Proton- and α-induced reaction rates in normal and inverse kinematics

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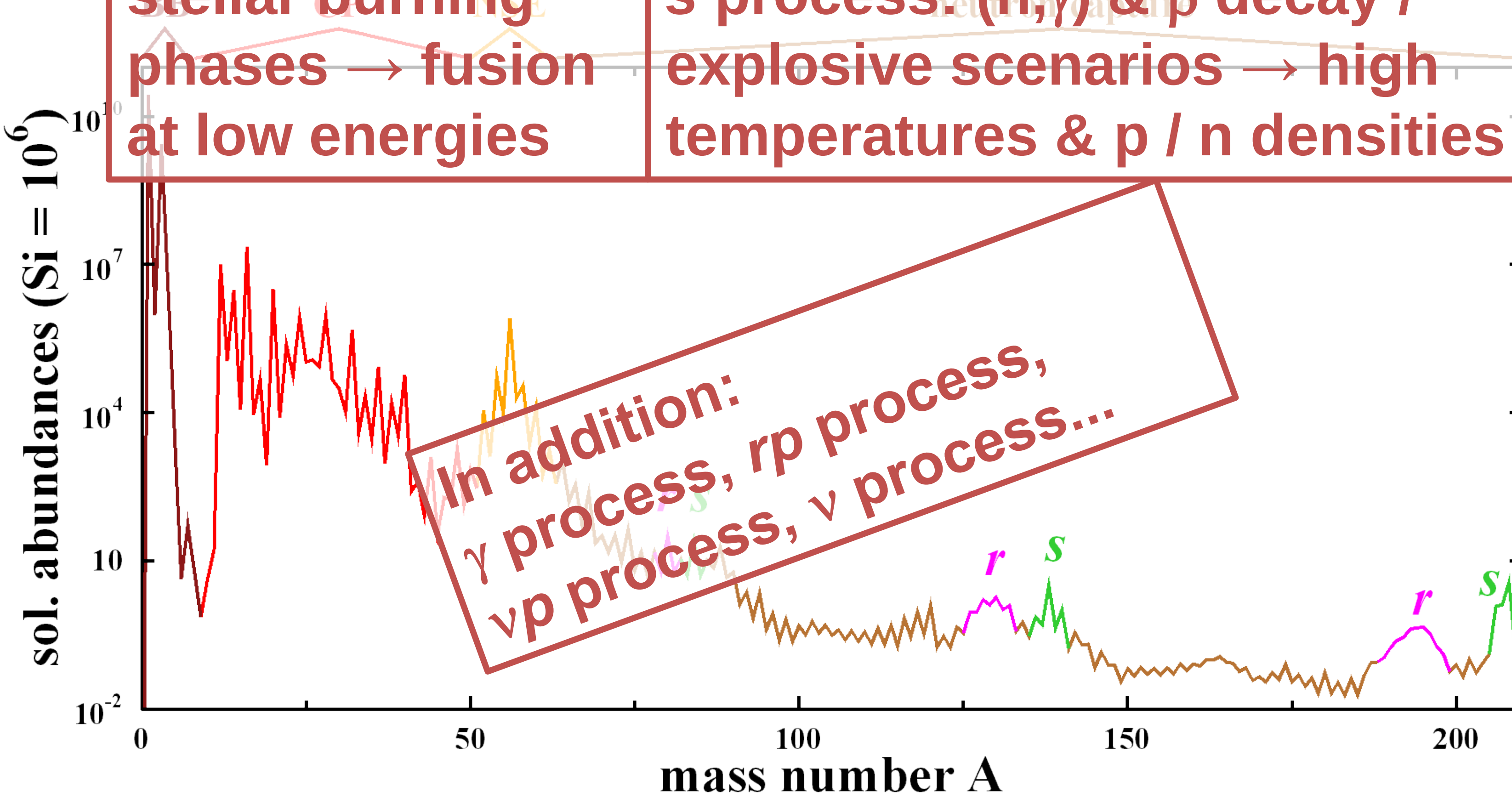
Astrophysical motivation

Solar abundance distribution & nucleosynthesis processes

stellar burning phases → fusion at low energies

s process: (n,γ) & β decay / explosive scenarios → high temperatures & p / n densities



