Nuclear Reactions 3 & 4
Cross Section Measurements

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Nuclear Reactions 3 & 4
(Direct) Cross Section Measurements (for Astrophysics)

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Outline

- Introduction
- Charged Particle Induced Reaction Measurements
  - stable beams (example LUNA)
  - radioactive beams (examples ISOLDE and GSI)
- Neutron Induced Reaction Measurements
  - radiative capture
  - n,cp

Acknowledgements: Material partly from Colleagues of the NP Edinburgh Group (M. Aliotta, PJ Woods, A. Murphy, C.G. Bruno, …) and n_TOF Collaboration

Introduction

Nuclear Reactions

- collision process between projectile p and target nuclei T:

$$p + T \rightarrow e + R \quad \text{or} \quad T(p,e)R$$

- ejectile (e) and recoil (R) may be the same as p and T (scattering)

- Examples
  - Elastic Scattering: $p + T \rightarrow p + T$
  - Inelastic Scattering: $p + T \rightarrow p + T^* \rightarrow p + T + \gamma$
  - Radiative Capture: $p + T \rightarrow R^* \rightarrow R + \gamma$

Nuclear Reactions

- Energy conservation:

$$m_p c^2 + E_p + m_T c^2 + E_T = m_e c^2 + E_e + m_R c^2 + E_R$$

E…. kinetic energy

- Q-value of a reaction: $Q = m_p c^2 + m_T c^2 - m_e c^2 - m_R c^2$

Q>0 ….. exothermic (energy is released)
Q<0 …… endothermic (energy is required)

- Threshold energy (lab) for projectile p reacting with stationary target T:

$$E_{th} = (-Q) x (1 + m_p/m_T)$$

Nuclear Reaction Cross Section

- cross section σ = quantitative measure of probability for a reaction to occur
- Dimension: area   Unit: barn (b) = 10^{-24} cm^2
- cross sections are energy (i.e. velocity) dependent
- In general: not possible to determine reaction cross section from first principles

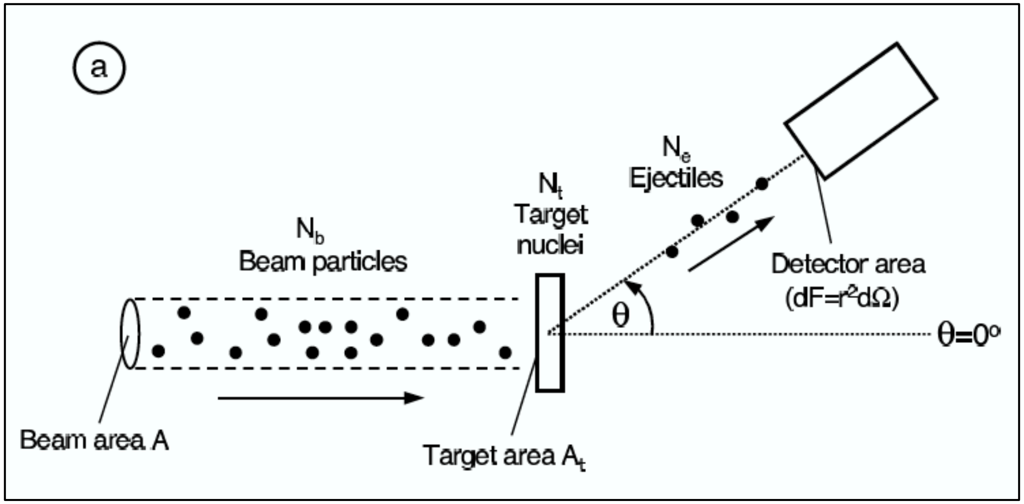
$$\sigma = \frac{N_e/t}{(N_b/tA)N_t}$$

N_e/t… Number of reactions per time
N_b/tA… Number of beam particles per time per area
N_t… Number of target nuclei in the beam

- Differential cross section:

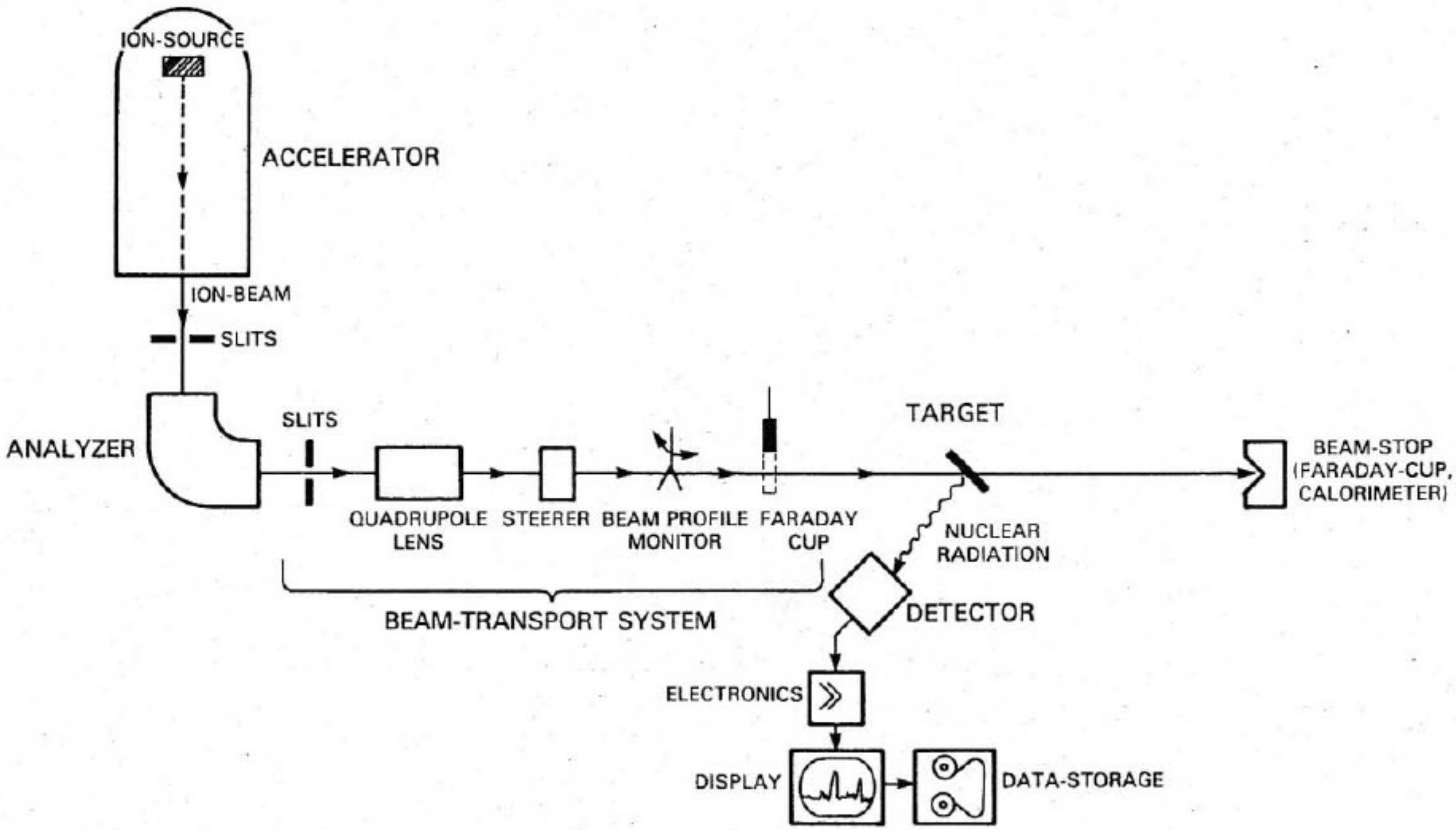
$$\frac{d\sigma}{d\Omega} = \frac{N_e^{d\Omega}/t}{(N_b/tA)N_t}\frac{1}{d\Omega}$$

and $\sigma = \int \frac{d\sigma}{d\Omega} d\Omega$



Reactions with Ion Beams

Schematic Layout for Nuclear Reaction Experiments



Cauldrons in the Cosmos
(Rolfs & Rodney)

Beam Requirements and Properties

- high intensity
  - for stable nuclei, μA-mA currents are possible, corresponding to ~ 10^{12}-10^{15} particles per second (pps)
  - for unstable nuclei, intensities vary greatly depending on isotope (10^{3}-10^{6} pps)
- low energy spread
  - ideally $\Delta E \leq 1$keV
- easily adjustable energy
  - few keV steps often required
- well collimated
- high purity
- small spot size on target
  - better definition of interaction point
- good absolute energy calibration

Target Requirements and Properties

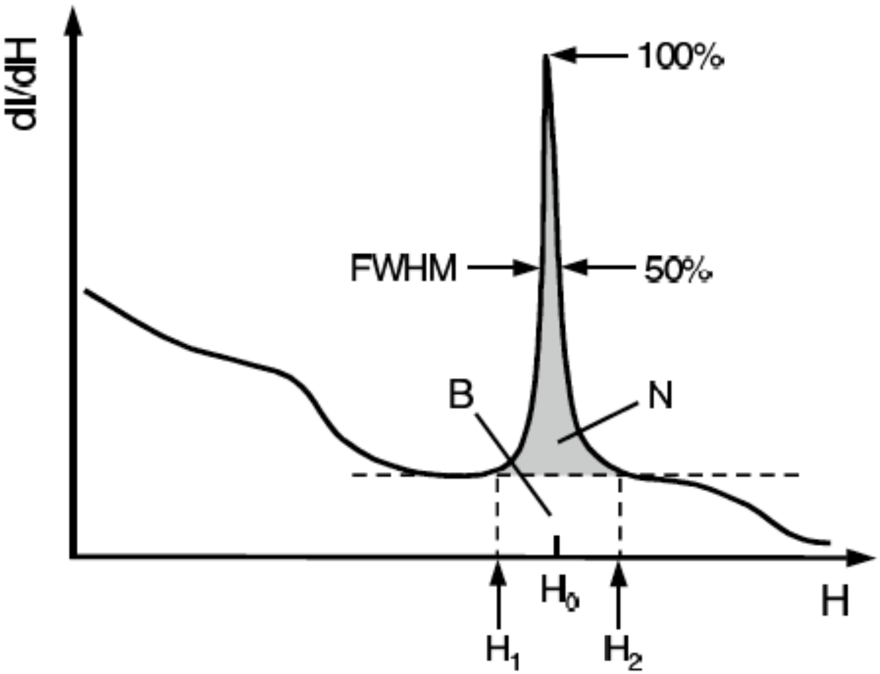
- high purity
  - avoid background reactions on contaminants
- known and stable stoichiometry (for compound targets)
- appropriate and uniform thickness
  - thin enough to let beam pass through (transmission targets)
  - thick enough to stop the beam (beam-stop targets)
  - anywhere in between
- for solid targets
  - evaporated, sputtered, implanted
  - with or without backing
  - allow for water-cooling if high beam intensities are used
- for gas target
  - extended, or jet-like
  - with or without containment windows
  - recirculation (especially for expensive gases)

Detector Requirements and Properties

- nuclear reactions are studied by measuring reaction products
  - mostly protons, neutrons, α particles, or γ rays
- different types of radiation interact in different ways with
- type of detector used will depend on radiation to be measured

- electric signal produced in detector with amplitude proportional to energy deposited by radiation

- high efficiency
- good energy resolution $R=FWHM/H_0$
- good solid angle coverage



Reactions with Ion Beams

Yield measurements and Cross Section

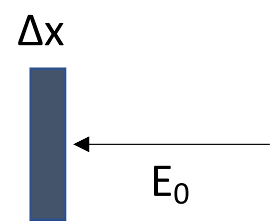
Reaction Yield

$$\text{Yield} = \frac{\text{total number of reactions}}{\text{total number of incident particles}}$$

yield vs bombarding energy = *yield curve* or *excitation function*

Yield over slice of target with thickness Δx, assuming **σ** and **stopping power ε constant** (energy lost by beam small)

$$\Delta Y = \frac{N_R}{N_B} = \sigma n \Delta x$$



With stopping power ε(E)=-1/n *x* dE/dx and particles per volume n

Total yield from integration over all target slices:

$$Y(E_0) = \int \sigma(x) n(x) dx = \int \sigma(x) n(x) dx \frac{dE(x)}{dx} \frac{dx}{dE(x)}$$

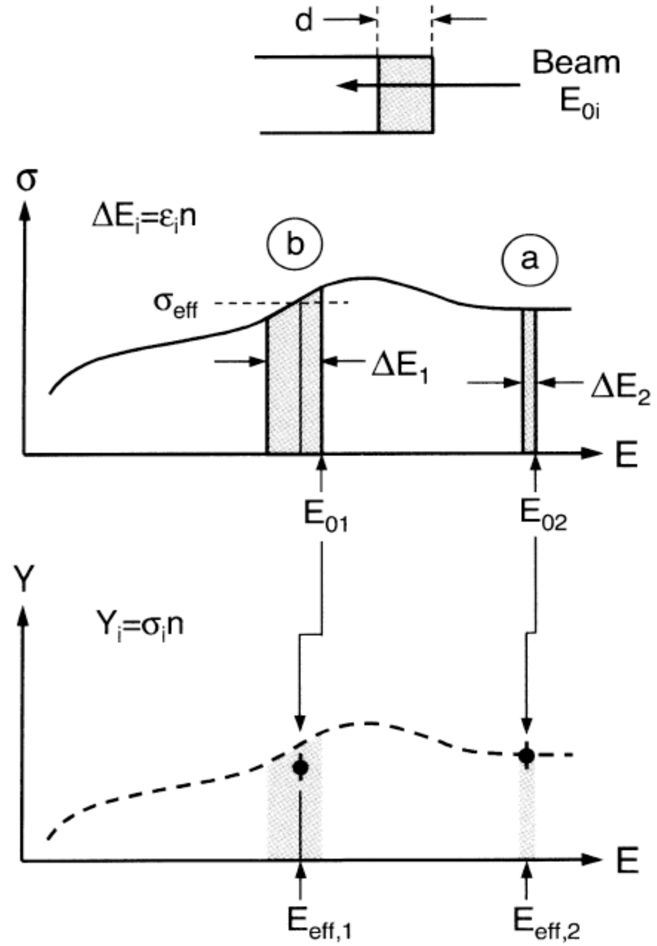
$$Y(E_0) = \int_{E_0 - \Delta E}^{E_0} \frac{\sigma(E)}{\varepsilon(E)} dE$$

where ΔE is the energy lost by the beam over the target thickness for non-resonant reactions or for broad resonances

cross section and stopping power ε(E) are almost constant within small energy region

$$Y(E_0) = \int_{E_0-\Delta E}^{E_0} \frac{\sigma(E)}{\varepsilon(E)} dE = \frac{\sigma(E_{eff})}{\varepsilon(E_0)} \Delta E(E_0)$$

E_{eff} .... energy at which the cross section, evaluated at this energy, equals the cross section averaged over the target thickness; energy at which 50% of total yield is obtained



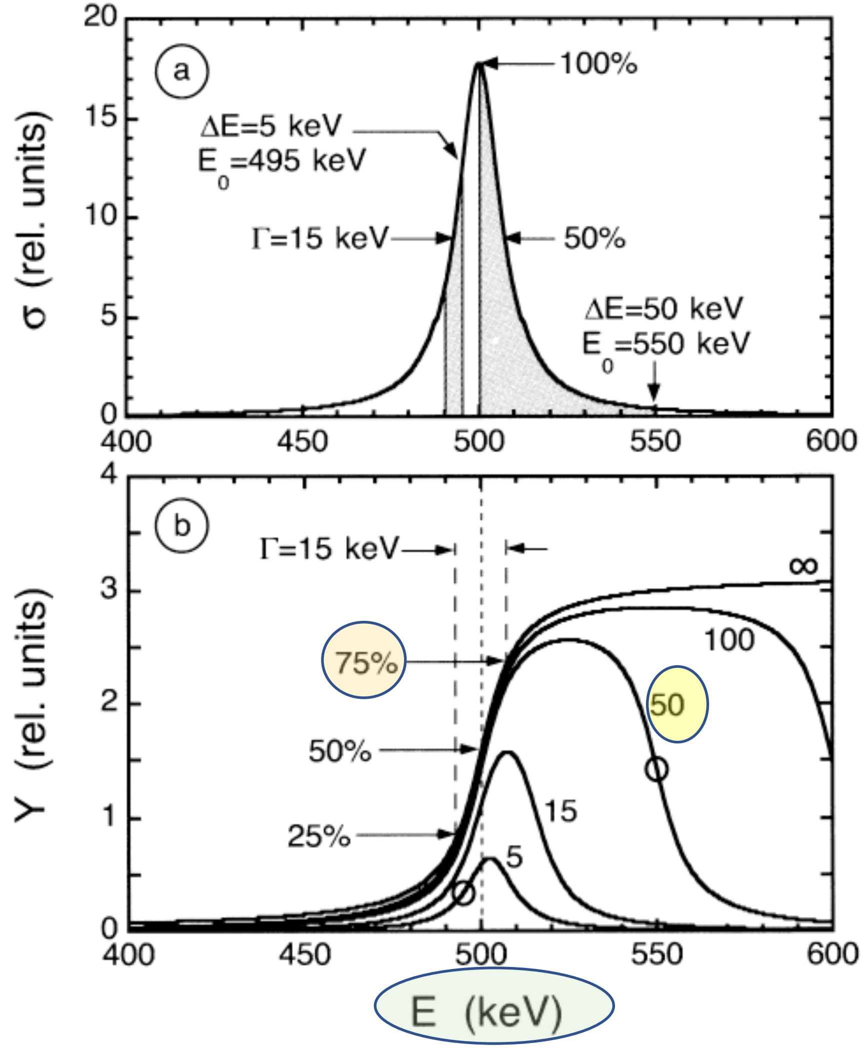
Iliadis, 2007

for resonant reactions:
yield depends strongly on bombarding energy and target thickness

beam energy (E_0)

target thickness in energy loss units ΔE

% of maximum yield that can be measured for ΔE→ ∞



for resonant reactions:
yield depends strongly on bombarding energy and target thickness

thin target thickness $\Delta E << \Gamma$

yield curve resembles cross section curve

- max yield at E_R
- FWHM ≈ Γ of resonant state

thick target thickness $\Delta E >> \Gamma$

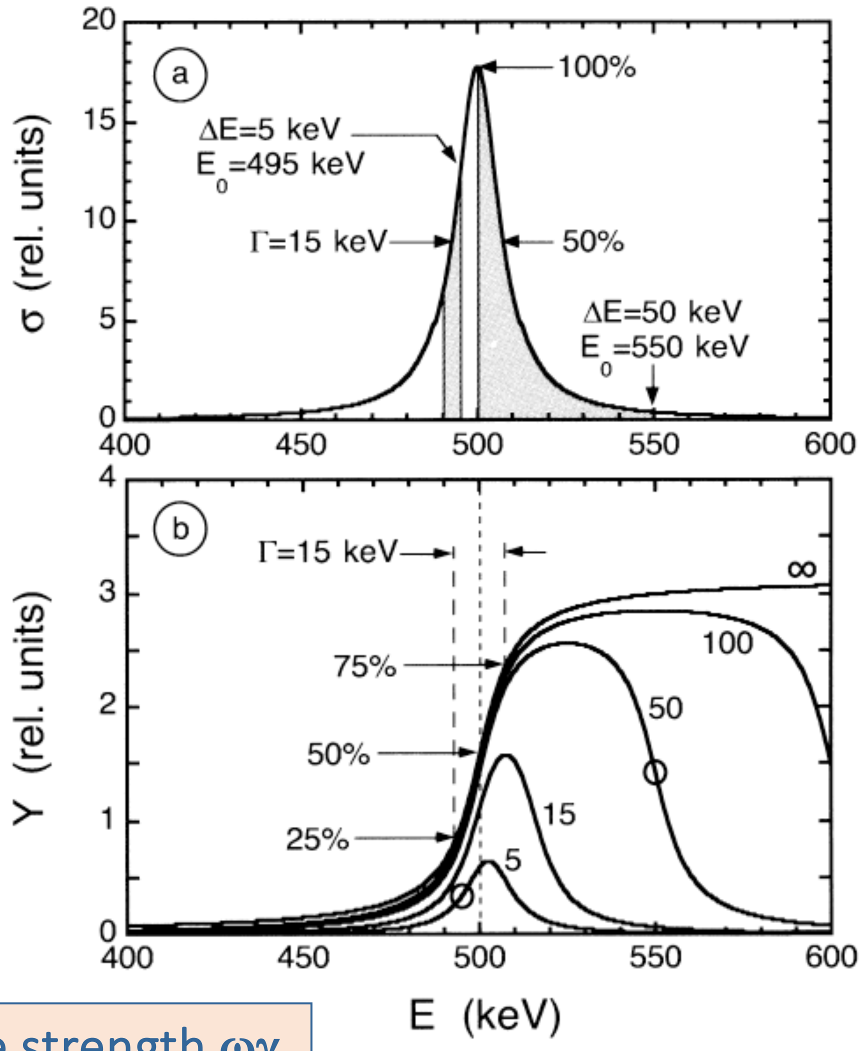
yield approaches flat plateau

- max yield at $E_R + \Delta E/2$
- FWHM ≈ ΔE

For $\Delta E \rightarrow \infty$ $\quad \Gamma = E_{0,75\%} - E_{0,25\%}$

$$Y_{max} = \frac{\lambda_r^2}{2}\frac{1}{\varepsilon_r}\omega\gamma$$

ε stopping power at E_R
λ de Broglie at E_R
E_R resonance energy



yield measurement gives **directly resonance strength ωγ**

Reactions with Stable Ion Beams

Quiescent burning stages of stellar evolution

- Nuclear reactions in stable (quiescent) burning phases of stars happen energies below the Coulomb Barrier due to low the temperature $T \sim 10^6 - 10^8$ K

