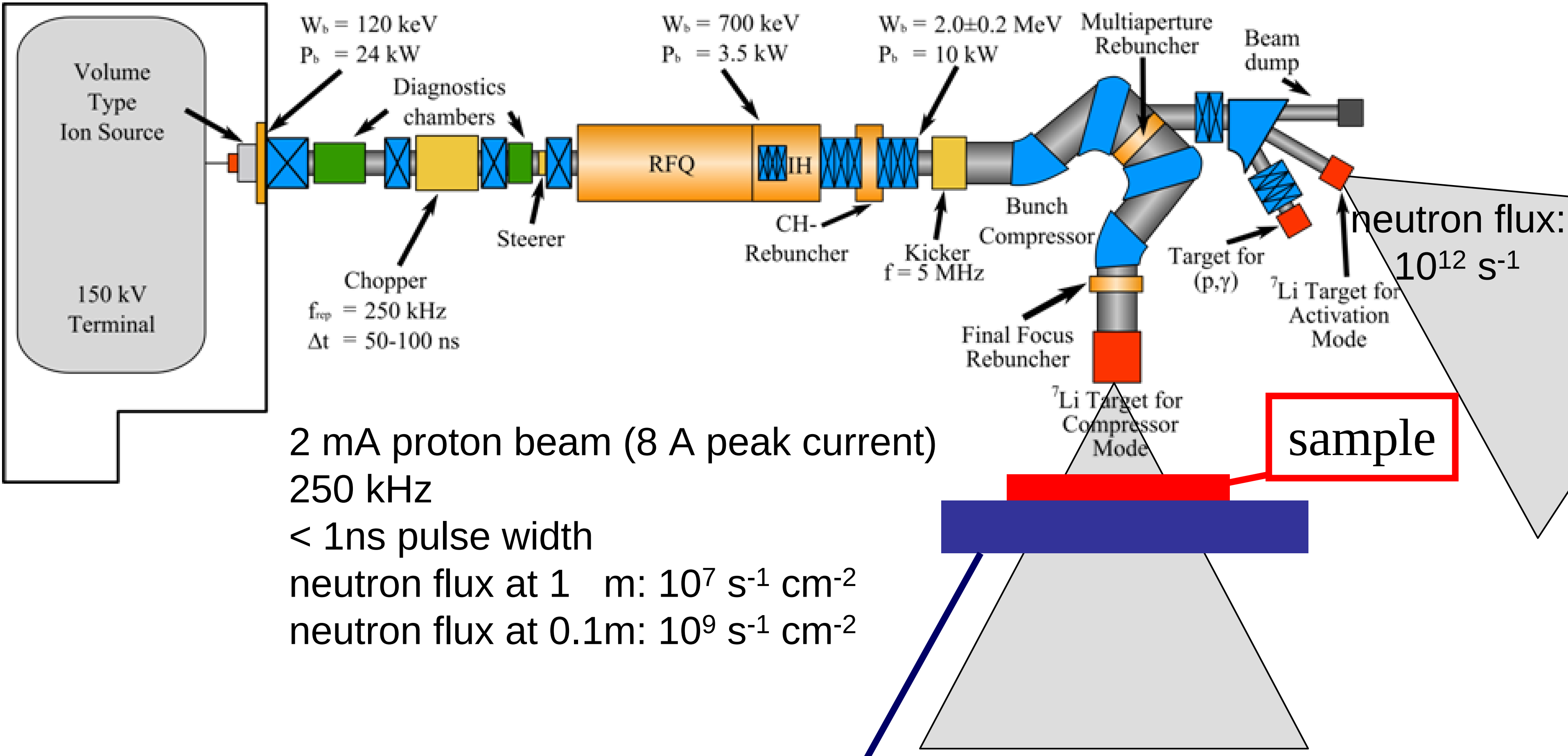
The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)



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

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,γ)
- Neutron poisons for the s-process: ^{12}C(n,γ), ^{16}O(n,γ), ^{22}Ne(n,γ).
- 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,γ) and ^{60}Fe(n,γ)
- Branch point nuclei, e.g. ^{85}Kr(n,γ), ^{95}Zr(n,γ), ^{147}Pm(n,γ), ^{154}Eu(n,γ), ^{155}Eu(n,γ), ^{153}Gd(n,γ), ^{185}W(n,γ)

Some dreams ...

TOF measurement on ^{60}Fe

- Need isotopically enriched samples
- 10^{16-18} atoms
- Probably not any time soon ...

$^{59}Fe(n,\gamma)$

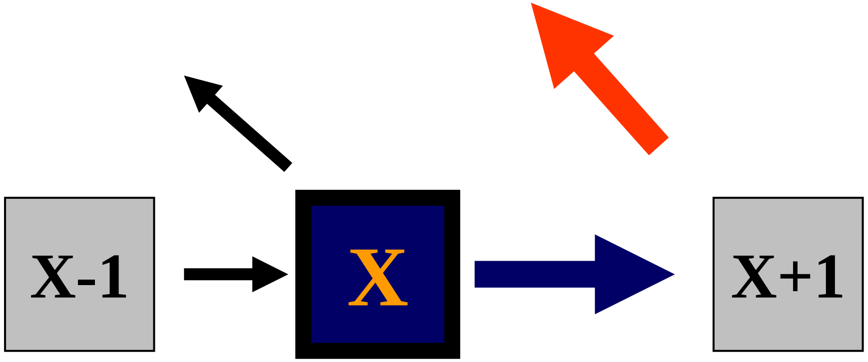
- 45 days of half-life
- 10^{11} n/s/cm^2 needed for TOF measurement