In addition:
γ process, *rp* process,
νp process, ν process…

Astrophysical motivation

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^{92}Tc *4.4 m*	^{93}Tc *2.7 h*	^{94}Tc *4.9 h*	^{95}Tc *20 h*	^{96}Tc *4.3 d*	^{97}Tc *$4*10^6$ a*	^{98}Tc *$4*10^6$ a*	^{99}Tc *$2*10^5$ a*	^{100}Tc *15.8 s*	^{101}Tc *14.2 m*
^{91}Mo *15.5 m*	^{92}Mo 14.84	^{93}Mo *$4*10^3$ a*	^{94}Mo 9.25	^{95}Mo 15.92	^{96}Mo 16.68	^{97}Mo 9.55	^{98}Mo 24.13	^{99}Mo *66 h*	^{100}Mo 9.63
^{90}Nb *14.6 h*	^{91}Nb *680 a*	^{92}Nb *$4*10^7$ a*	^{93}Nb 100	^{94}Nb *$2*10^4$ a*	^{95}Nb *34.97 d*	^{96}Nb *23.4 h*	^{97}Nb *74 m*	^{98}Nb *2.9 s*	^{99}Nb *15 s*
^{89}Zr *78.4 h*	^{90}Zr 51.45	^{91}Zr 11.22	^{92}Zr 17.15	^{93}Zr *$2*10^6$ a*	^{94}Zr 17.38	^{95}Zr *64.0 d*	^{96}Zr 2.80	^{97}Zr *16.8 h*	^{98}Zr *30.7 s*
^{88}Y *106.6 d*	^{89}Y 100	^{90}Y *64.1 h*	^{91}Y *58.5 d*	^{92}Y *3.54 h*	^{93}Y *10.1 h*	^{94}Y *18.7 m*	^{95}Y *10.3 m*	^{96}Y *5.34 s*	^{97}Y *3.75 s*
^{87}Sr 7.00	^{88}Sr 82.58	^{89}Sr *50.5 d*	^{90}Sr *28.64 a*	^{91}Sr *9.5 h*	^{92}Sr *2.71 h*	^{93}Sr *7.45 m*	^{94}Sr *74 s*	^{95}Sr *24.4 s*	^{96}Sr *1.0 s*

Astrophysical motivation

Production of *p* nucleus ^{92}Mo by proton-capture reactions

^{91}Ru 9 s	^{92}Ru 3.65 m	^{93}Ru 59.7 s	^{94}Ru 51.8 m	^{95}Ru 1.65 h	^{96}Ru 5.52	^{97}Ru 2.9 d	^{98}Ru 1.88	^{99}Ru 12.7	^{100}Ru 12.6	^{101}Ru 17.0	^{102}Ru 31.6
^{90}Tc 8.7 s	^{91}Tc 3 m	^{92}Tc 4.4 m	^{93}Tc 2.7 h	^{94}Tc 4.9 h	^{95}Tc 20 h	^{96}Tc 4.3 d	^{97}Tc $4{*}10^6$ a	^{98}Tc $4{*}10^6$ a	^{99}Tc $2{*}10^5$ a	^{100}Tc 15.8 s	^{101}Tc 14.2 m
^{89}Mo 2.15 m	^{90}Mo 5.7 h	^{91}Mo 15.5 m	^{92}Mo 14.84	^{93}Mo $4{*}10^3$ a	^{94}Mo 9.25	^{95}Mo 15.92	^{96}Mo 16.68	^{97}Mo 9.55	^{98}Mo 24.13	^{99}Mo 66 h	^{100}Mo 9.63
^{88}Nb 14.3 m	^{89}Nb 2 h	^{90}Nb 14.6 h	^{91}Nb 680 a	^{92}Nb $4{*}10^7$ a	^{93}Nb 100	^{94}Nb $2{*}10^4$ a	^{95}Nb 34.97 d	^{96}Nb 23.4 h	^{97}Nb 74 m	^{98}Nb 2.9 s	^{99}Nb 15 s
^{87}Zr 1.6 h	^{88}Zr 83.4 d	^{89}Zr 78.4 h	^{90}Zr 51.45	^{91}Zr 11.22	^{92}Zr 17.15	^{93}Zr $2{*}10^6$ a	^{94}Zr 17.38	^{95}Zr 64.0 d	^{96}Zr 2.80	^{97}Zr 16.8 h	^{98}Zr 30.7 s