$\Rightarrow$ $E_0 \sim 100$ keV << E_{coul} $\Rightarrow$ tunnel effect

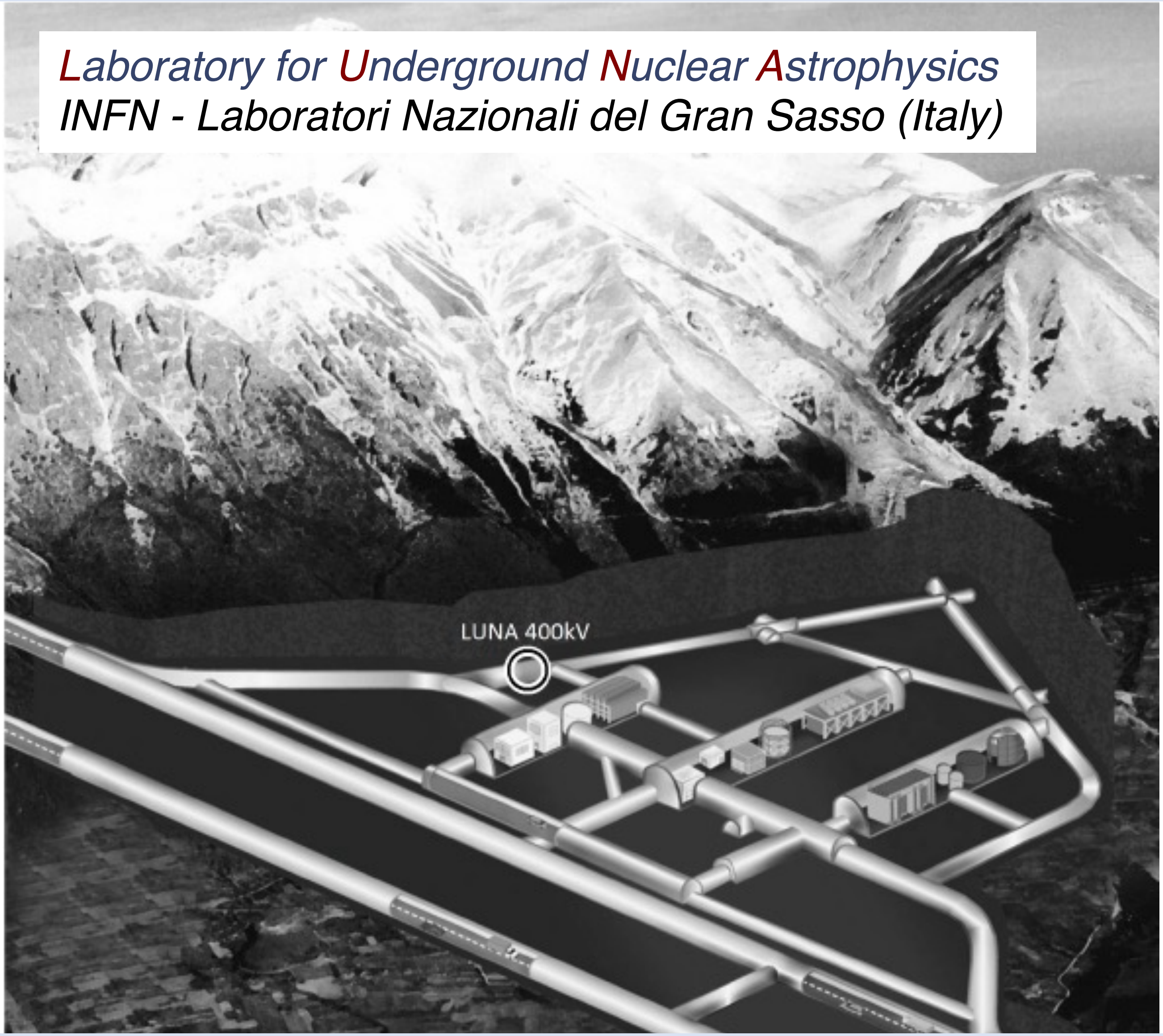
$\Rightarrow$ 10^{-18} barn < σ < 10^{-9} barn

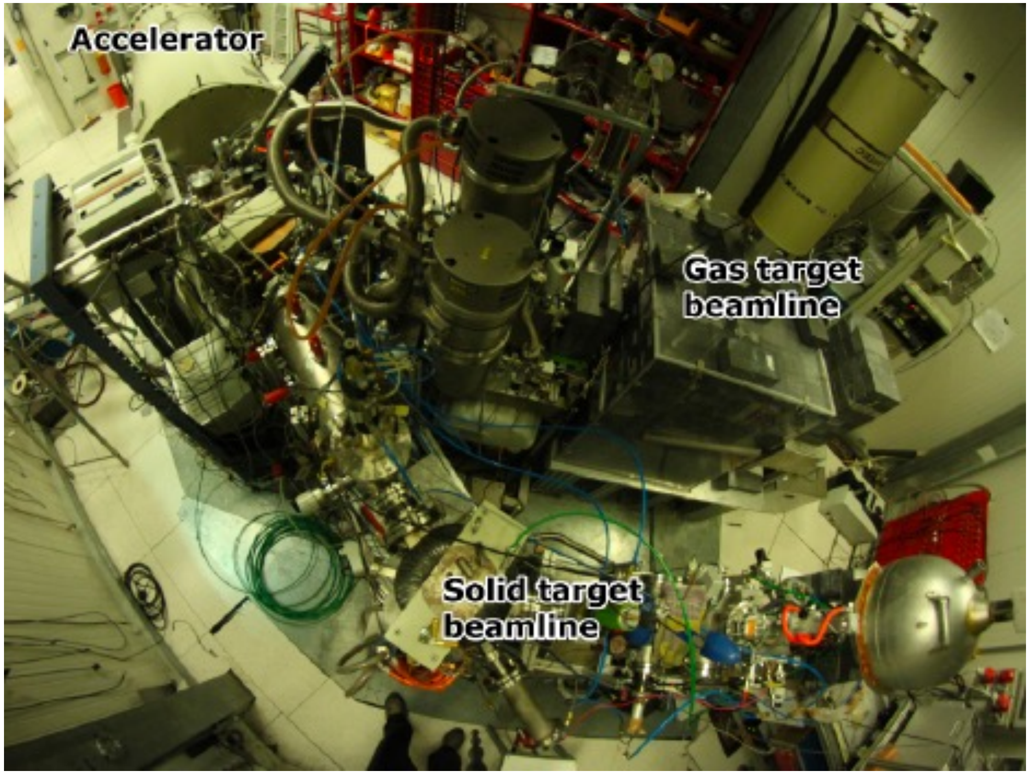
$\Rightarrow$ average interaction time $\tau \sim \langle\sigma v\rangle^{-1} \sim 10^9$ y, hence unstable species DO NOT play significant role

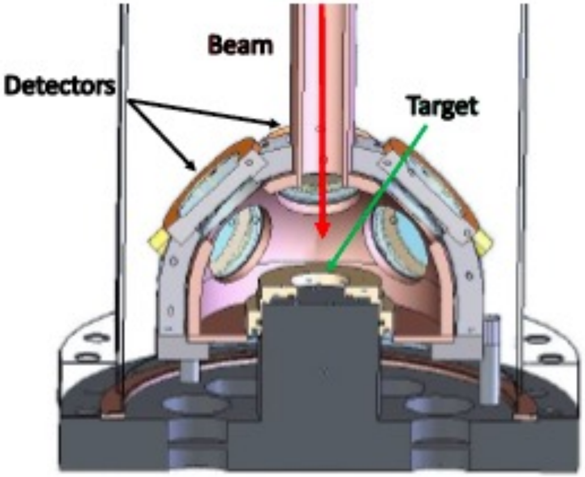
- Low count rates (and poor signal-to-noise ratios) require
  - $\Rightarrow$ long measurements
  - $\Rightarrow$ ultra pure targets
  - $\Rightarrow$ high beam intensities
  - $\Rightarrow$ high detection efficiency
  - $\Rightarrow$ reducing natural background

Measurements underground

$^{17}O(p,\alpha)$ Cross Section at LUNA

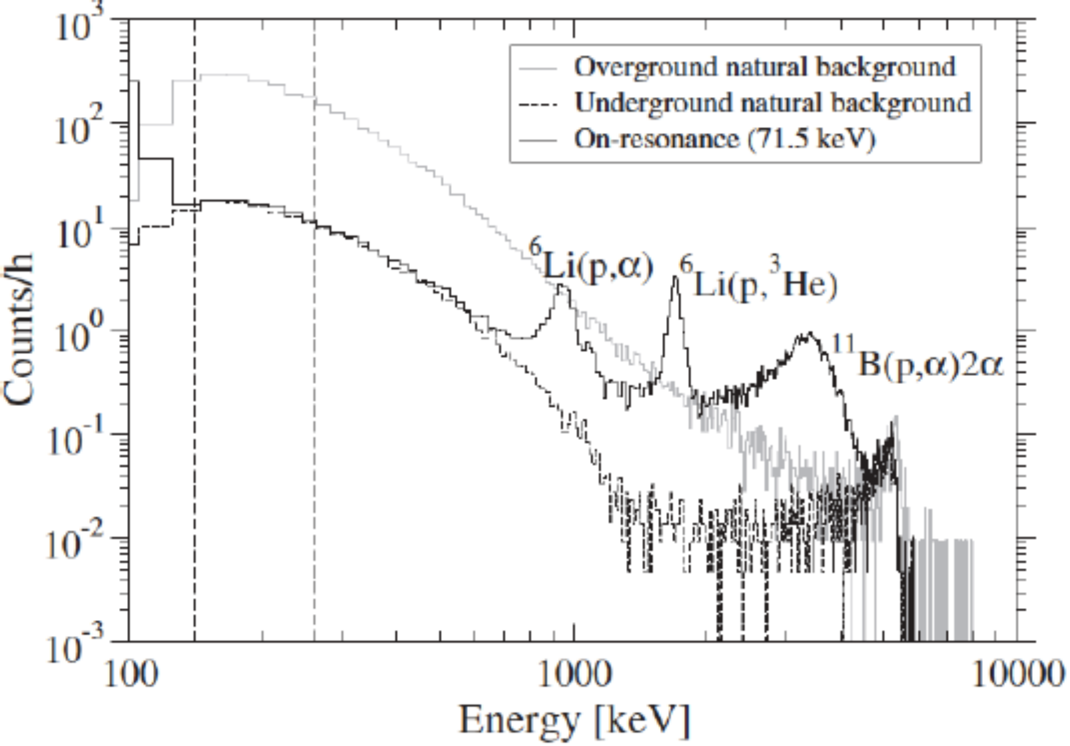






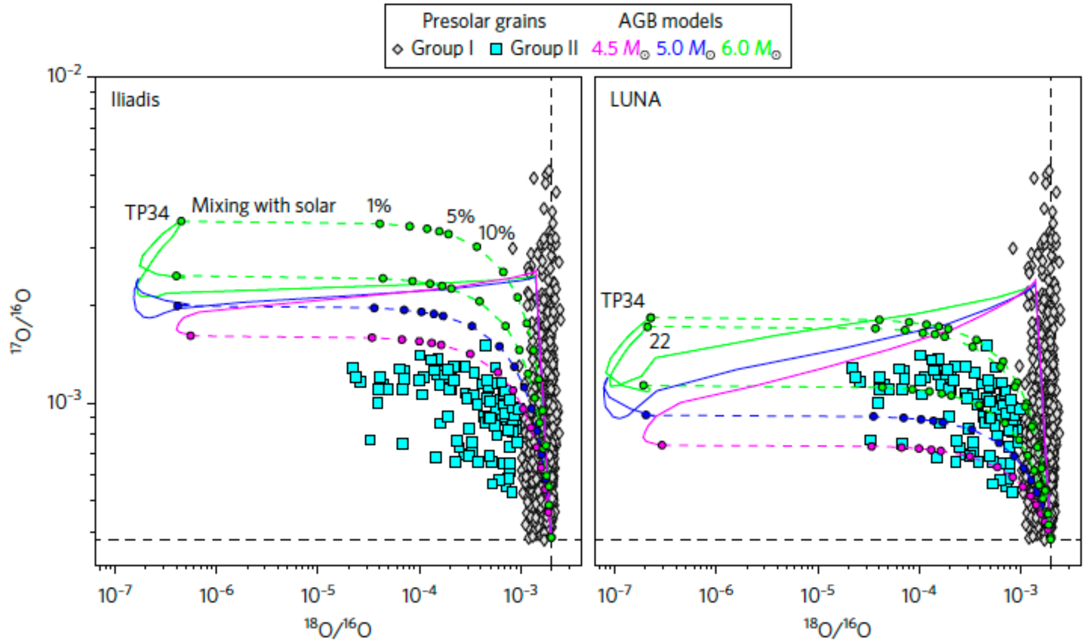
- typical beam intensities 100-200 µA
- expected alpha particle energy E ~ 200 keV (from 70 keV resonance in $^{17}O(p,a)^{14}N$)
- protective aluminized Mylar foils before each detector

C.G. Bruno et al., Physical Review Letters, 117, 14 (2016)
C.G. Bruno, PhD Thesis (U. Edinburgh)



C.G. Bruno et al., Physical Review Letters, 117, 14 (2016)
C.G. Bruno, PhD Thesis (U. Edinburgh)

Revised $^{17}O(p,\alpha)$ rate showed that a group of meteoritic grains is produced in massive Asymptotic Giand Branch stars



M. Lugaro et al, Nature Astronomy 1, 0027 (2017)

Reactions with Radioactive Ion Beams

Explosive burning stages of stellar evolution

- Nuclear reactions in explosive environments (T~ GK) typically happen at higher energies (near Coulomb barrier) → higher cross sections
- Reactions on protons and alphas: Measurements in Inverse Kinematics

CHALLENGES unstable nuclei ⇒ short half-lives

⇒ low beam currents

REQUIREMENTS

⇒ Radioactive Ion Beam facilities

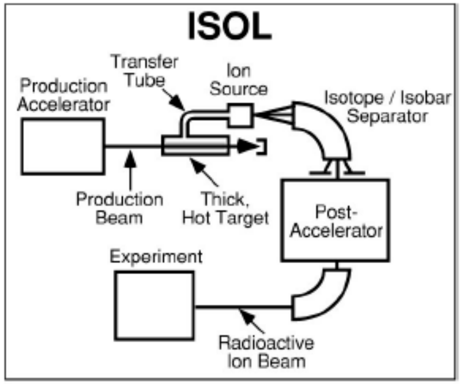
⇒ produce and accelerate ions of interest

⇒ dedicated detection systems

Radioactive Ion Beam Production

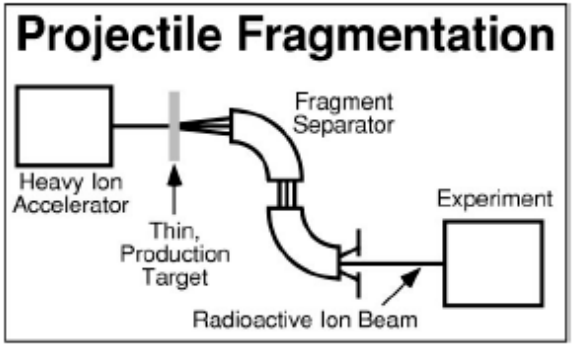
- Off-Line Production and subsequent installation in accelerator (limited to long-lived isotopes)

- ISOL Technique



- excellent quality (small emittance)
- limited number of species and half lives

- In-Flight / fragmentation



- independent of chemical properties
- small half lives possible
- larger beam spot, poorer emittance
- energies generally too high for nuclear astrophysical studies

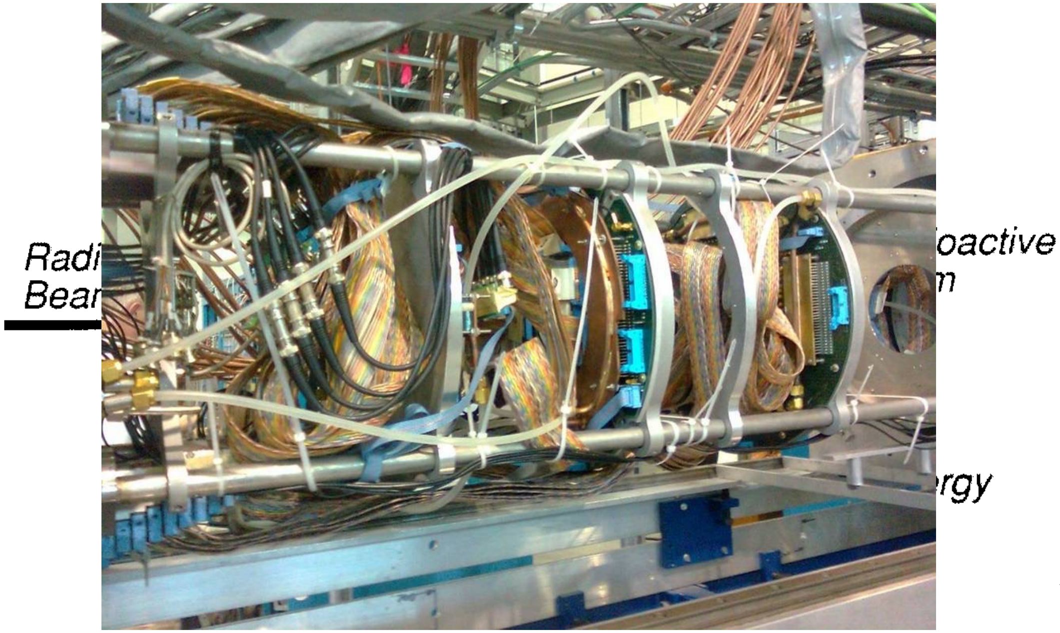
Smith and Rehm, Annu. Rev. Nucl. Part. Sci. 2001. 51:91–130

NUCLEAR REACTIONS

mainly X(p,α)Y and X(α,p)Y

light-heavy nuclei coincidence

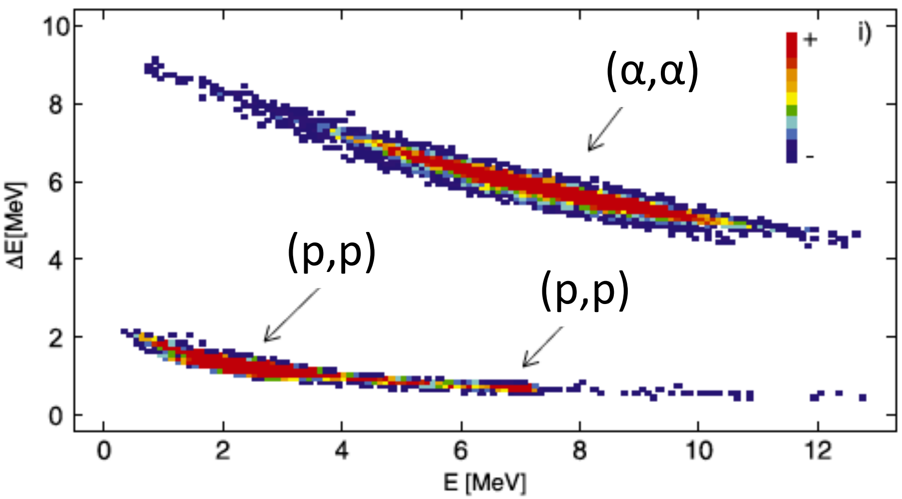
silicon strip detector arrays $\Rightarrow$ large solid angle coverage (e.g.TUDA at TRIUMF)

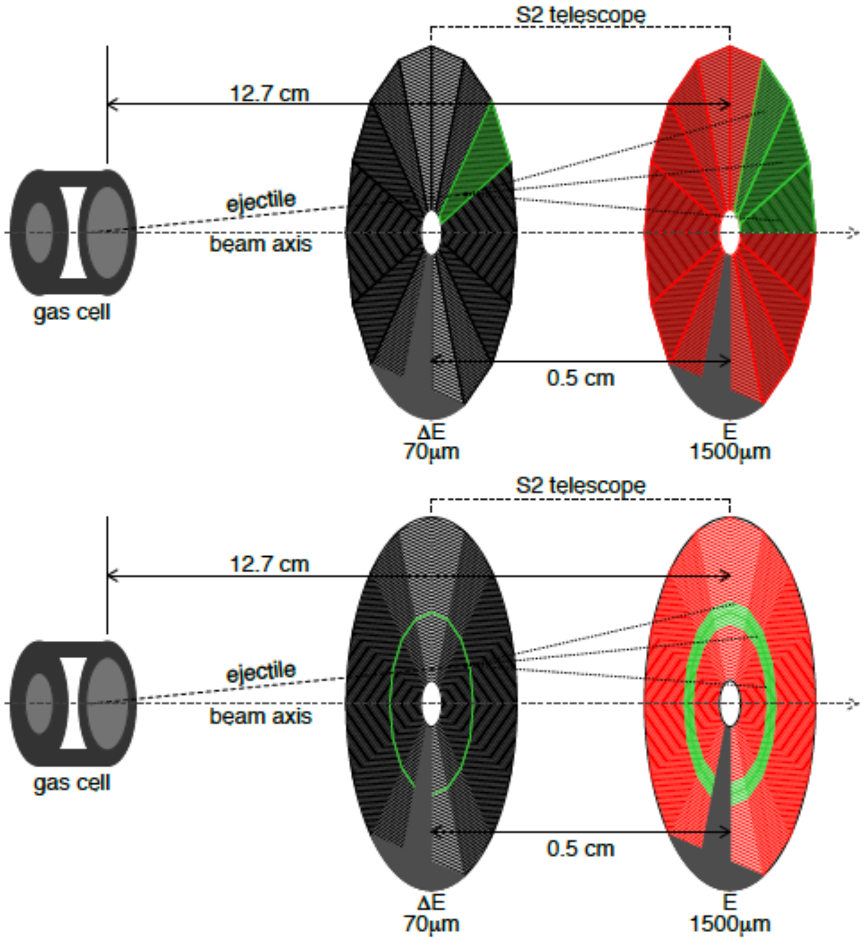


- Coincident detection of heavy recoil and light ion (i.e. proton, alpha)
- High segmentation of detectors for accurate determination of kinematics
- If possible dE-E particle identification