  No.
- Activation / AMS?
  - Bring sample to Frankfurt
  - Make sample on site

^{59}Fe - sample

- irrradiate ^{58}Fe in reactor
- Do mass separation with mass set to 58.5, then ^{60}Fe gone
- irradiate sample in Frankfurt, produce ^{60}Fe
- Do AMS to get ratio ^{60}Fe/^{58}Fe
- Some Numbers:
  - 1 g ^{58}Fe (10^{22} atoms)
  - 3 10^{18} ^{59}Fe after 1 month irradiation at reactor (10^{14} n/s/cm^2, thermal)
  - 10^{17} ^{59}Fe after separation
  - 5 10^{9} ^{60}Fe after 1 month irradiation at FRANZ (10^{12} n/s/cm^2, keV neutron)
  - Hence: ^{60}Fe/^{58}Fe ratio: 5 10^{-13} (doable with AMS)

Double neutron capture

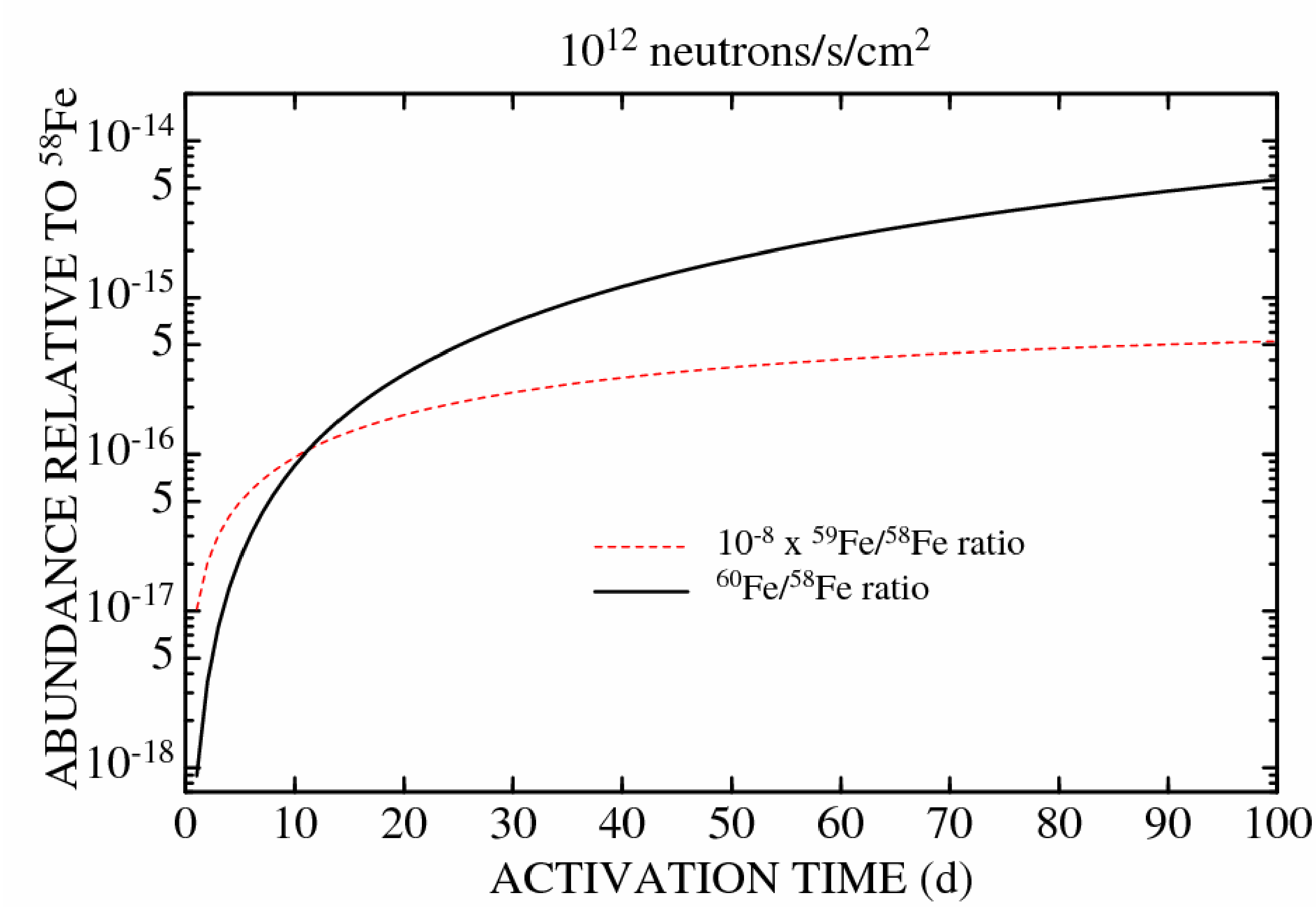


$t_{1/2} \sim 1..100$ d

- produce the sample “on the fly”
- 10^{12} n/s/cm^2 @ 25 keV ~ 5 10^3 n/cm^3

^{59}Fe(n,γ) at FRANZ ($t_{1/2}$=45 d)

- activate ^{58}Fe, wait for 2nd neutron capture
- measure ^{60}Fe/^{58}Fe ratio via AMS



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Summary

- The stellar cross section of ^{60}Fe has been measured within the ERWAST initiative
- Further measurements of thermal an hotter keV-spectra are planned
- Current research uses the s-process as a link between abundance observations and stellar models
- Data on radioactive nuclei are needed to enhance the reliability of that approach
- 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!)
- Extreme lack of data outside valley of stability

Thank you & stay tuned!