- Temperature range: T = (1.86 – 3.60) · 10^9 K, densities: (1.28 – 2.24) · 10^7 g/cm^3
- Data taken from: M. Kusakabe *et al.*, The Astrophysical Journal **726**, 25 (2011)

Measurements in normal kinematics

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Available data on proton-capture reactions

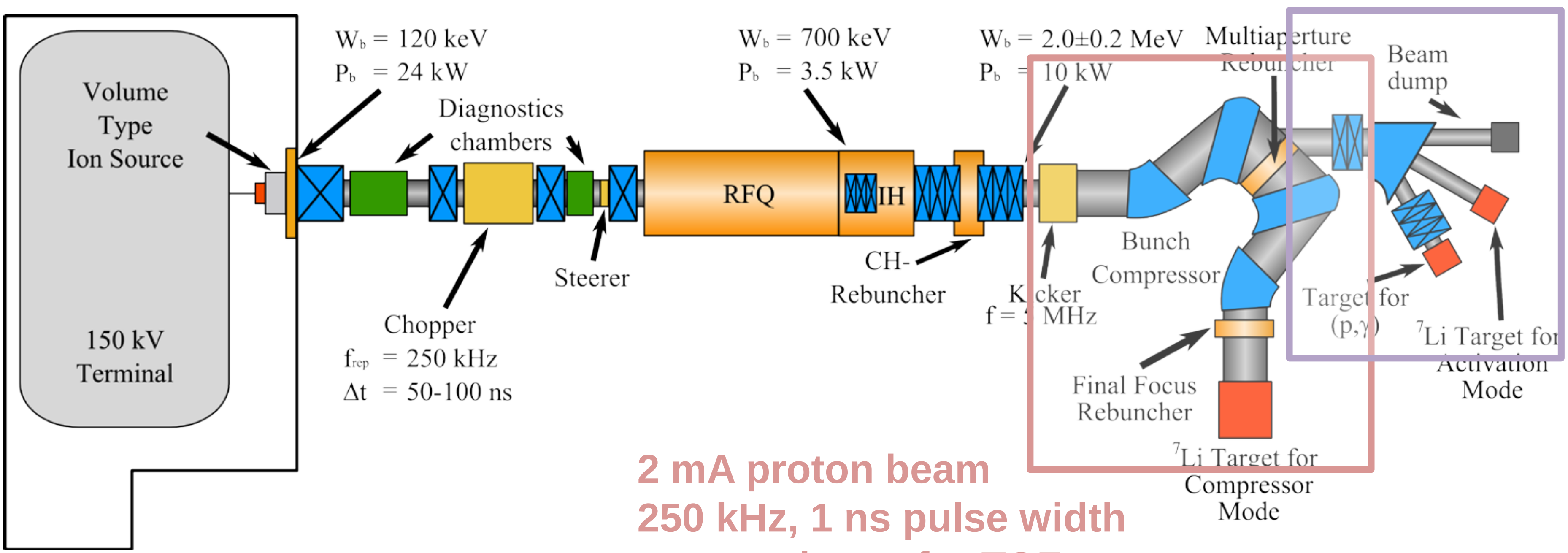
- **^{90}Zr(p,γ)**
  - Some data available:
    - E_p = 1.77 – 6.50 MeV
      C.E. Laird *et al.*, Phys. Rev. C 35, 1265 (1987) – in-beam technique
    - E_p = 1.9 – 5.7 MeV
      N.A. Roughton *et al.*, At. Data Nucl. Data Tab. **23**, 177 (1979) – activation technique
  - Measurement @ FRANZ possible at $E_p \approx 2$ MeV

- **^{91}Nb(p,γ)**
  - No data available so far: $t_{1/2}(^{91}\text{Nb}) = 680$ a
  - Possible approaches:
    - Inverse kinematics @ storage ring with proton target
    - Standard kinematics @ FRANZ with sample of ^{91}Nb at $E_p \approx 2$ MeV

Measurements in normal kinematics

The Frankfurt Neutron Source FRANZ

20 mA proton beam
175 MHz, 1 ns pulse width
neutron beam for activation:
flux $1\cdot10^{12}$ s^{-1} cm^{-2}



2 mA proton beam
250 kHz, 1 ns pulse width
neutron beam for TOF:
flux $4\cdot10^{7}$ s^{-1} cm^{-2}