^{44}Ti(α,p) Cross Section at REX-ISOLDE

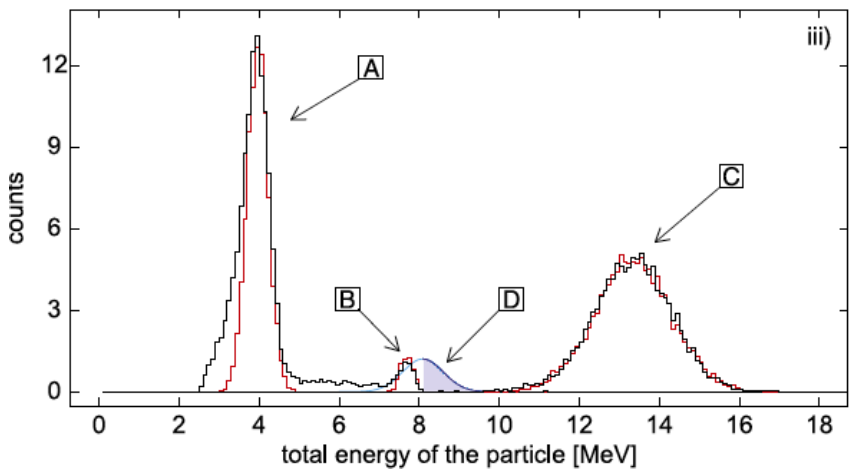
- Important destruction reaction of cosmic γ-ray emitter ^{44}Ti
- ^{44}Ti from highly irradiated components of the SINQ spallation neutrons source (PSI)
- Detection of Proton using ΔE-E technique
- *ΔE = fraction of energy lost in thin detector* $\sim MZ^2/E_{ini}$

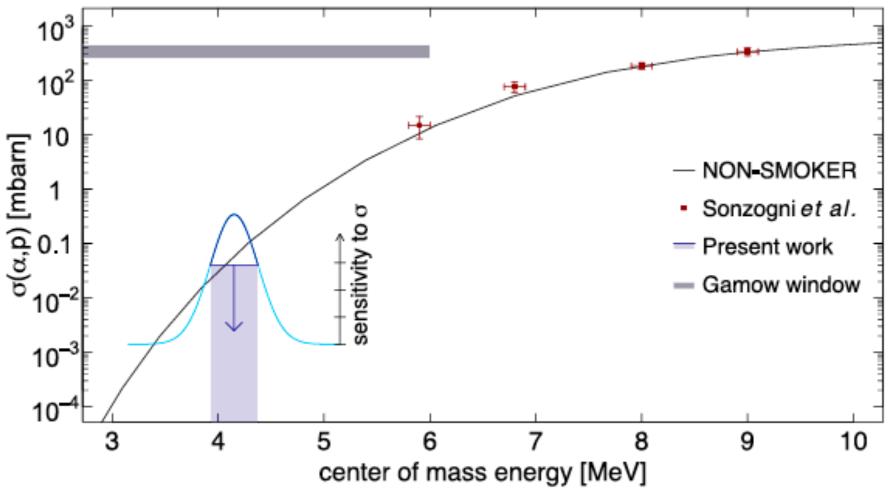


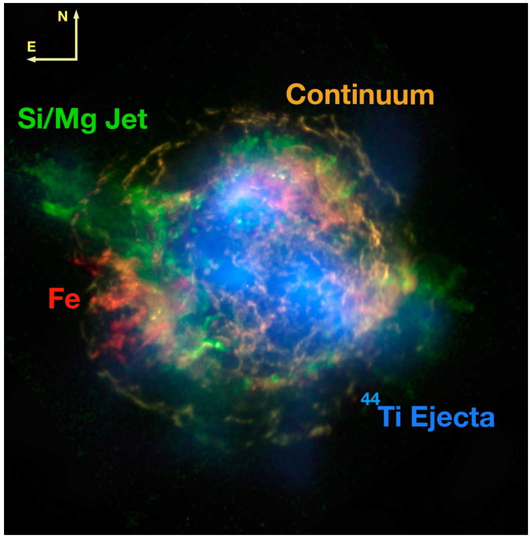


V. Margerin et al. Physics Letters B 731 (2014) 358–361 ; V. Margerin, PhD Thesis (U. Edinburgh)

^{44}Ti(α,p) Cross Section at REX-ISOLDE







- No signal above background
- Upper limit suggests lower destruction rate

V. Margerin et al. Physics Letters B 731 (2014) 358–361 ; V. Margerin, PhD Thesis (U. Edinburgh)

RADIATIVE CAPTURE

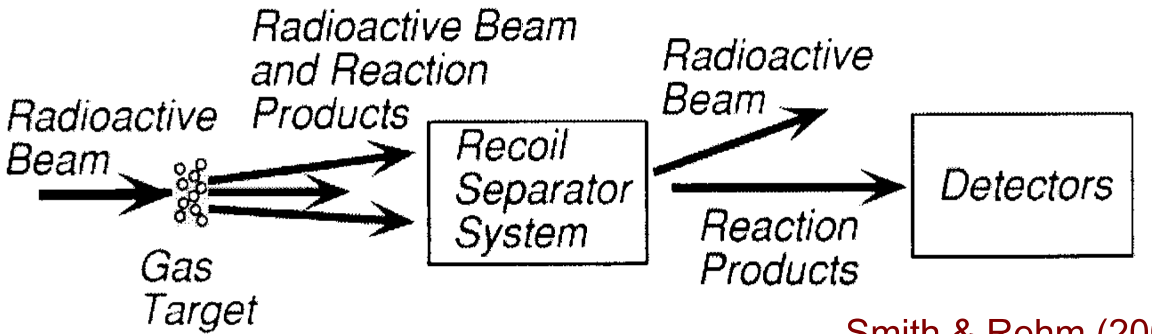
$X(p,\gamma)Y$
$X(\alpha,\gamma)Y$
among the most common reactions in nuclear astrophysics

1. **heavy recoil detection**

inverse kinematics $\Rightarrow$ forward peaked emission ($\theta \sim 1^o$)

$\Rightarrow$ detection efficiency ~ 100%

BUT: high suppression factors required (10^{10}-10^{15})



Smith & Rehm (2001)

2. **γ-ray detection** low efficiency $\Rightarrow$ ~ 4π coverage needed

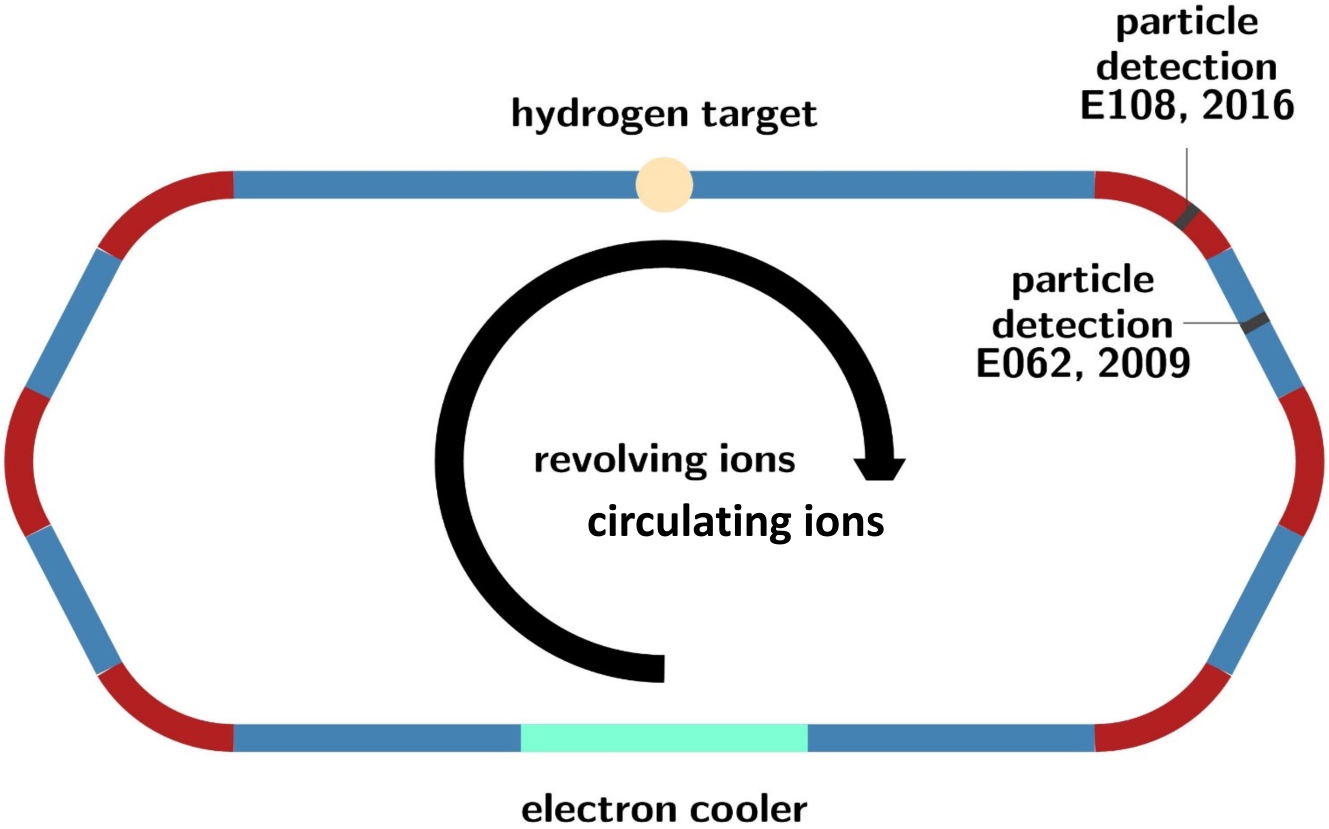
γ-ray background induced by β^+ beam decay

3. **delayed decay measurement** for example: $^{19}Ne(p,\gamma)^{20}Na(\beta^+)^{20}Ne^*(\alpha)^{16}O$

Reaction measurements at ion storage rings

Advantages of using inverse kinematics in storage rings:

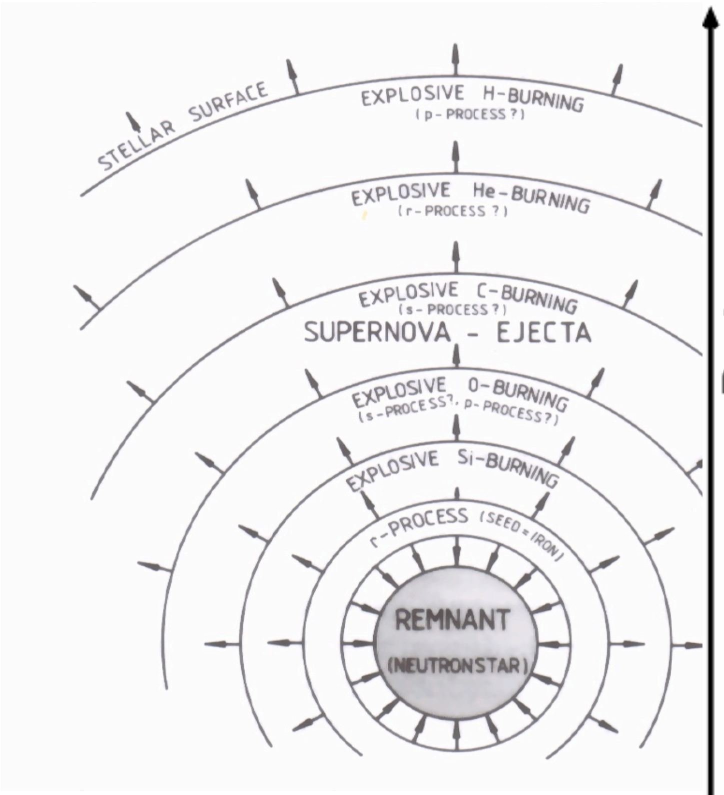
1. Heavy isotope can be radioactive or stable
2. Gas/jet target and beam species are pure

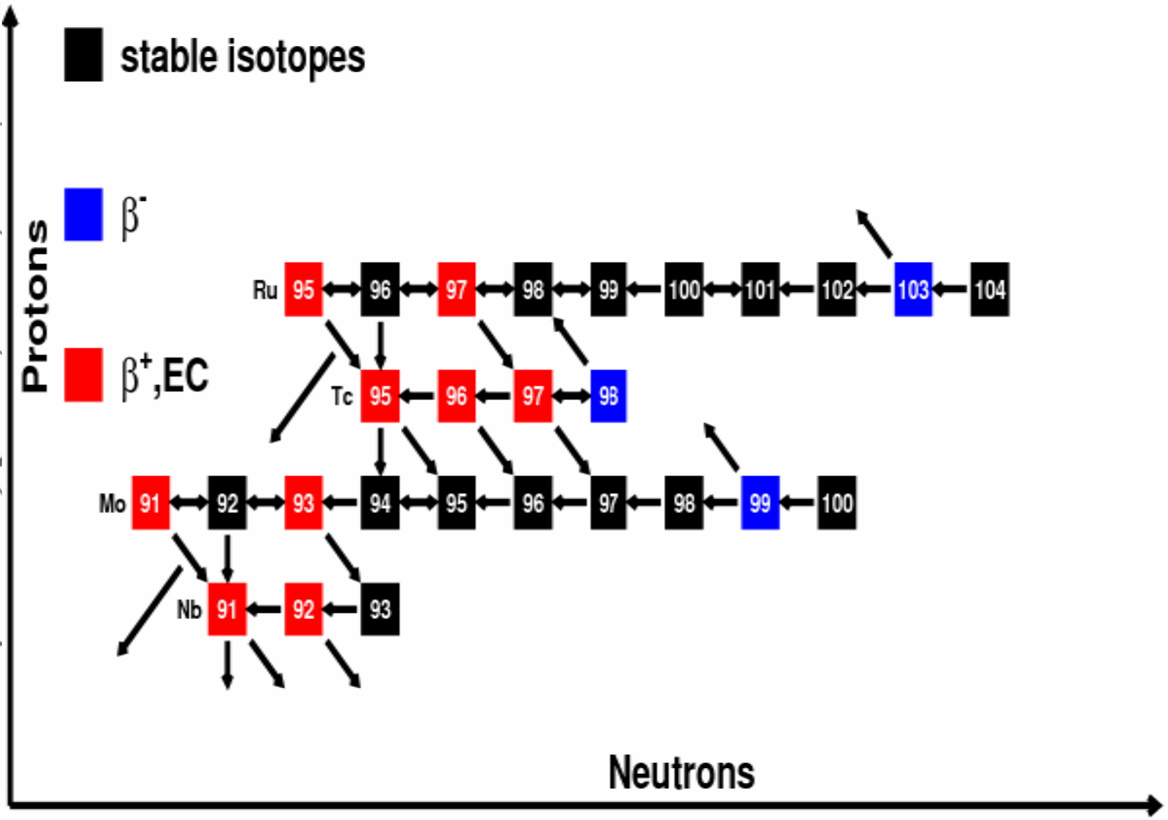


NucAR

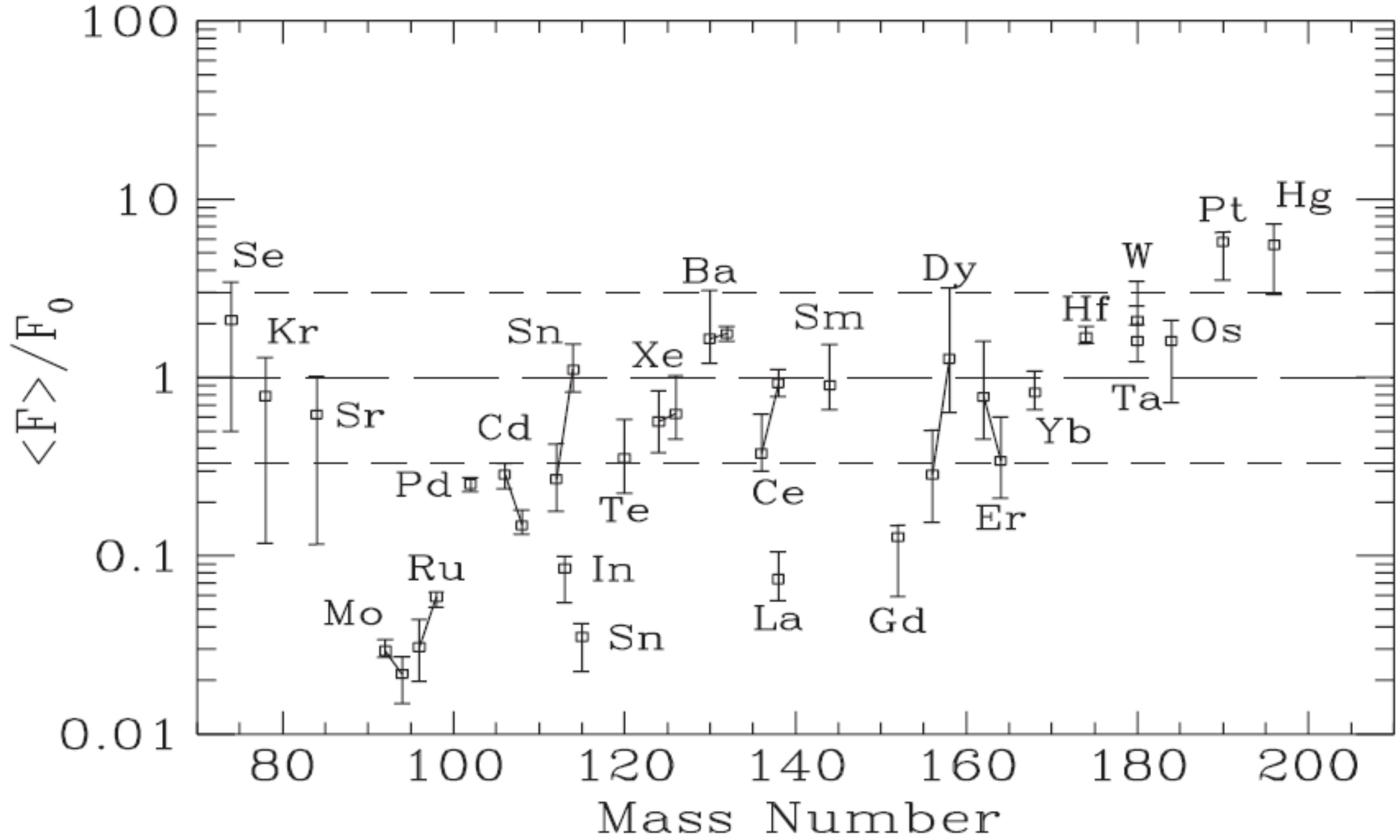
Puzzle of the origin of certain highly abundant p-nuclei

eg ^{92,94}Mo and ^{96}Ru



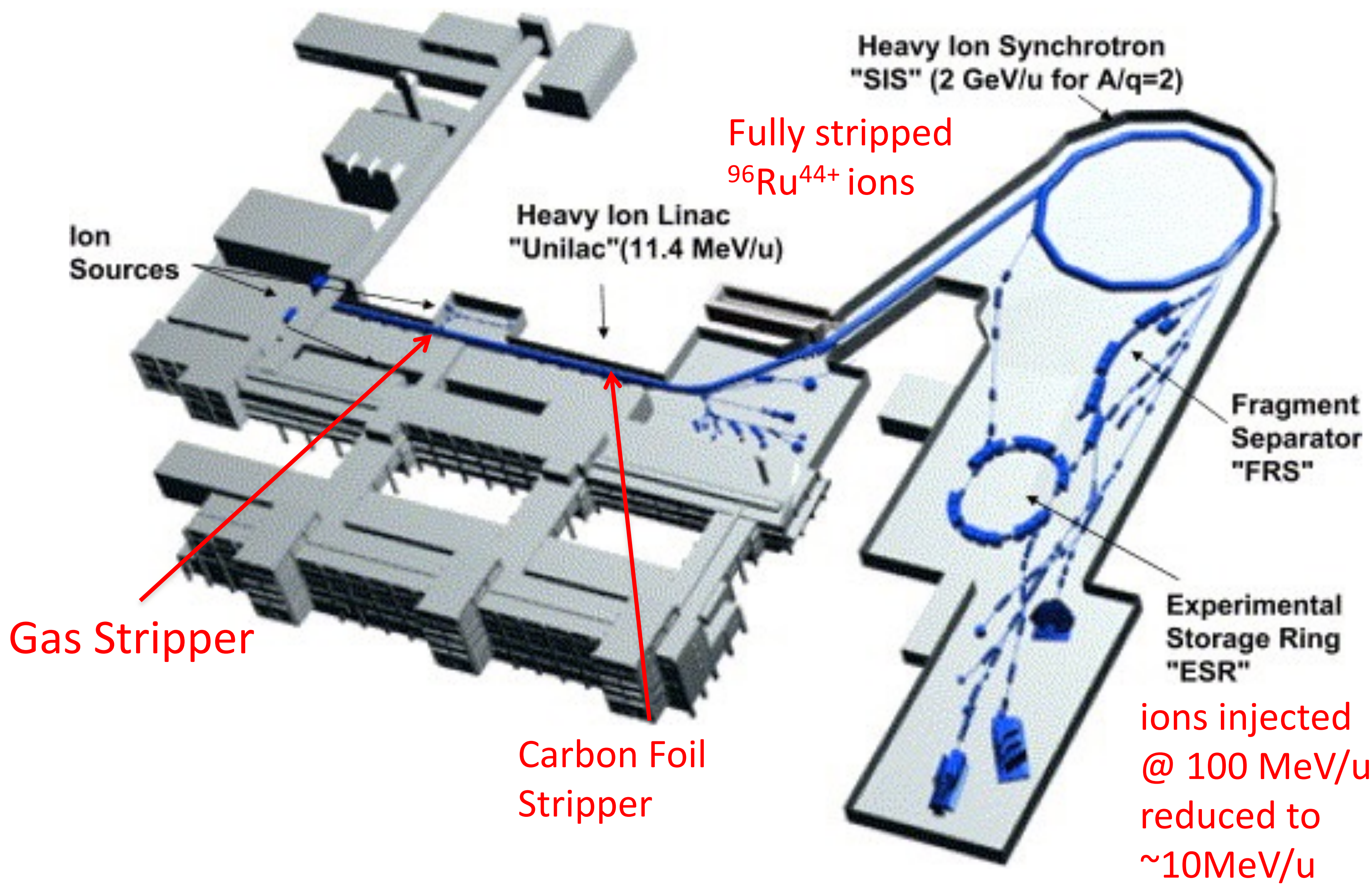


Predicted p-process abundances compared to observations

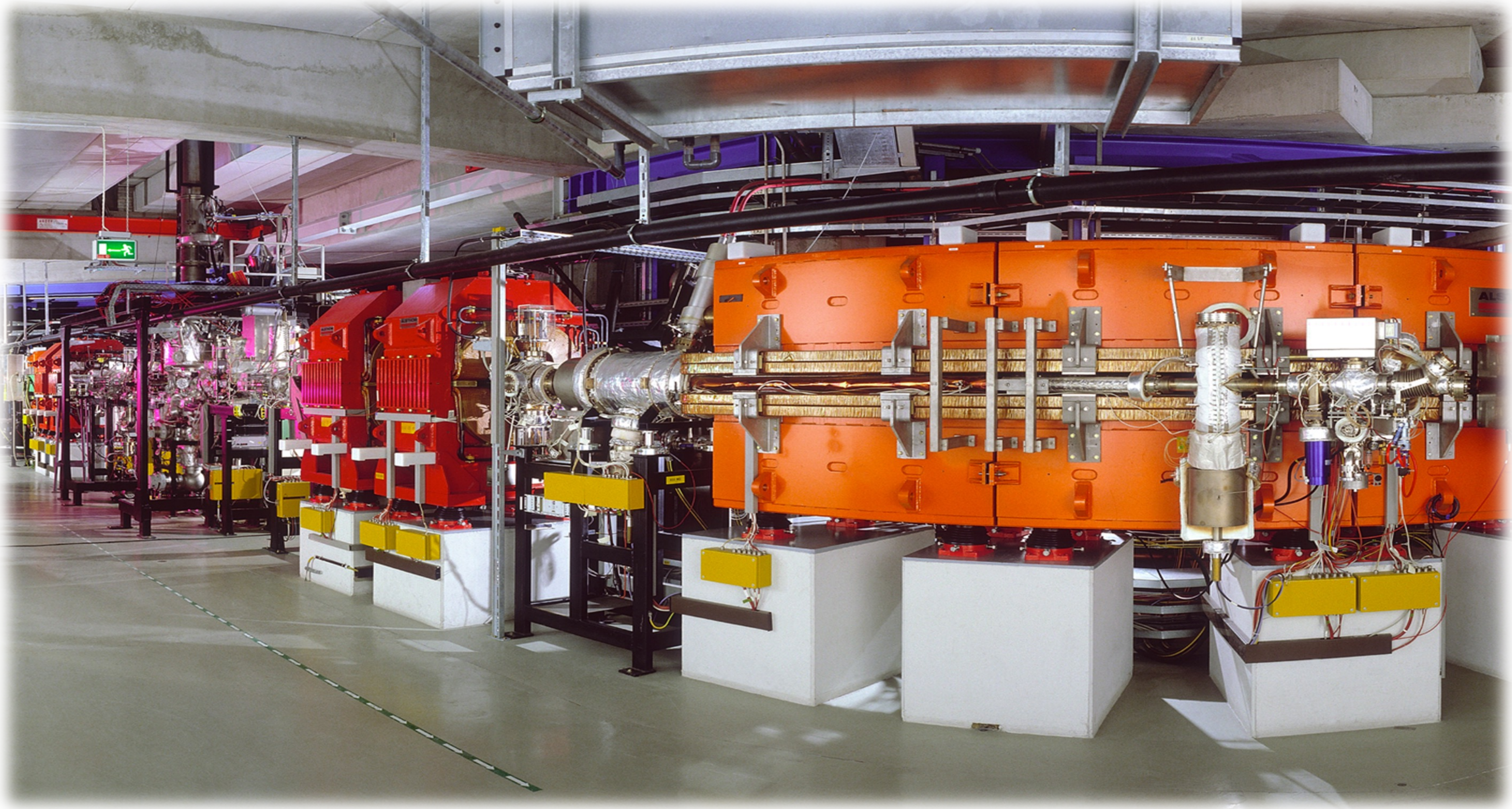


Arnould & Goriely Phys. Rep. **384**,1 (2003)

Study of $^{96}Ru(p,\gamma)^{97}Rh$ reaction with decelerated beams using the ESR storage ring at GSI

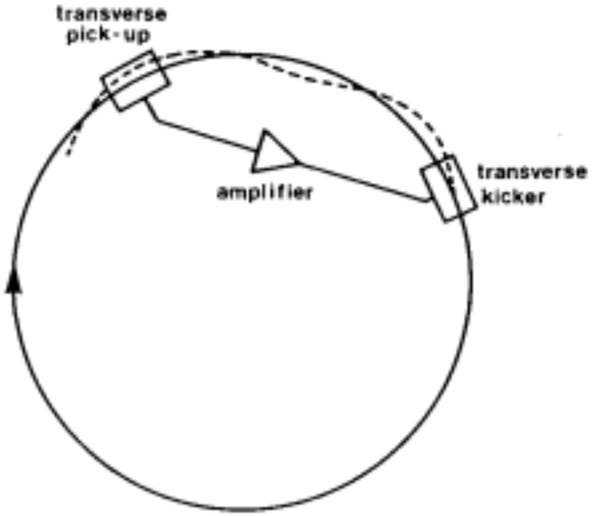


Ions cooled and decelerated to ~10 MeV/u in ESR



Stochastic Cooling

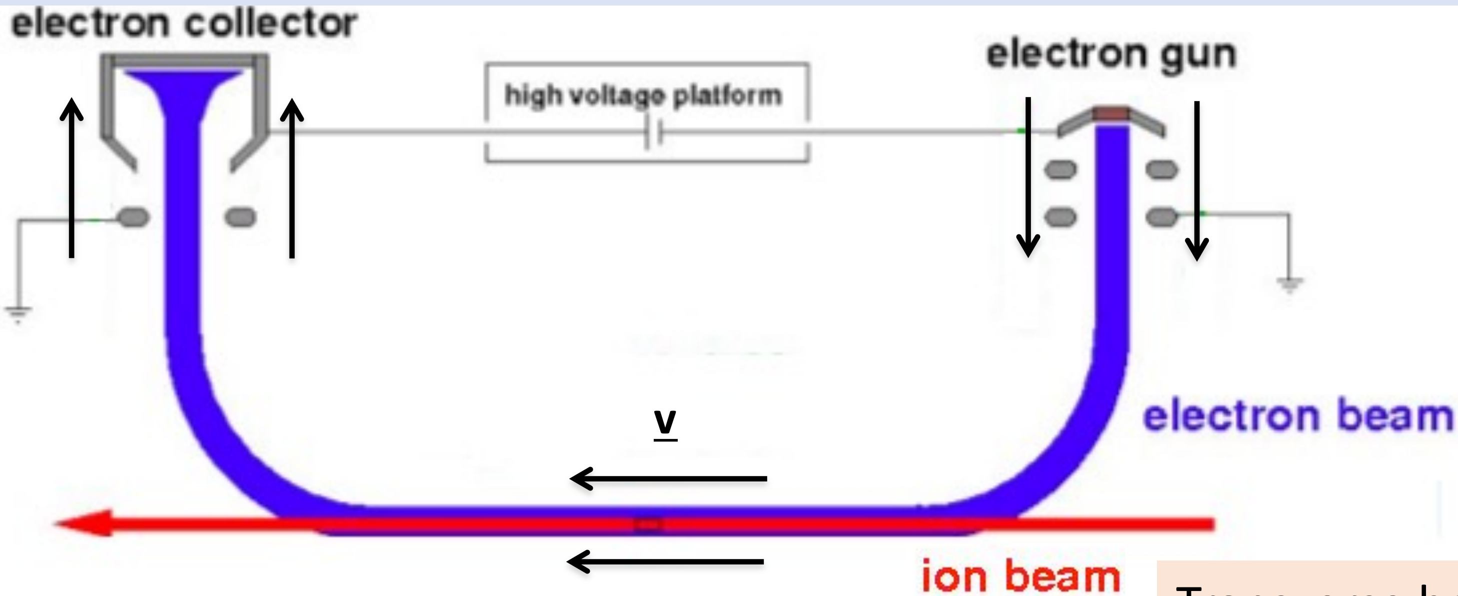
- Used for fast pre-cooling of **hot fragment beams.**
- Simon Van der Meer shared Nobel prize with Carlo Rubbia (1984).



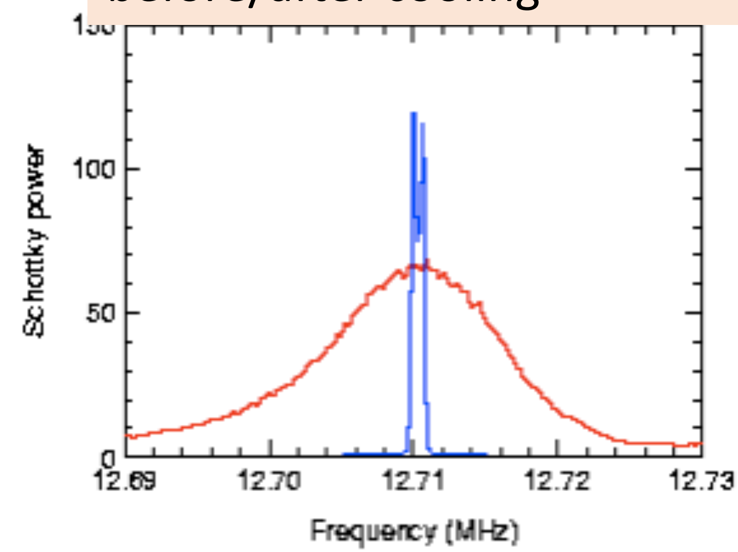
Demonstration of Stochastic cooling for a single ion.

Taken from Simon Van der Meer Nobel prize lecture, 1984

Electron Cooling of the Beam



Transverse beam profile
before/after cooling



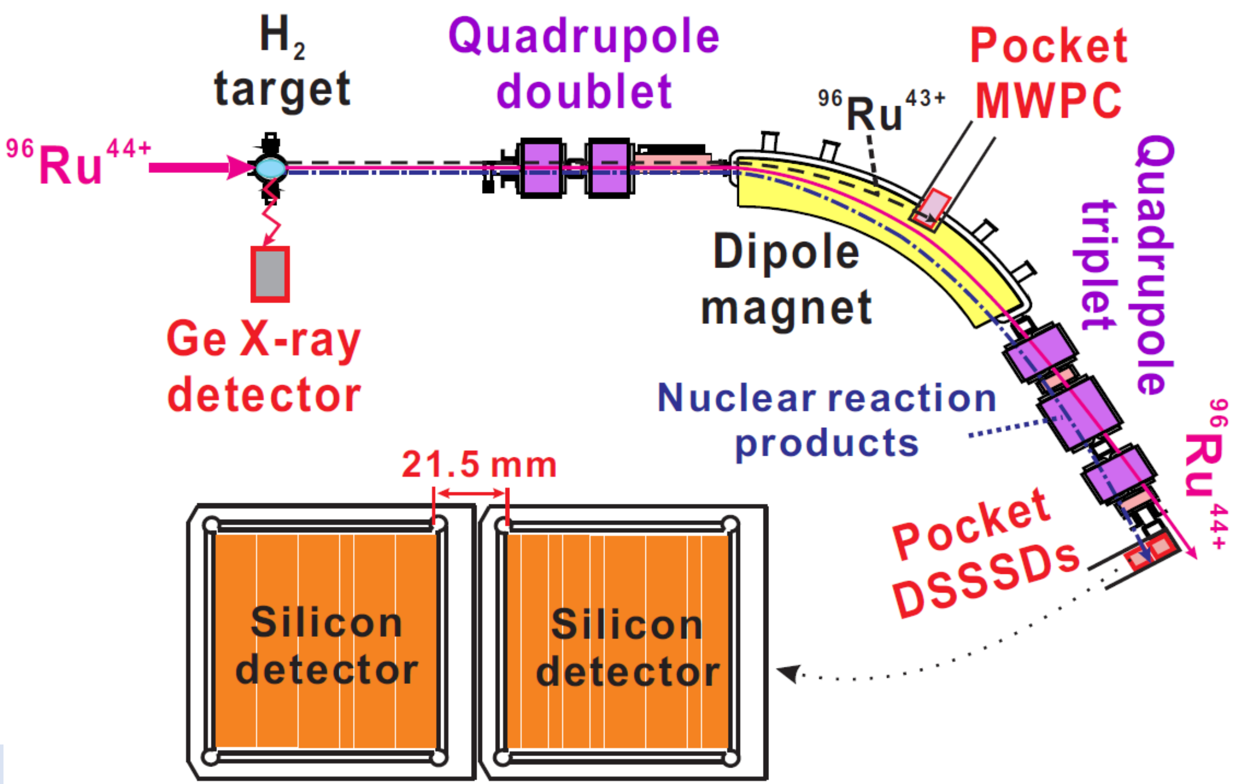
Electron cooler
at the ESR

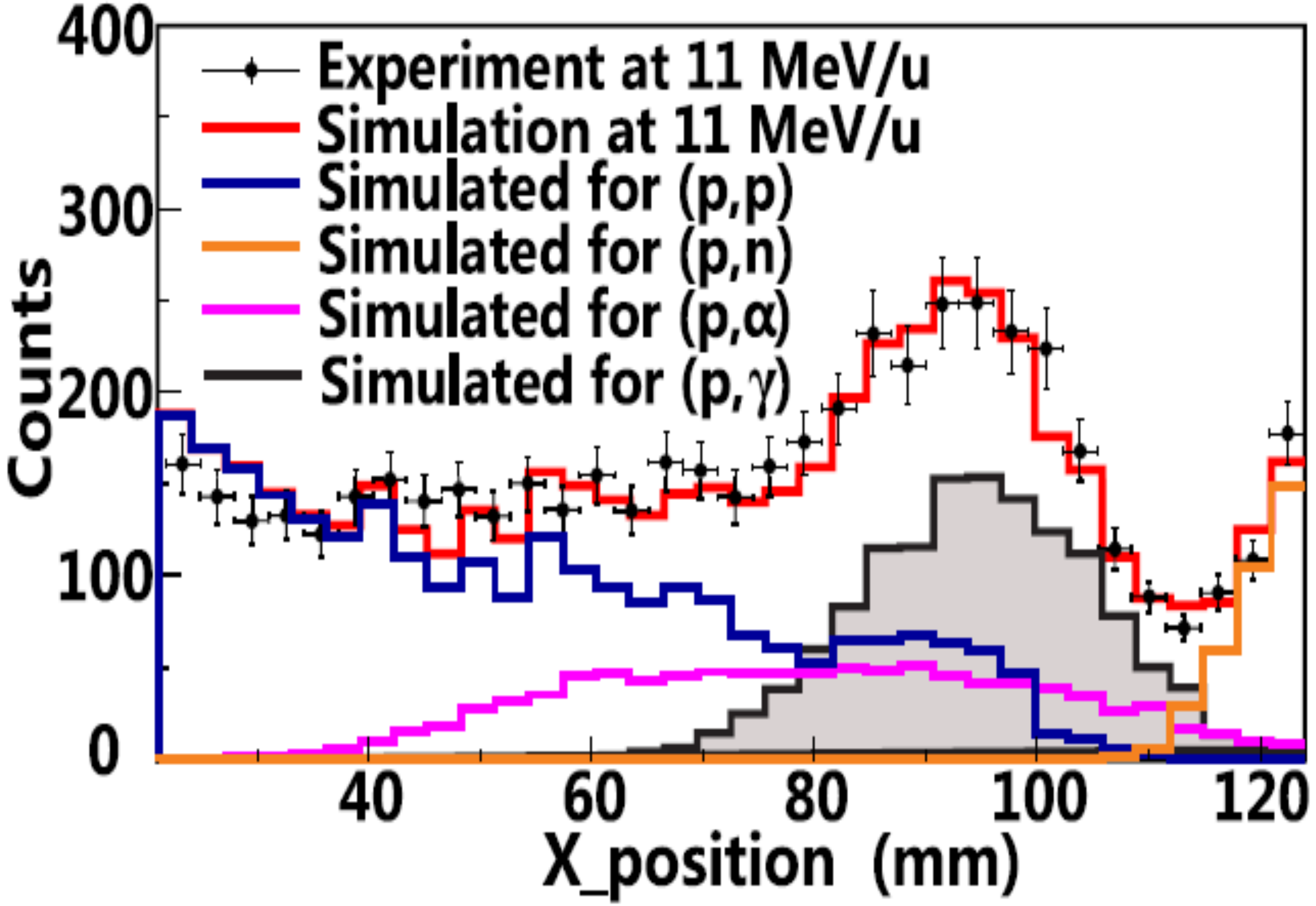
Physics Today
search and discovery
Physics Today **68**, 11, 12 (2015)

Particle storage ring enables a role reversal in proton capture

PHYSICAL REVIEW C **92**, 035803 (2015)

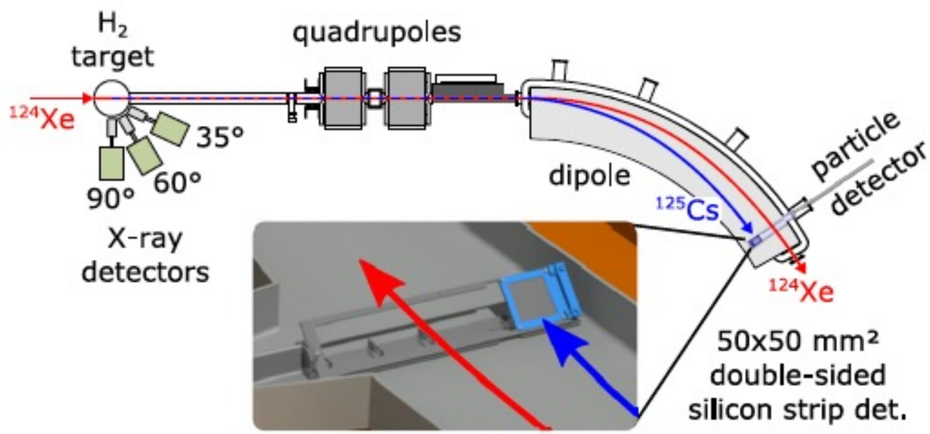
First measurement of the ^{96}Ru$(p,\gamma)^{97}$Rh cross section for the p process with a storage ring



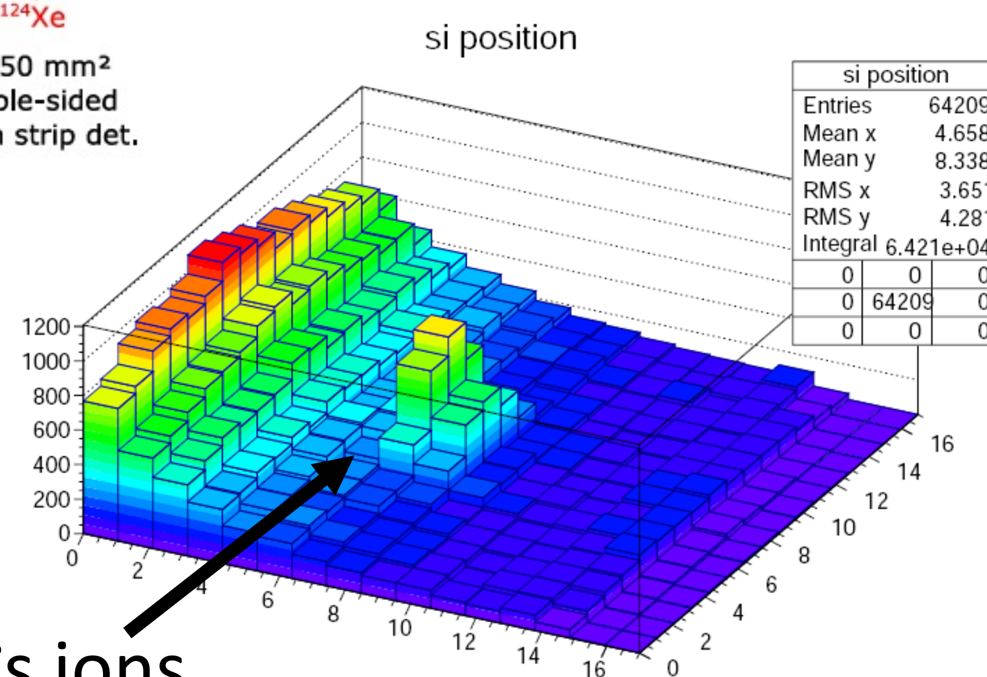

Experiment at 11 MeV/u
Simulation at 11 MeV/u
Simulated for (p,p)
Simulated for (p,n)
Simulated for (p,α)
Simulated for (p,γ)
Counts
X_position (mm)
400
300
200
100
0
40
60
80
100
120