Measurements in normal kinematics

In-beam measurements @ FRANZ

- 4π BaF_2 calorimeter:
  41 crystals, ≈90% total efficiency, ≈50% FE peak efficiency
- Background reduction:
  - Pulsed beam
  - Sum energy

Measurements in normal kinematics

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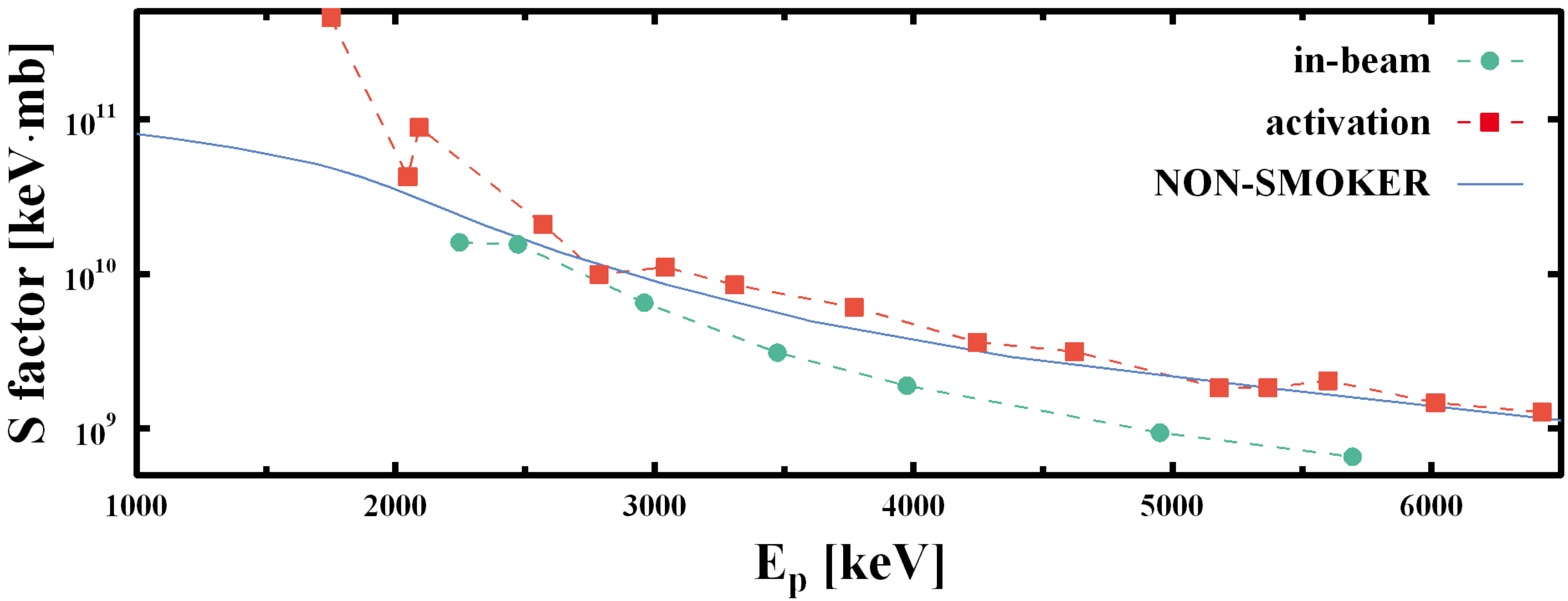
Comparison of old data on $^{90}Zr(p,\gamma)$