$^{124}Xe(p,\gamma)^{125}Cs$ particle detectors in Ultra High Vacuum

J. Glorius et al., Phys. Rev. Lett. 122, 092701 (2019)



… allowed to measure reactions close to stellar particle energies



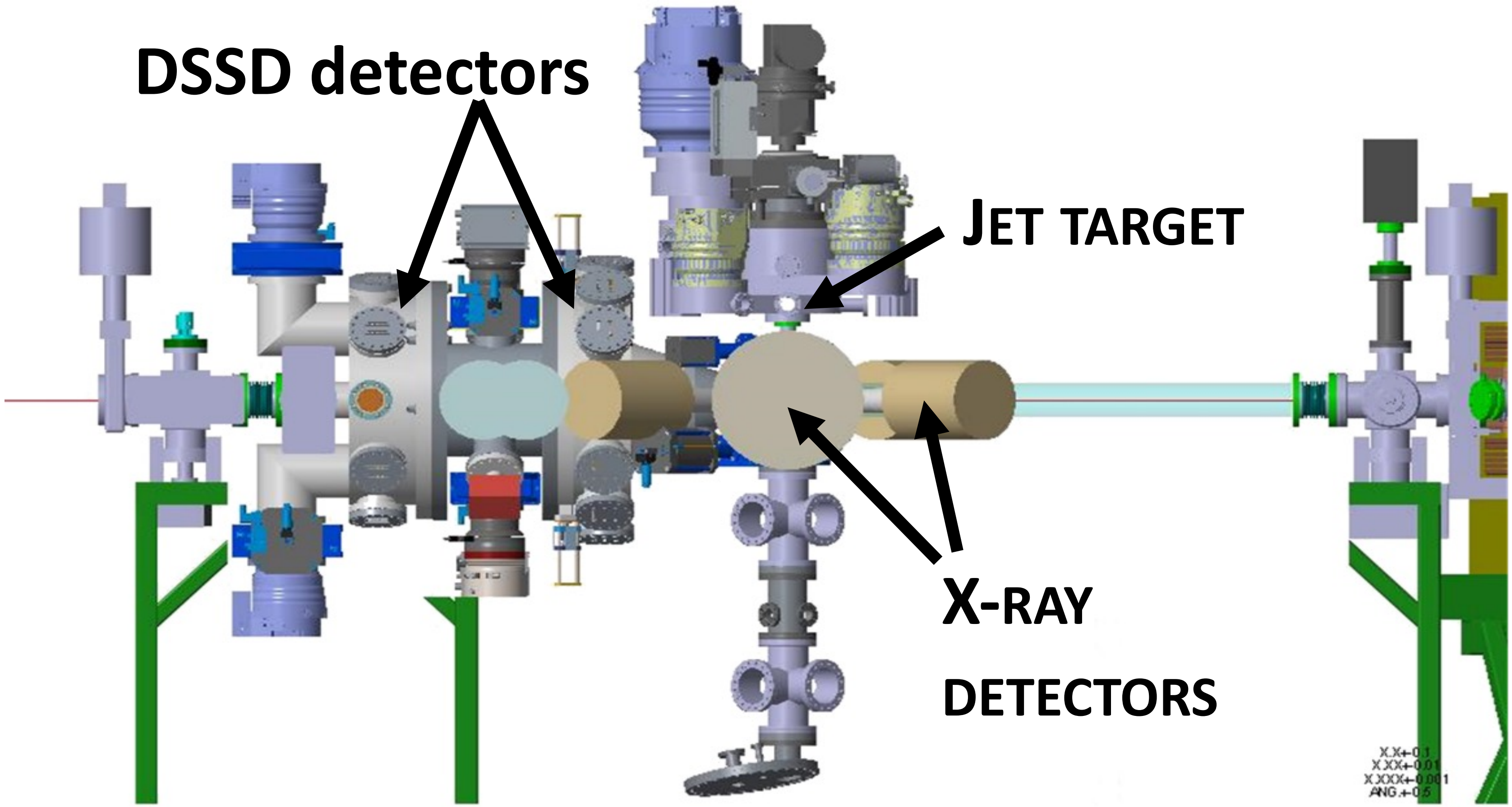
^{125}Cs ions

Measurements at Stellar Energies

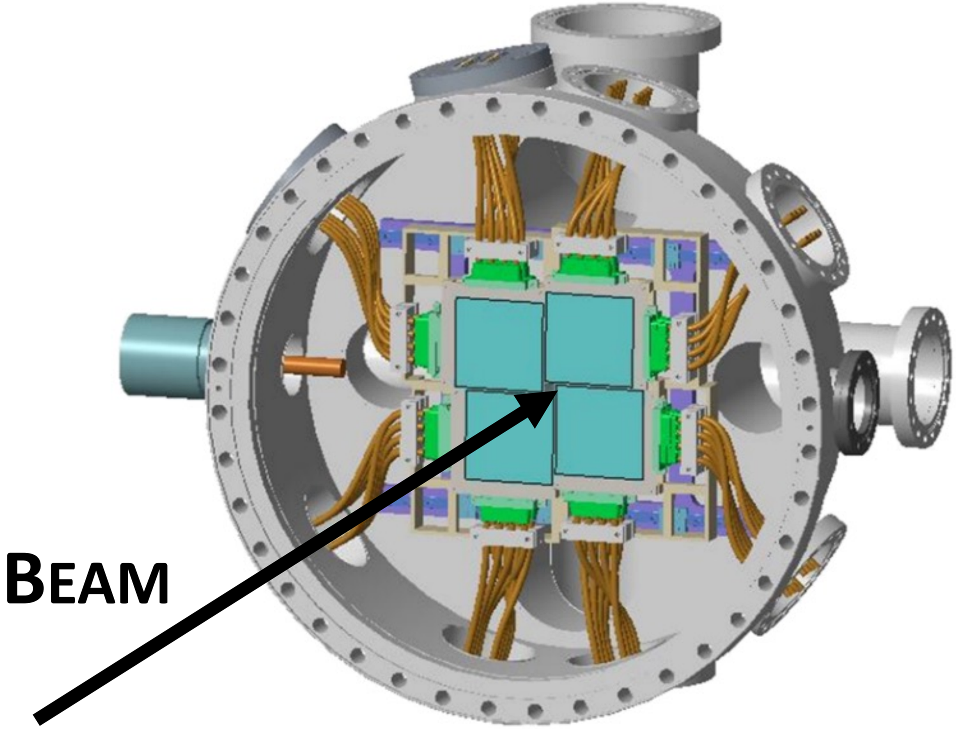
CRYRING

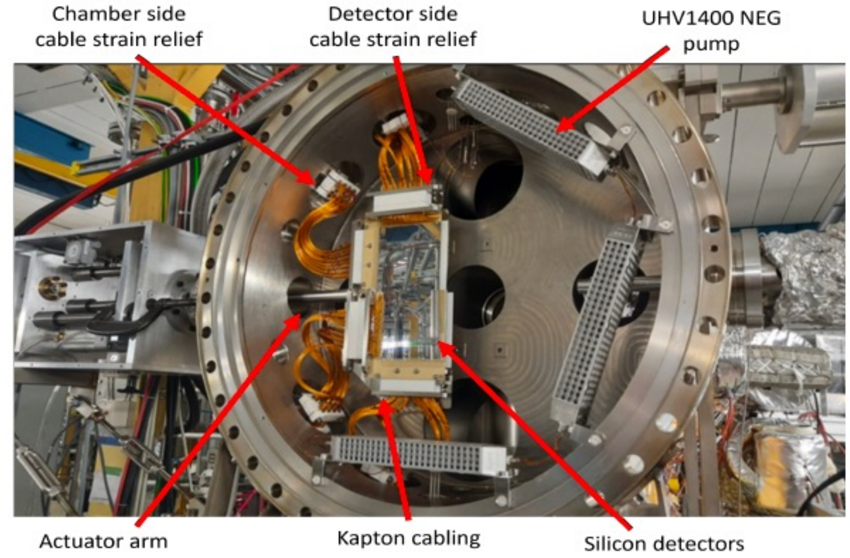
PART OF FAIR PHASE-0

NUCLEAR ASTROPHYSICAL REACTION STUDIES USING THE CRYRING ARRAY FOR REACTION MEASUREMENTS (CARME)



C. Bruno et al.,NIMA Volume 1048, (2023), 168007
J. Marsh, PhD Thesis (U. Edinburgh 2023)





J. Marsh, PhD Thesis (U. Edinburgh 2023)

This system will be used for **high resolution** charge particle reaction studies for nuclear astrophysics including:

I. Direct astrophysical reaction measurements e.g. (p,α),(α,p)
II. Indirect reactions probing key resonance properties e.g. (d,p)

First nuclear astro measurement scheduled for Feb 2023 (Ultra-high resolution study of the ^{15}O(α,α)^{15}O, PIs Bruno & Woods)

Reactions with Neutron Beams

FEATURES ⇒ no Coulomb barrier

⇒ neutrons to not lose energy in target – either transmitted or absorbed/scattered

CHALLENGES ⇒ free neutrons unstable, hence stable or long-lived reaction partners

⇒ neutron energy cannot be ‘tuned’ in accelerator

⇒ background from scattered neutrons

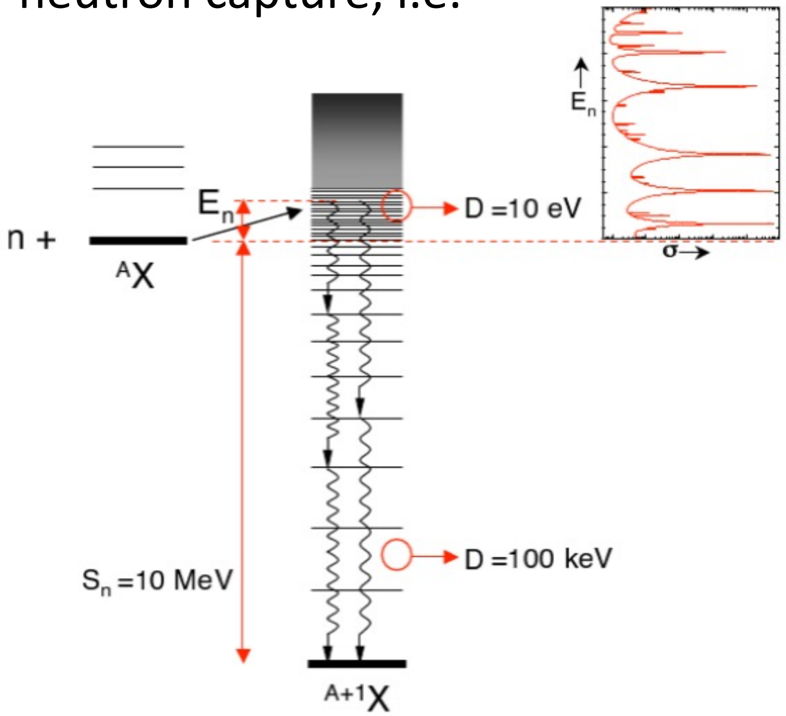
REQUIREMENTS ⇒ Intense neutron source

⇒ ‘white’ neutron spectrum or spectrum with the ’right’ energy for the application

⇒ detection system insensitive to neutrons

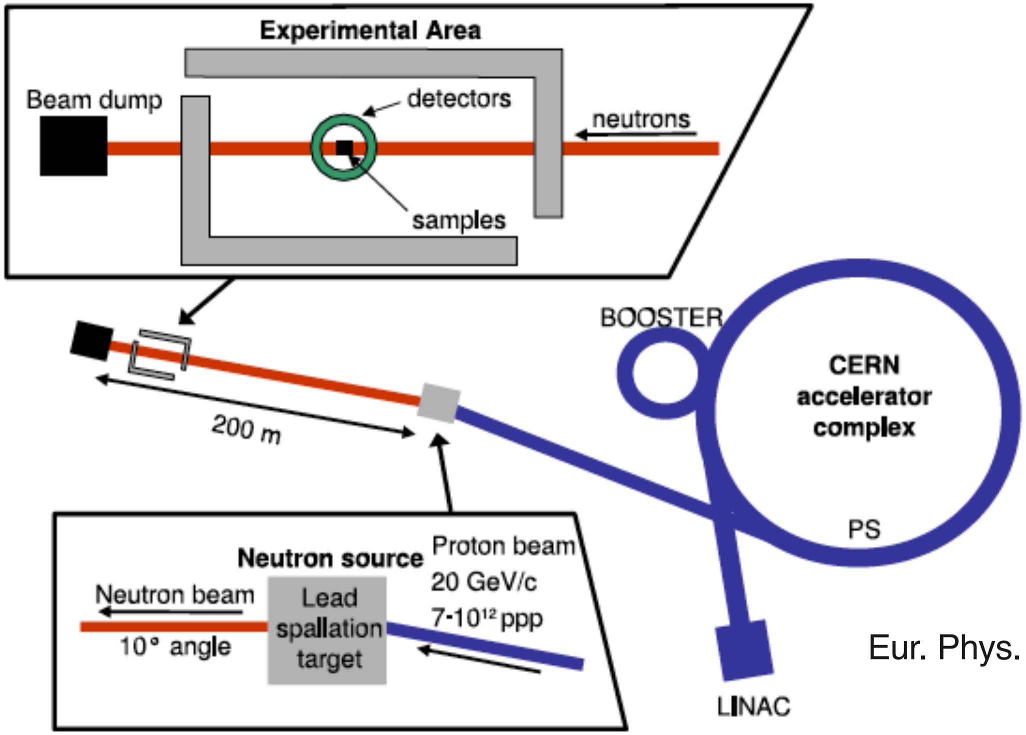
Time-of-Flight technique

- applicable to all stable and long-lived nuclei
- need pulsed neutron source for E_n determination via ToF
- measurement of prompt emission after neutron capture, i.e. prompt γ-rays or p,α, etc
- measurement of resonance properties
- main background: neutrons scattered from the target: → need γ-ray detectors insensitive to neutron reaction

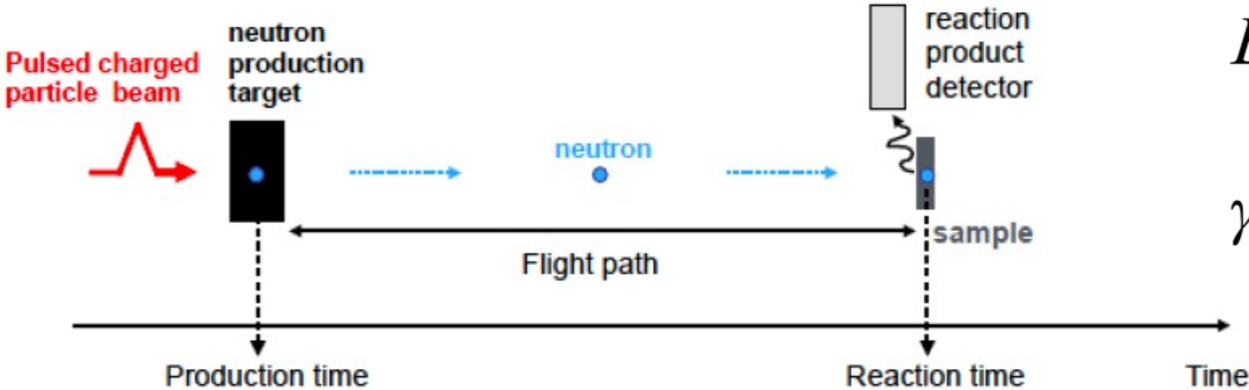


compound neutron capture reaction

The n_TOF facility at CERN



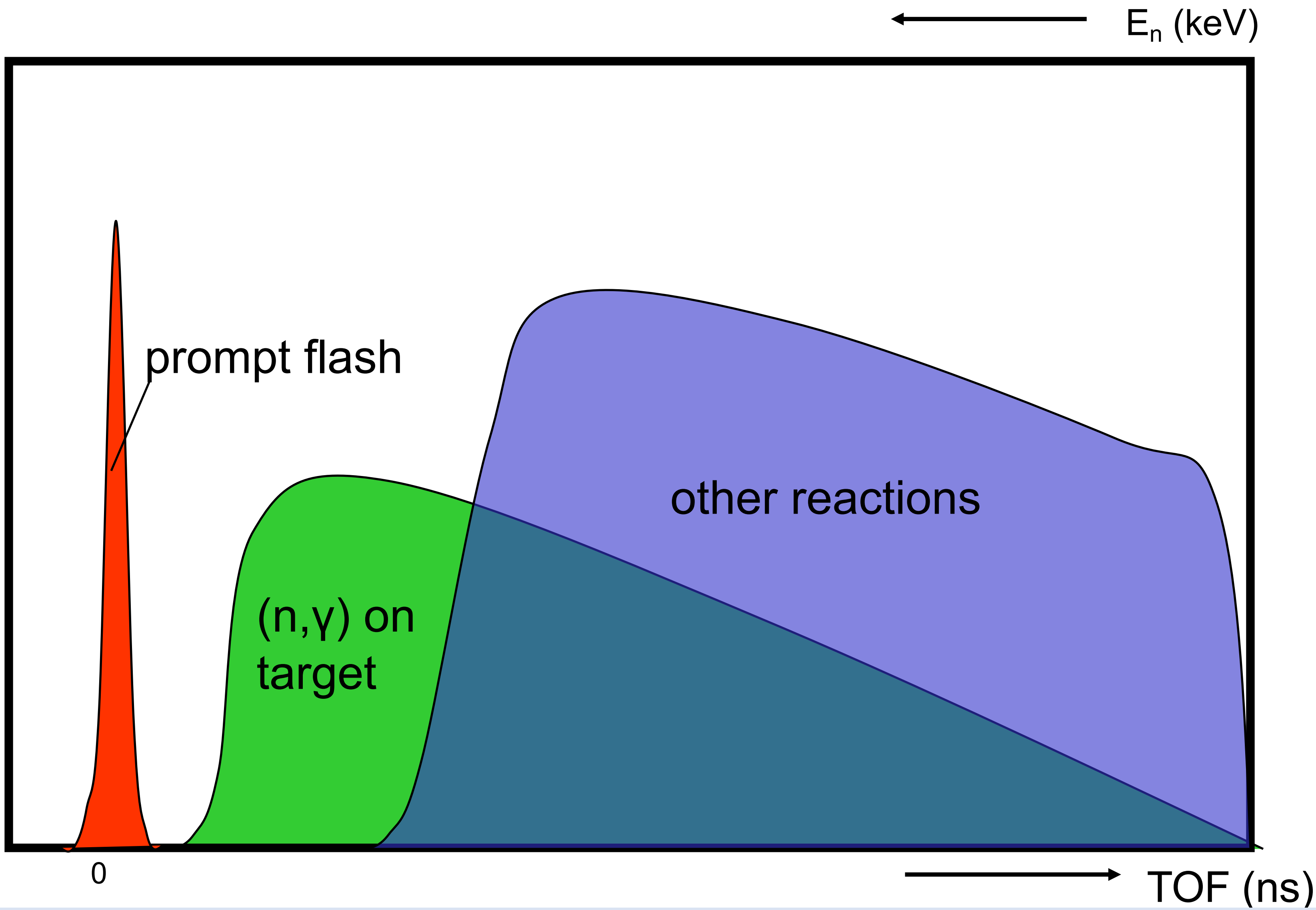
Eur. Phys. J. A (2013) 49: 27



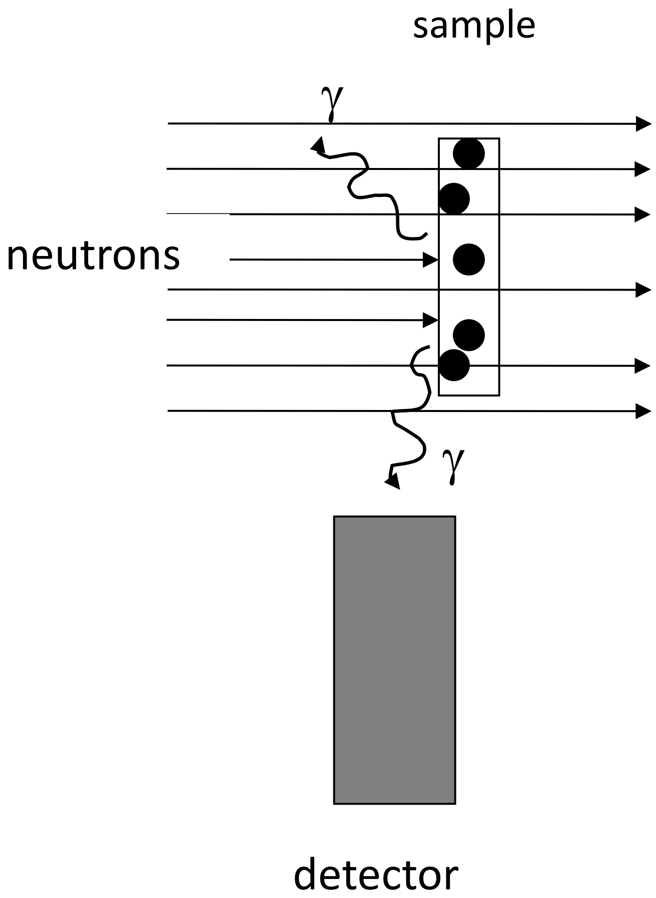
$$E_n = mc^2(\gamma - 1)$$

$$\gamma = \left(1 - \frac{(L/tof)}{c^2}\right)^{-1/2}$$

Schematic TOF Spectrum



Radiative Neutron Capture Yield



Capture Yield $Y_R(E_n)$:

Probability that reaction takes place →

0<Y<1

$$Y_R(E_n) = C \,/\, \varepsilon\,\Phi(E_n)$$

Counts

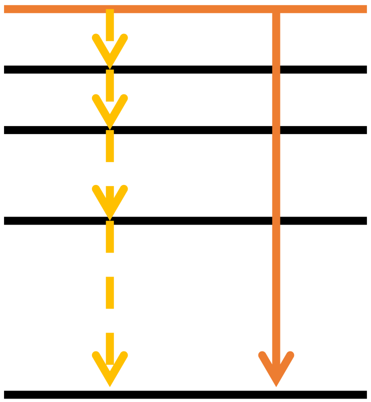
Incident neutrons on sample

Efficiency to detect a capture event

γ-ray Detection

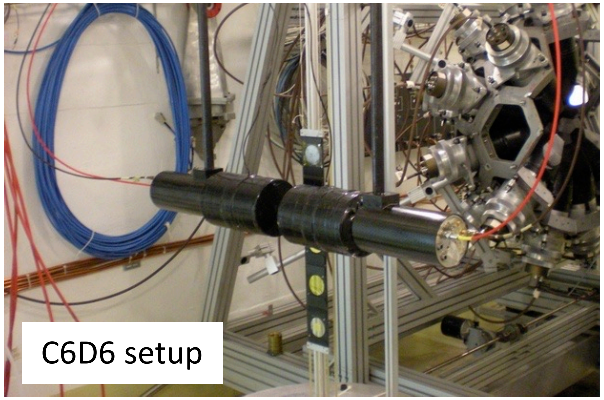
Considerations:

- Efficiency to detect capture event ε_C independent of fluctuations in cascade
- Good timing characteristics
- low sensitivity to neutrons



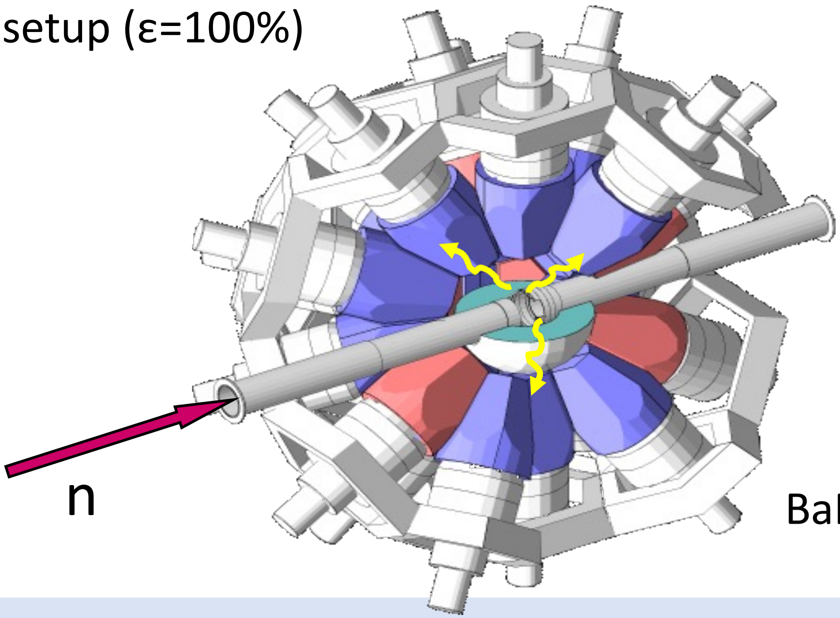
Single γ's (Total Energy Detection)

- Moxon-Rae
- Pulse Height Weighting



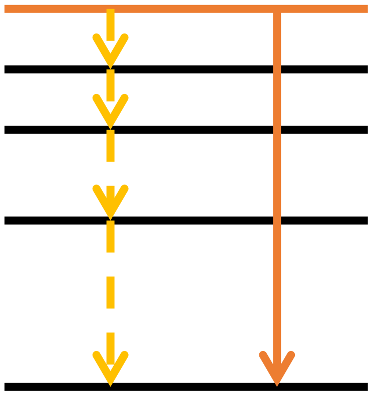
Total Cascade detection

- 4π setup (ε=100%)



BaF_2 array

Total Energy Detection



For γ-detection efficiency ε_γ proportional to γ-ray energy E_γ and small detection efficiency the cascade efficiency ε_C is proportional to the excitation energy E_C of the nucleus:

$$\varepsilon_\gamma = kE_\gamma \quad \Rightarrow \quad \varepsilon_c = 1 - \prod_i (1 - \varepsilon_{\gamma,i})$$

$$\Rightarrow \quad \varepsilon_C \approx \sum_i \varepsilon_{\gamma,i} = \sum_i k\, E_{\gamma,i} = kE_c$$

1) Design detector with $\varepsilon_\gamma = kE_\gamma$ (Moxon-Rae Detectors)

2) Manipulate signals a posteriori to achieve proportionality (Pulse Height Weighting Technique)

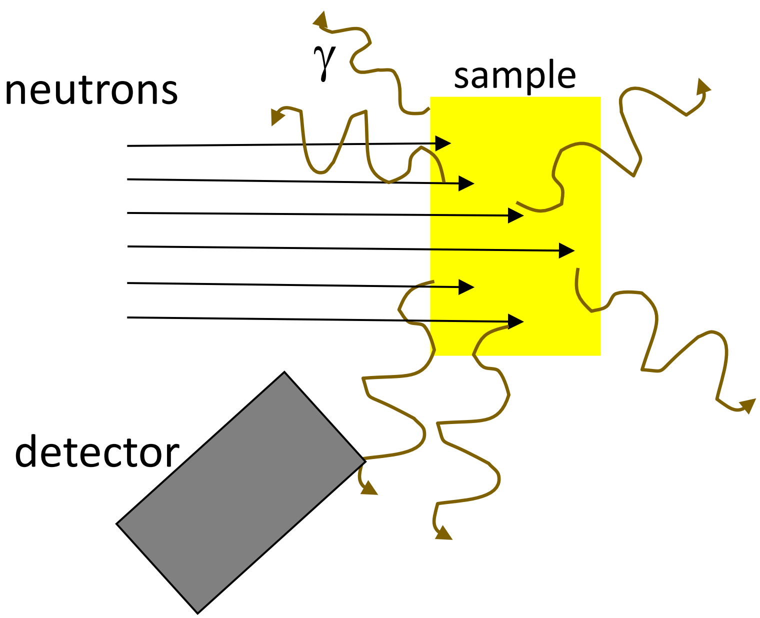
R. L. Macklin and R. H. Gibbons, Phys. Rev. 159, 1007 (1967).
U. Abbondanno and the n_TOF Collaboration, NIM A 521, 454 (2004).

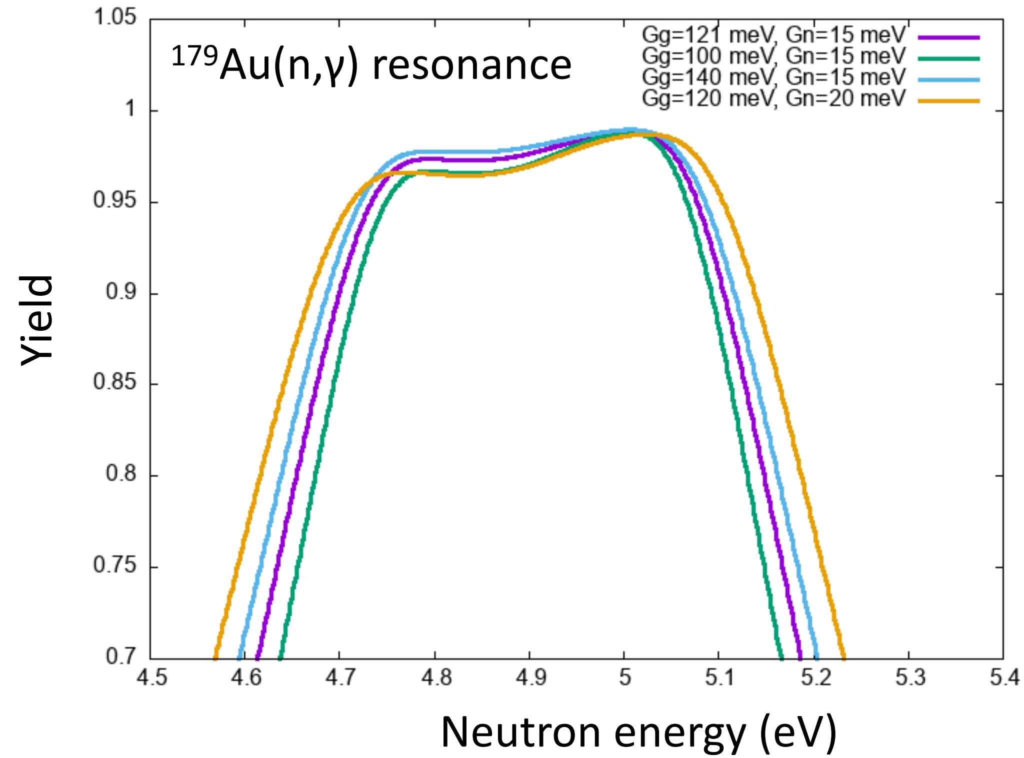
Neutrons incident on sample - Neutron flux ϕ

Determination of $\Phi(E_n)$ using a reaction(s) with a well known cross section.

In some cases, Φ at a particular energy can be determined with high accuray using the **Saturated Resonance technique:**

→ Find resonance with capture >> scattering and large cross section
→ make target thick enough so no neutron is transmitted
→ Close to 100% of neutrons react and cause a gamma cascade





R. L. Macklin et al. NIM 164, 213 (1979).

Neutron Capture Resonances

for a single isolated resonance:

resonant cross section given by **Breit-Wigner expression**

$$\sigma(E) = \pi ƛ^2 \frac{2J+1}{(2J_n+1)(2J_T+1)} \frac{\Gamma_\gamma \Gamma_n}{(E-E_R)^2 + (\Gamma_{TOT}/2)^2}$$

geometrical factor

$\propto 1/E$

spin factor g

J = spin of Resonance

J_n = spin of neutron (1/2)

J_T = spin of target

strongly energy-dependent term

Γ_n = partial width for decay via emission of neutron

= probability of compound formation via neutron

Γ_γ = partial width for decay via emission γ-ray

= probability of compound decay via γ-emission

Γ = total width of compound's excited state

$= \Gamma_n + \Gamma_\gamma + \ldots$

E_R = resonance energy

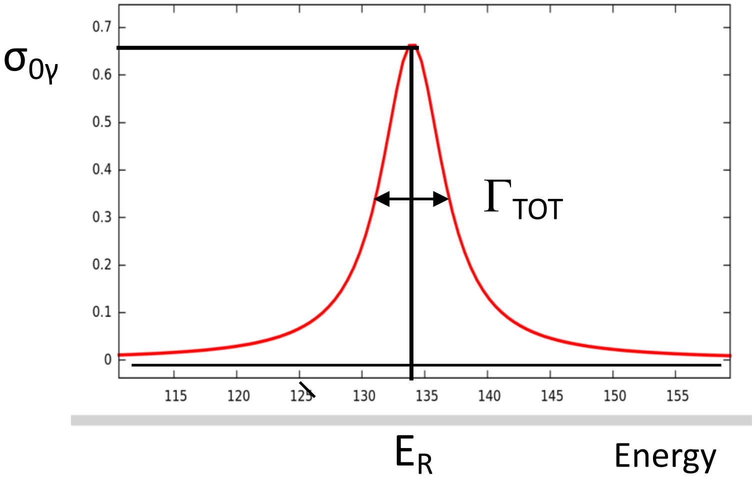
Neutron Capture Resonances

Assuming $\sigma_{TOT} \sim \sigma_\gamma + \sigma_n$

$$\sigma_{n\gamma}(E) = \pi ƛ^2 g \frac{\Gamma_\gamma \Gamma_n}{(E - E_R)^2 + (\Gamma_{TOT}/2)^2}$$

$$\sigma_{0\gamma} = \sigma(\mathrm{E}_R) = \pi ƛ^2 g \frac{\Gamma_\gamma \Gamma_n}{(\Gamma_{TOT}/2)^2} = \sigma_0 \frac{\Gamma_\gamma}{\Gamma_{TOT}}$$

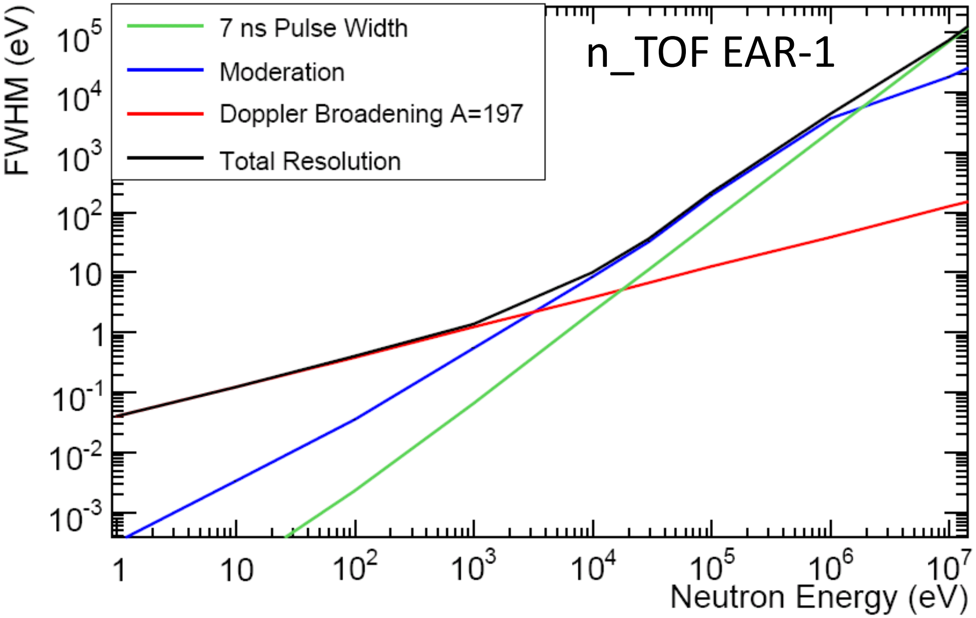
$$\sigma_0 = \sigma_{TOT}(\mathrm{E}_R) = 4\pi ƛ^2 g \frac{\Gamma_n}{\Gamma_{TOT}}$$

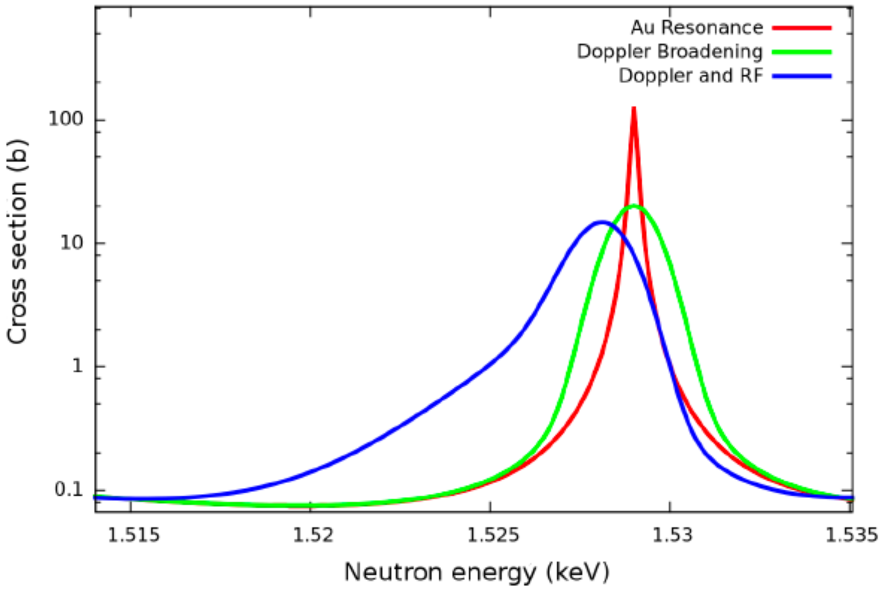


Very good resolution: all resonance parameters (E_R, J, Γ_γ, Γ_n) from capture and total cross section measurement

Resolution Broadening

- Pulse width
- Neutron production target + moderator
- Doppler broadening
- flight path length
- Data acquisition





Area Analysis

However $\Gamma_{exp} >> \Gamma_{nat}$ in most cases

→ Analysis yields the **Resonance Area**

$$A_{capture} \propto ng\Gamma_{\gamma}\Gamma_{n}/\Gamma_{TOT}$$

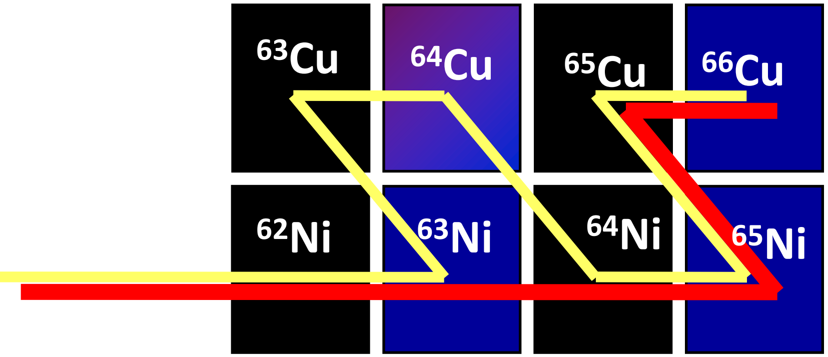
Can extract resonance parameters when combined with transmission measurement with a thin and thick sample:

$$A_{transmission,thick} \propto \sqrt{ng\Gamma_{n}\Gamma_{TOT}}$$

$$A_{transmission,thin} \propto ng\Gamma_{n}$$

thin... T~1
thick... T~0
n... areal density

s-process branching ^{63}Ni(n,γ)

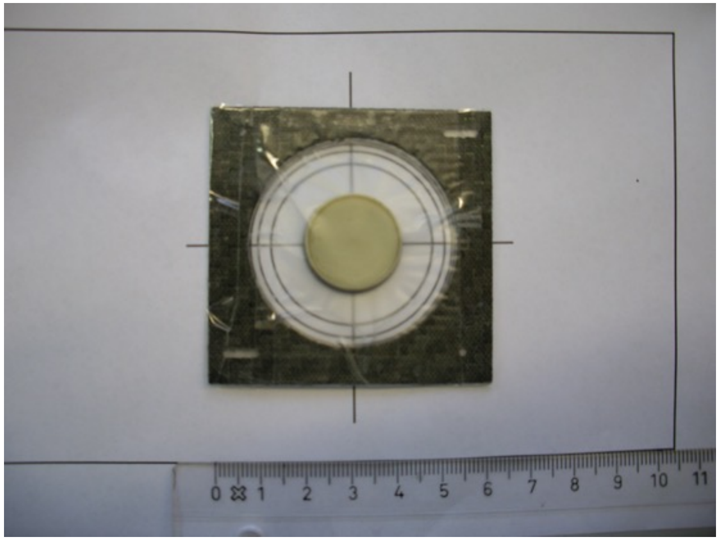


Measurement of ^{62}Ni(n,γ) and branching point ^{63}Ni(n,γ) at stellar energies at n_TOF

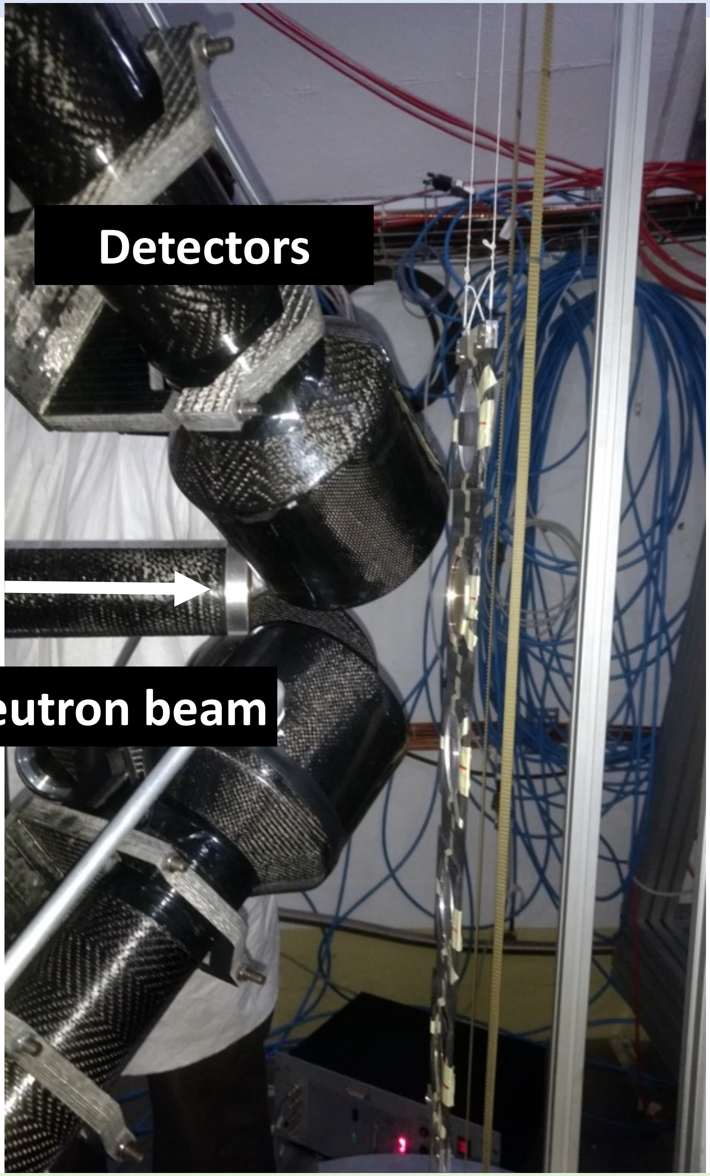
^{63}Ni is **radioactive** ($t_{1/2}$~100 y) → need to produce a radioactive target

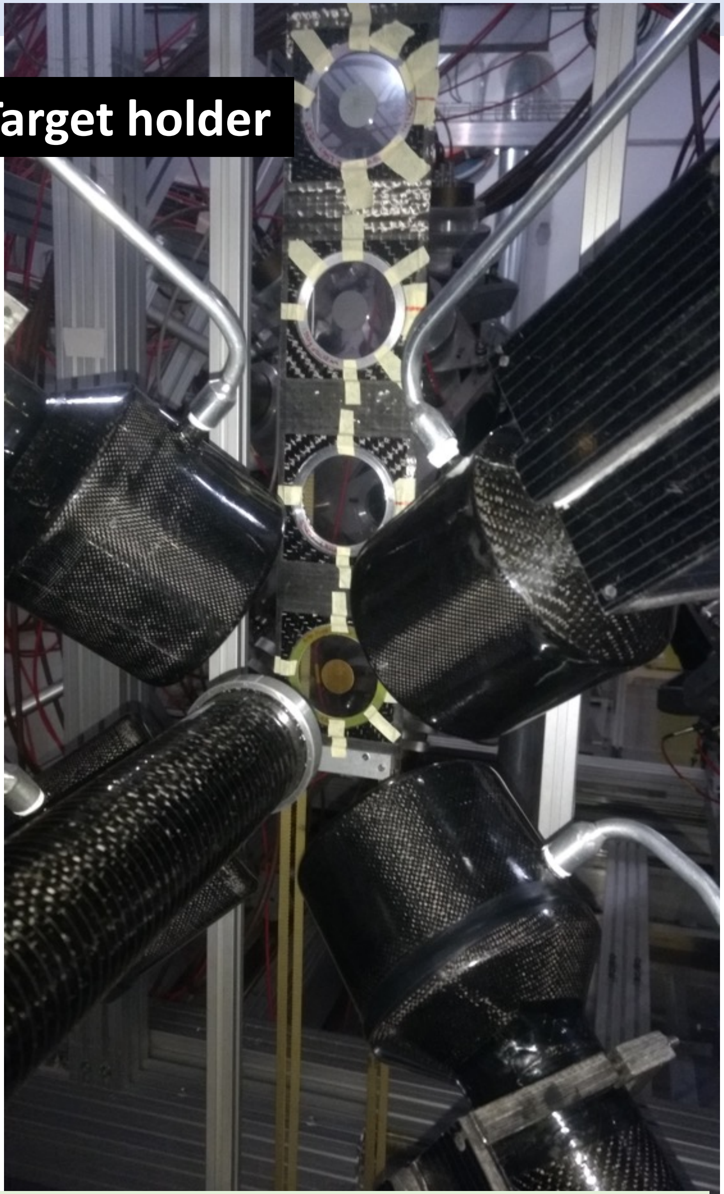
1) irradiation of ^{62}Ni at ILL thermal reactor (high cross sections and neutron flux)
2) chemical separation of contaminantsat PSI (other elements)

→ resulting target: ~100 mg ^{63}Ni, 900 mg ^{62}Ni



s-process branching $^{63}Ni(n,\gamma)$

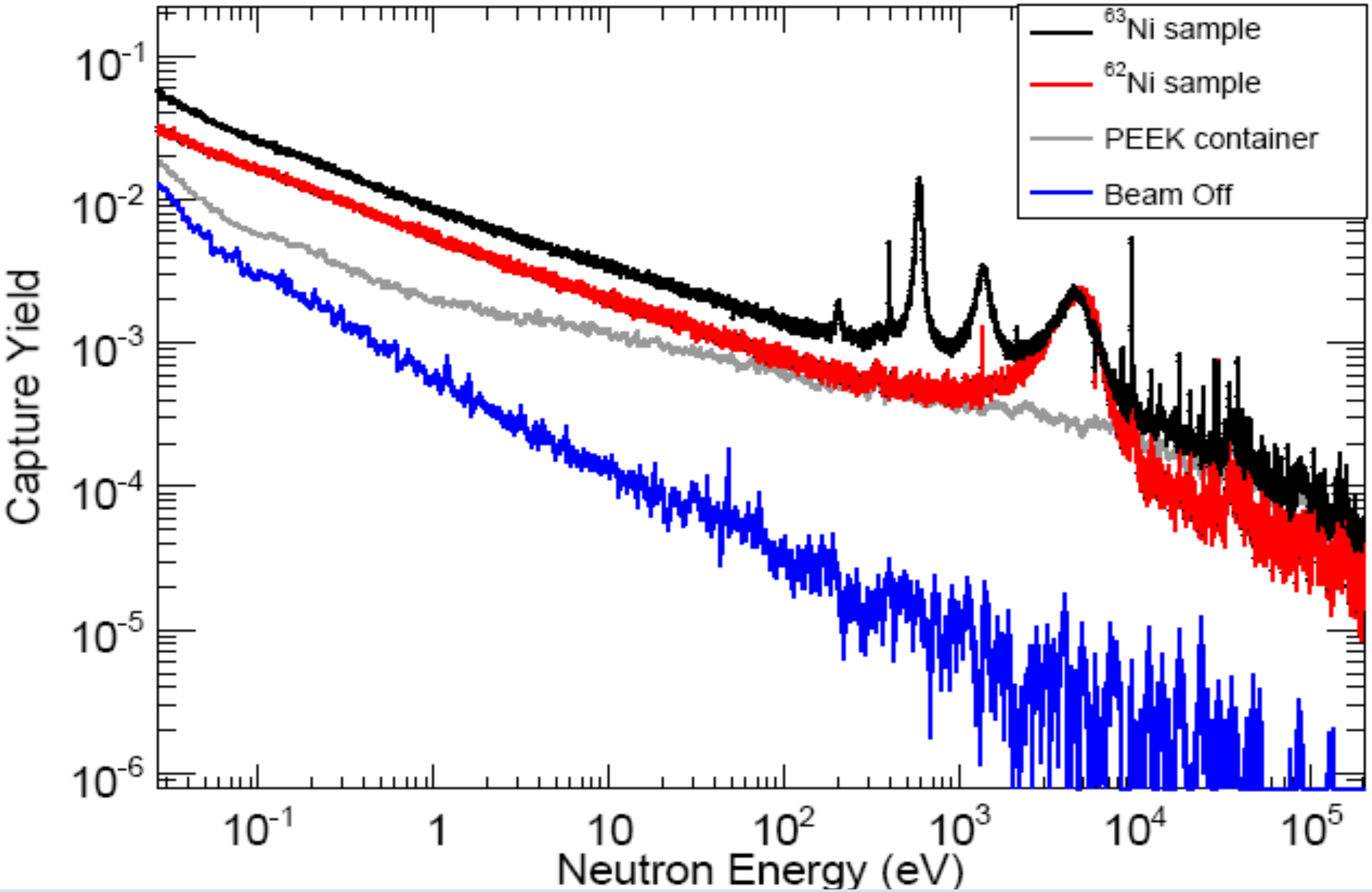




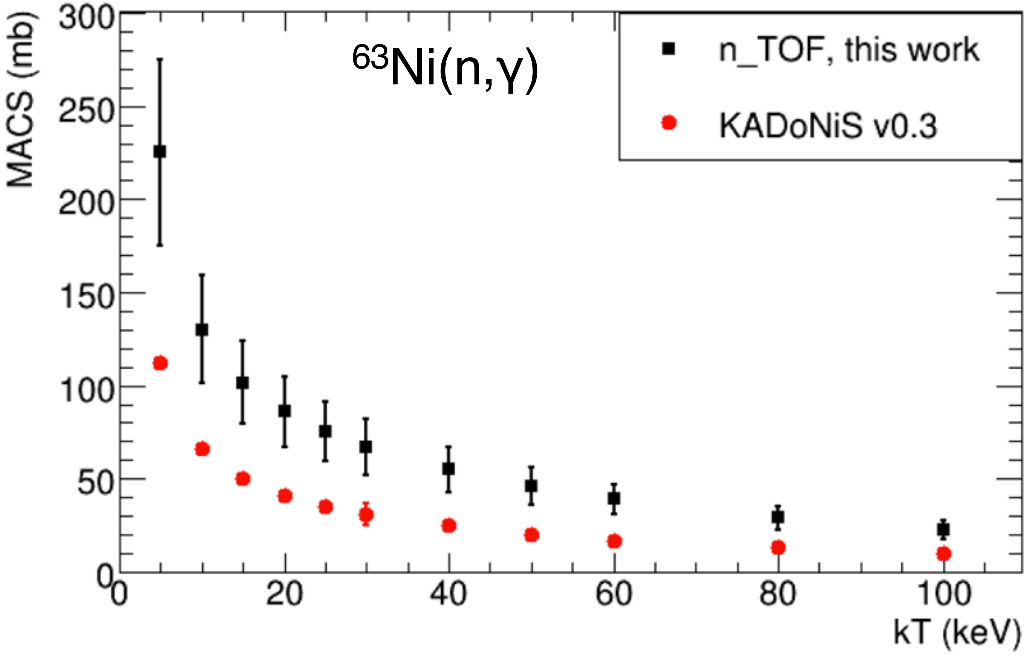
Setup for prompt γ-ray detection using scintillation detectors with low neutron sensitivity

s-process branching $^{63}Ni(n,\gamma)$

Typical neutron time-of-flight spectrum: neutron energy resolution $\Delta E/E \sim 10^{-3}$ at 1 keV → can access individual states for high A

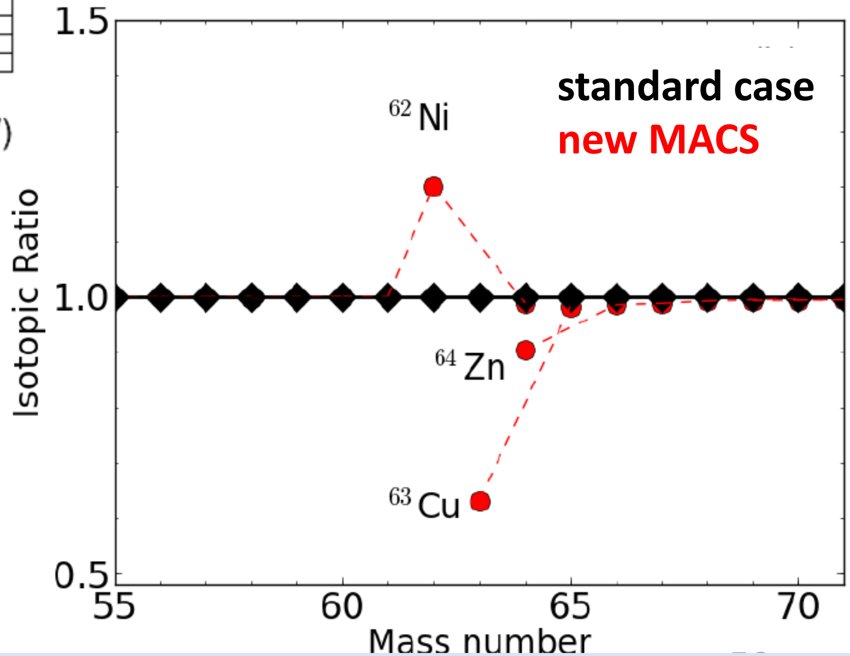


s-process branching $^{63}Ni(n,\gamma)$



Maxwellian averaged cross section ~2x higher than previous theoretical estimates + lower ^{62}Ni cross section than previous data

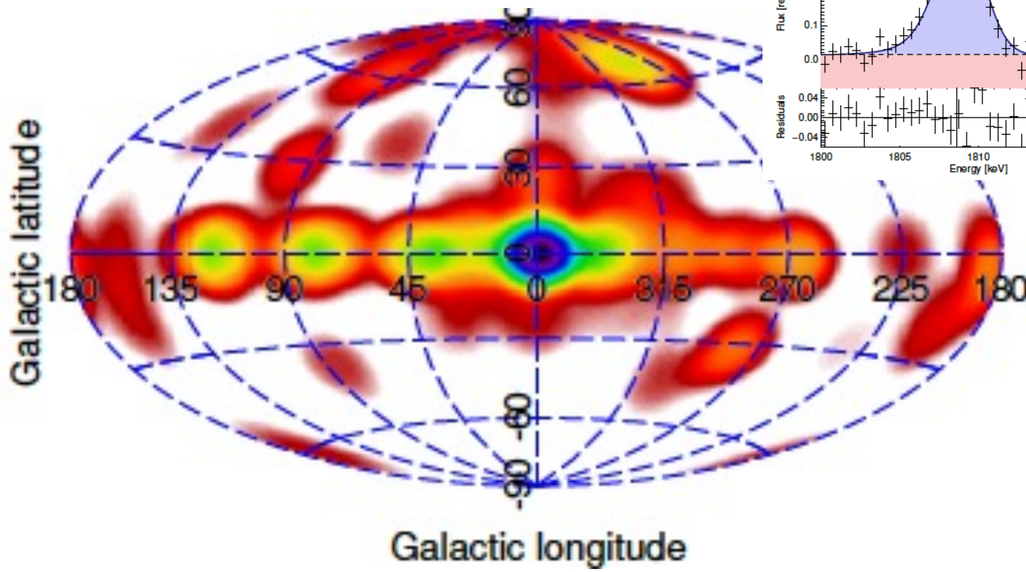
Abundances produced in a massive star relative to standard case

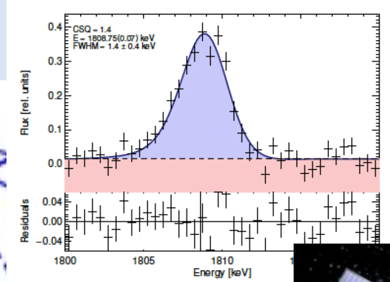


Impact on ^{62}Ni, ^{63}Cu and ^{64}Zn abundances produced in massive stars (weak component of the s process)

C. Lederer et al., PRL 110, 022501 (2013)
C. Lederer et al., PRC 89, 025810 (2014)

Cosmic γ-ray emitter ^{26}Al





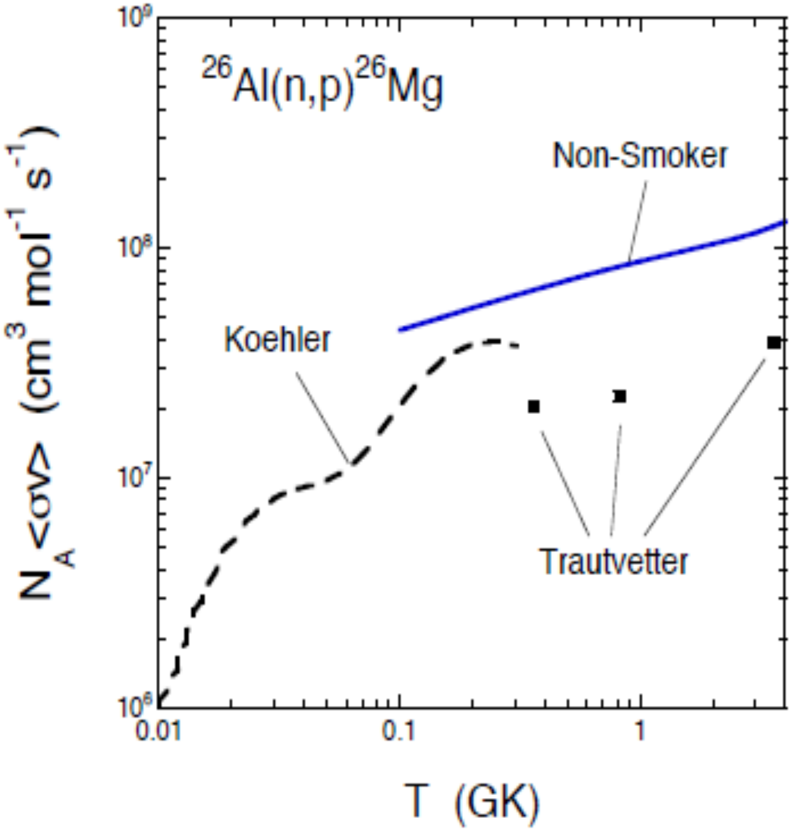
Main Origin of ^{26}Al in massive stars (Diehl et al, Nature 439 (2006))

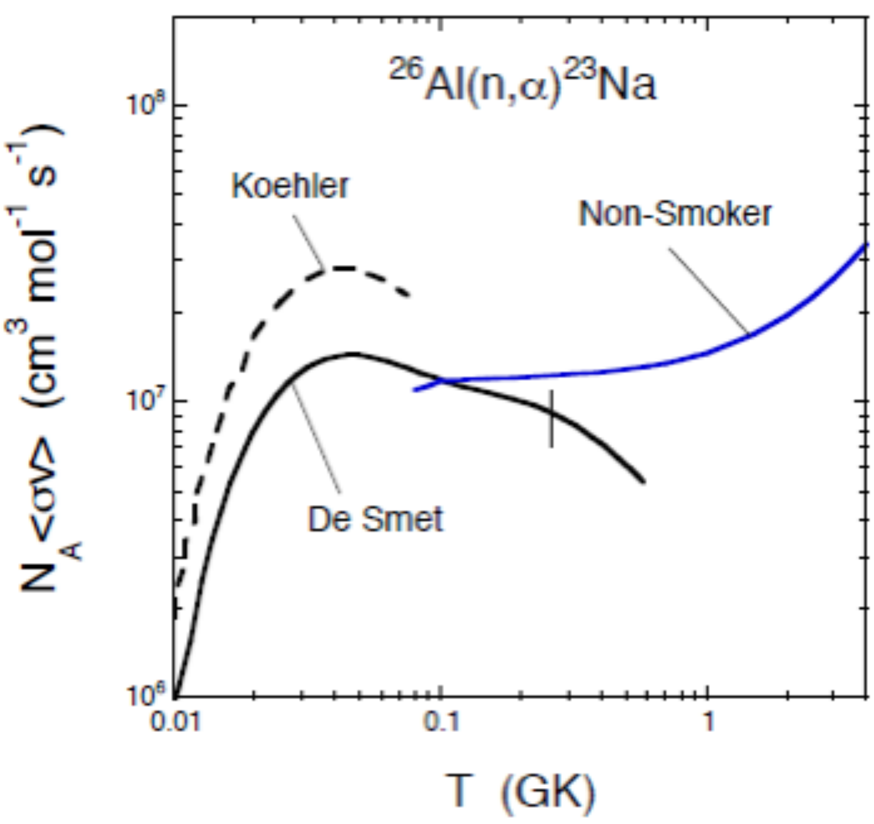
Mainly produced in

- convective hydrogen burning in Wolf-Rayet stars followed by ejection by stellar wind
- convective Carbon shell burning followed by ejection from core collapse supernova
- explosive Ne/C burning in core collapse phase of supernova

Key uncertainties for theoretical predictions of abundances: **^{26}Al(n,p)** and **^{26}Al(n,α)** reaction rates [Iliadis et al., Astrophys. J. Supp. 193, 16 (2011)]

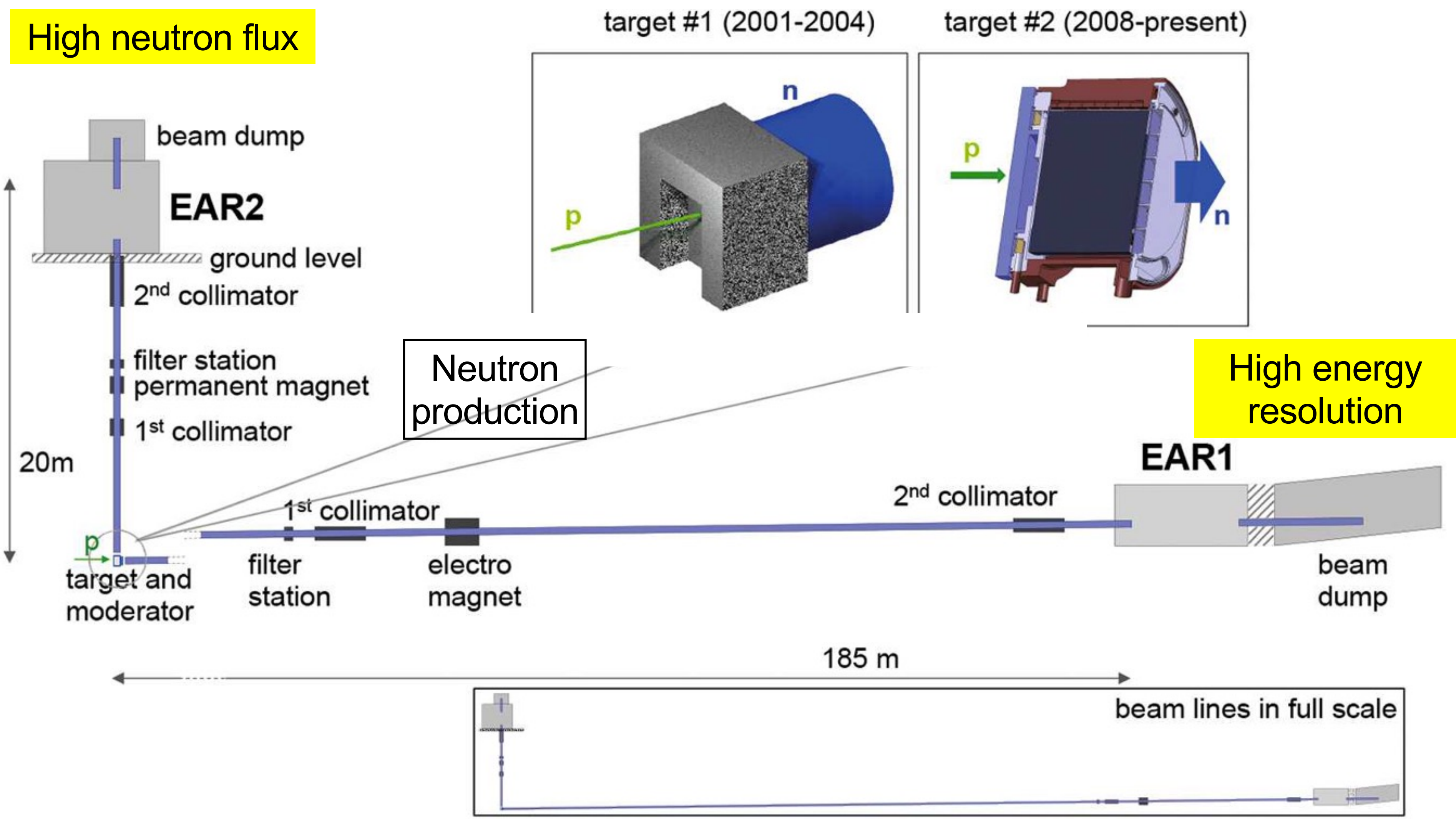
^{26}Al +n reactivities from previous measurements





C Iliadis et al., Ast. J. Supp. 193, 16 (2011)

n_TOF EAR-2


High neutron flux
target #1 (2001-2004)
target #2 (2008-present)
n
p
p
n
beam dump
EAR2
ground level
2nd collimator
filter station
permanent magnet
1st collimator
20m
Neutron production
High energy resolution
EAR1
2nd collimator
1st collimator
p
target and moderator
filter station
electro magnet
beam dump
185 m
beam lines in full scale

^{26}Al(n,p) and ^{26}Al(n,α)

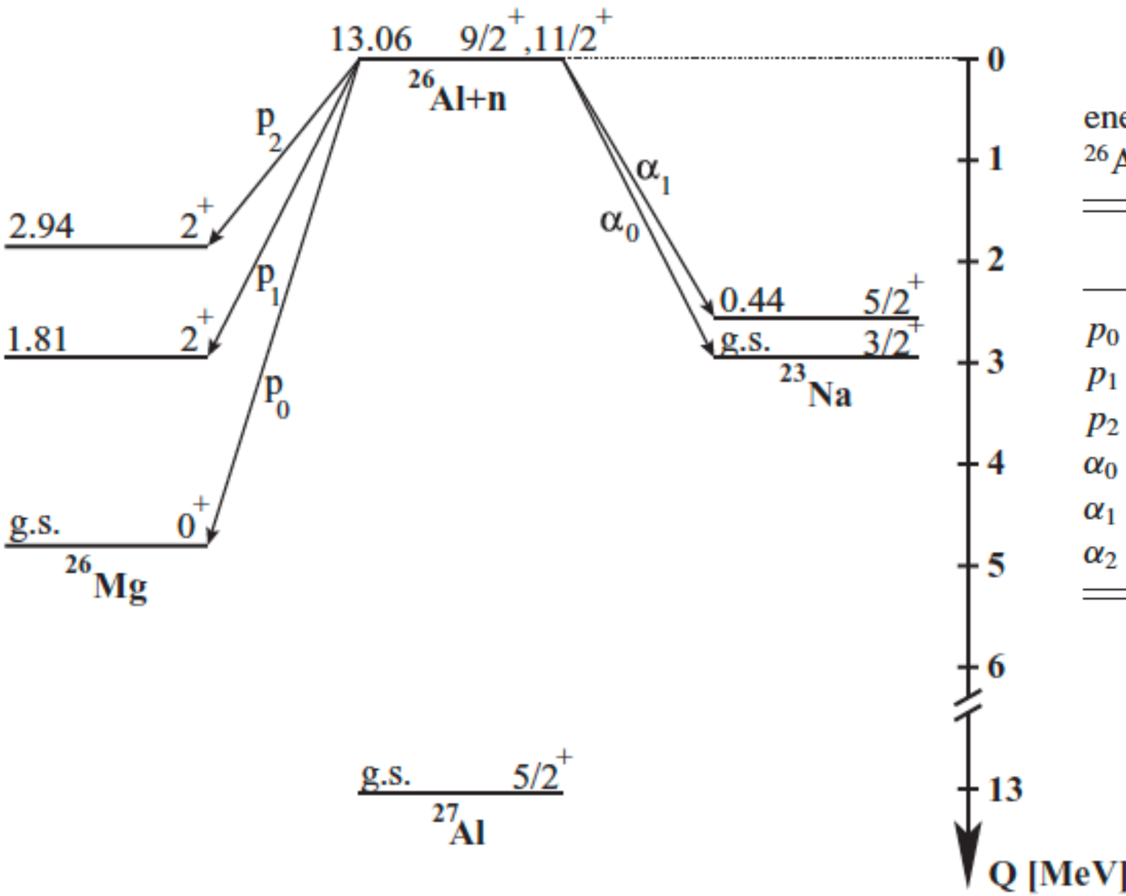
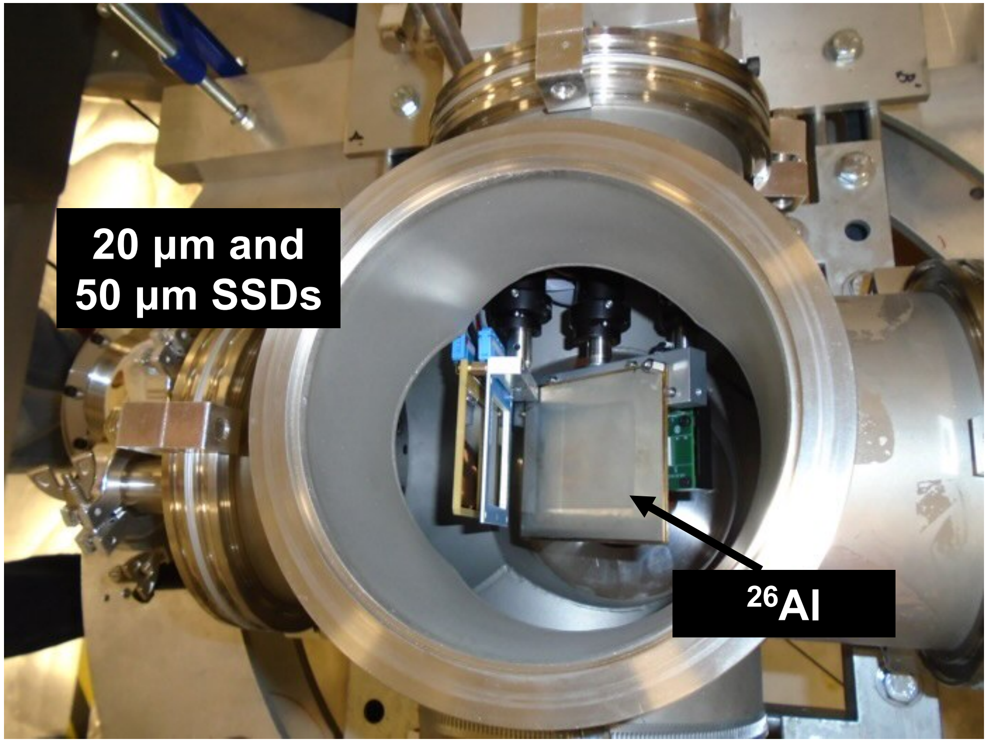


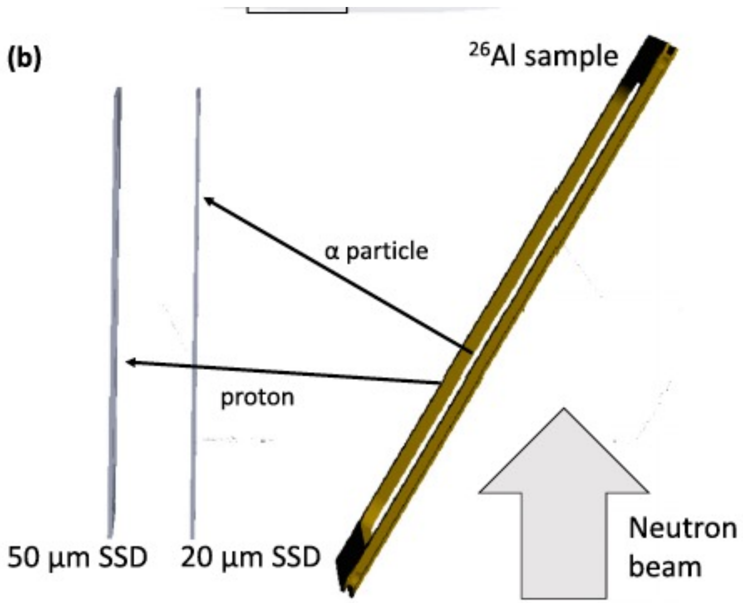
TABLE I. Q values and corresponding ejectile energies for the possible ^{26}Al$(n, \alpha_i)^{23}$Na and ^{26}Al$(n, p_i)^{26}$Mg reactions.

	Q value (MeV)	E (MeV)
p_0	4.78	4.60
p_1	2.98	2.87
p_2	1.85	1.78
α_0	2.97	2.53
α_1	2.53	2.16
α_2	0.89	0.76

de SMET et al PHYSICAL REVIEW C 76, 045804 (2007)

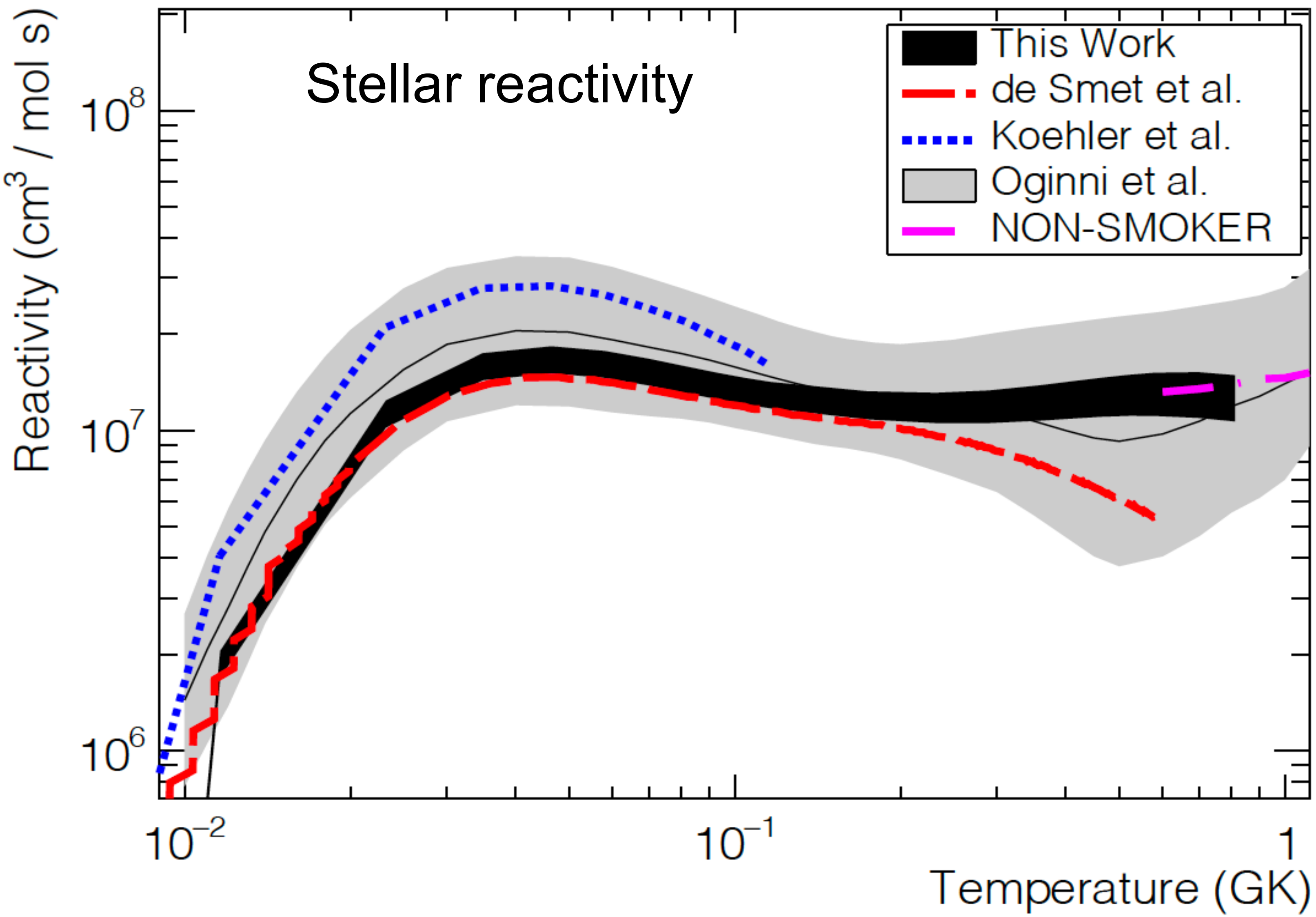
Silicon Strip Detection Setup: ΔE - E Technique





^{26}Al Target (JRC GELINA): 2.6 10^{17} atoms

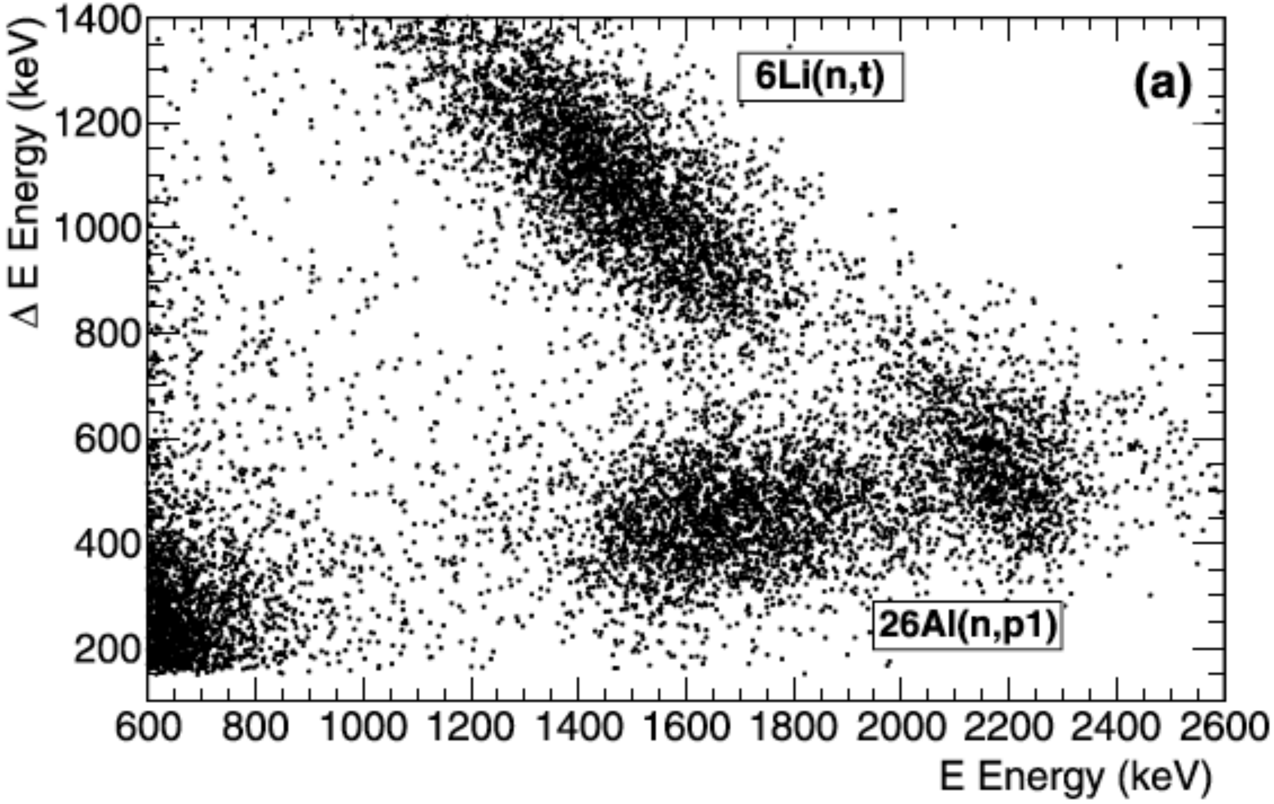
^{26}Al(n,α) measured at n_TOF / GELINA



C. Lederer-Woods et al., PHYSICAL REVIEW C 104, L032803 (2021)

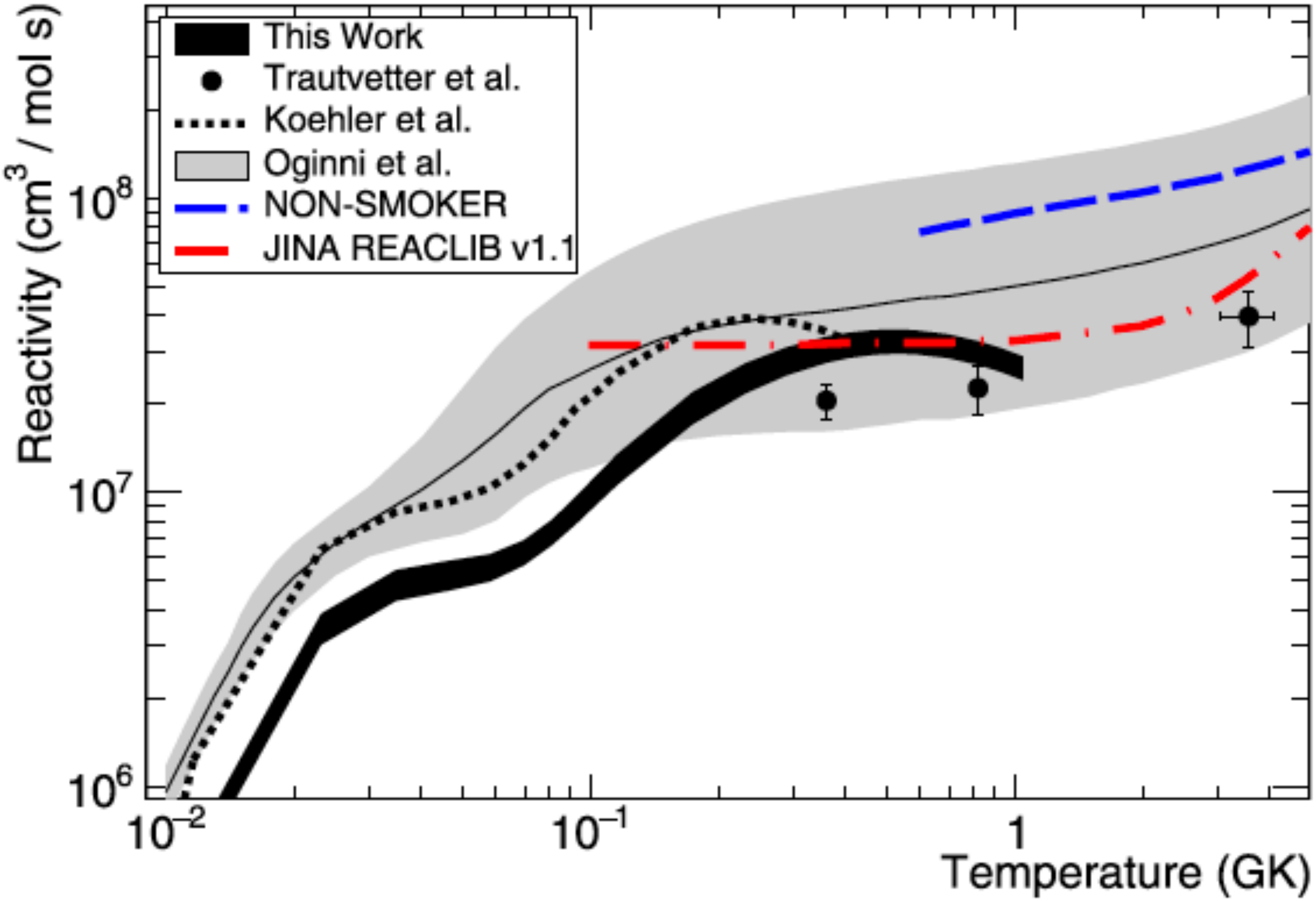
ΔE – E Spectra

Thin Detector



Thick Detector

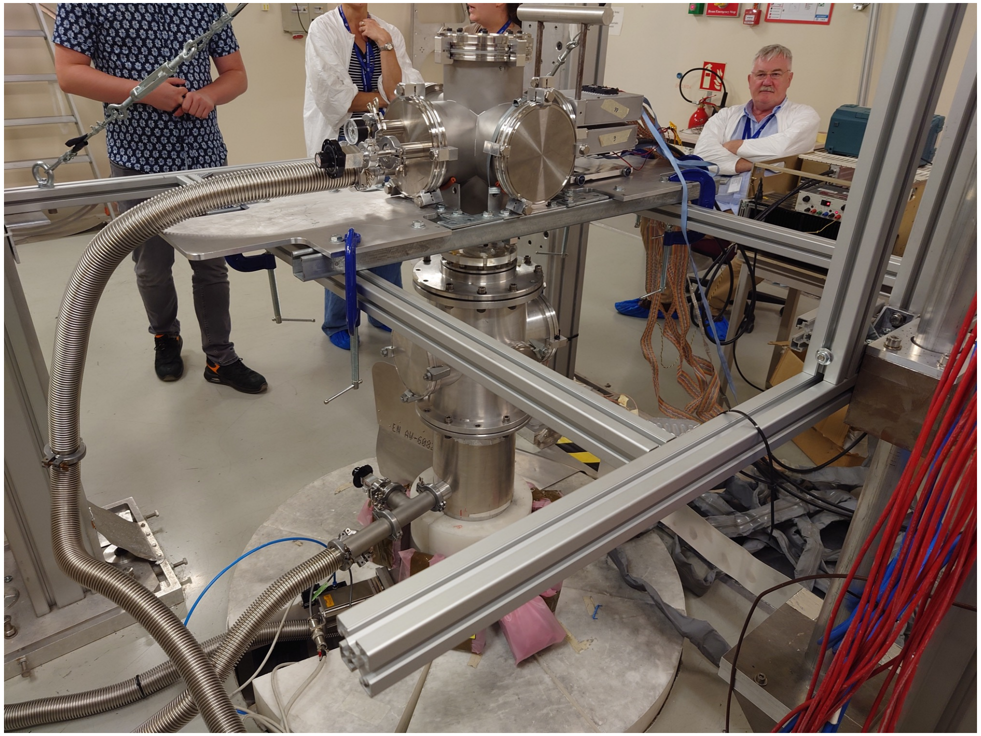
New n_TOF $^{26}Al(n,p)$ stellar reactivities

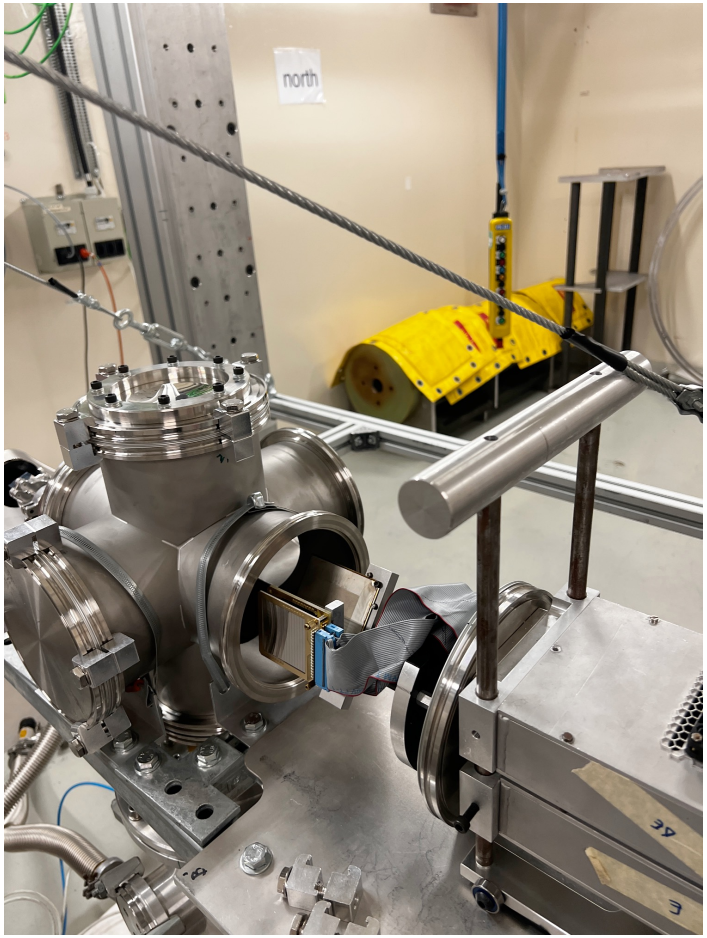


C. Lederer-Woods et al., PHYSICAL REVIEW C 104, L022803 (2021)

New Run at for high neutron energy 2023

… taking advantage of higher flux which allows use of better collimated neutron beam





THE END