- Activation significantly higher, different energy dependences

Measurements in normal kinematics

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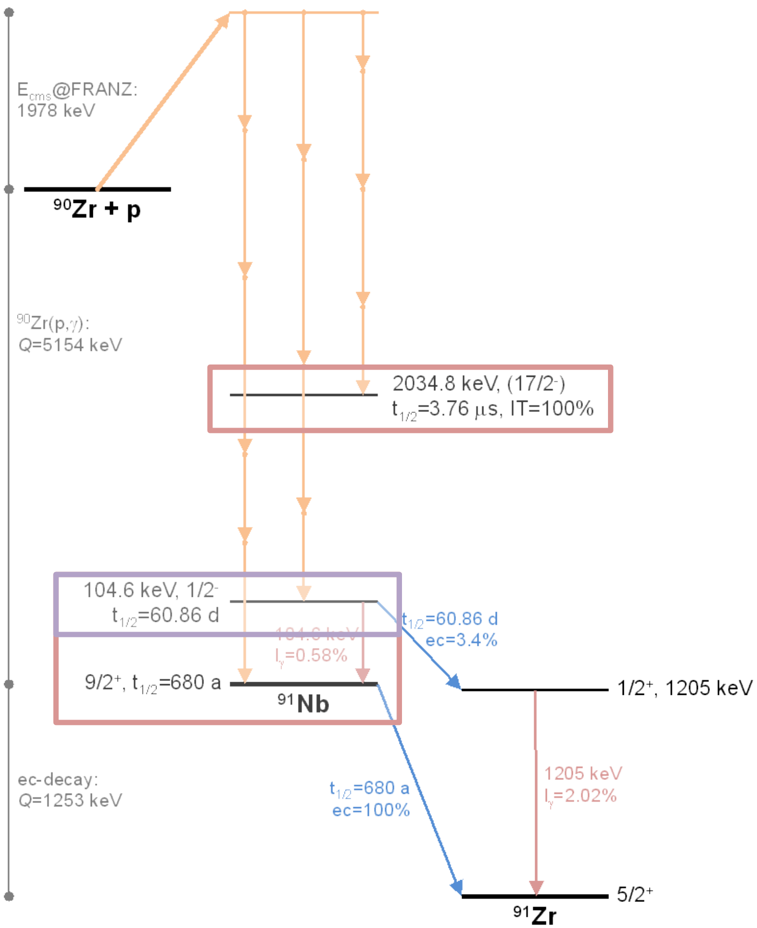
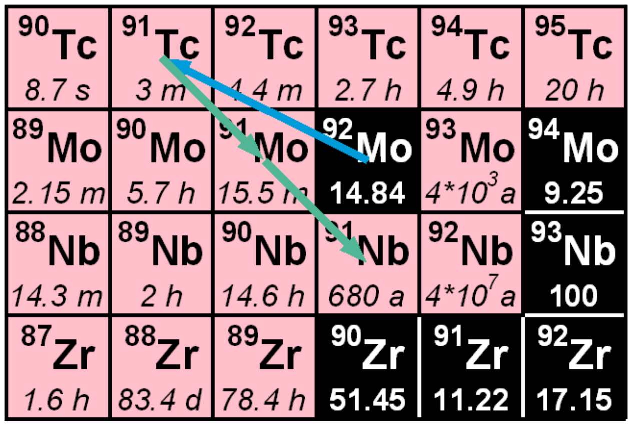
Measurement of ^{90}Zr(p,γ) @ FRANZ

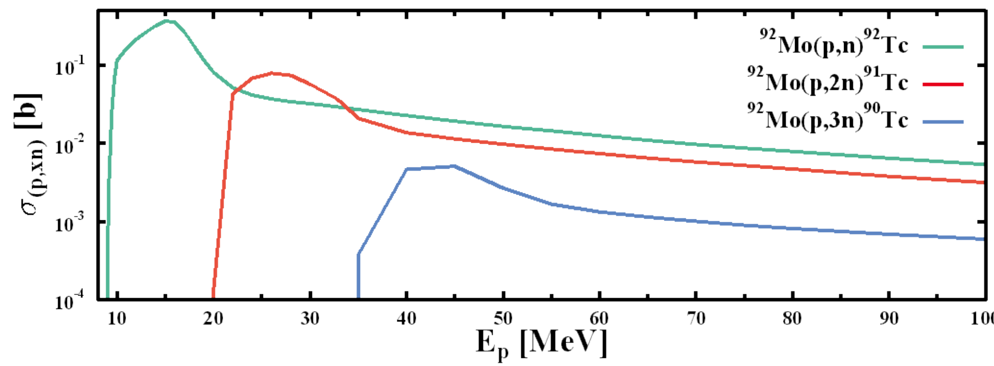


- Disentangle contributions of isomers and ground-state
- In-beam measurement: high-energy isomer vs. (low-energy isomer + ground state) by Q value
- Activation approach: low-energy isomer only

Measurements in normal kinematics

Production of ^{91}Nb sample for ^{91}Nb(p,γ) @ FRANZ





- Irradiation of enriched ^{92}Mo sample
  - Reaction channel (p,2n) dominates for 30 MeV protons
  - Subsequent β decays end in ^{91}Nb
- Chemical purification and sample preparation
- Measurement at $E_p \approx 2$ MeV at FRANZ

Measurements in inverse kinematics

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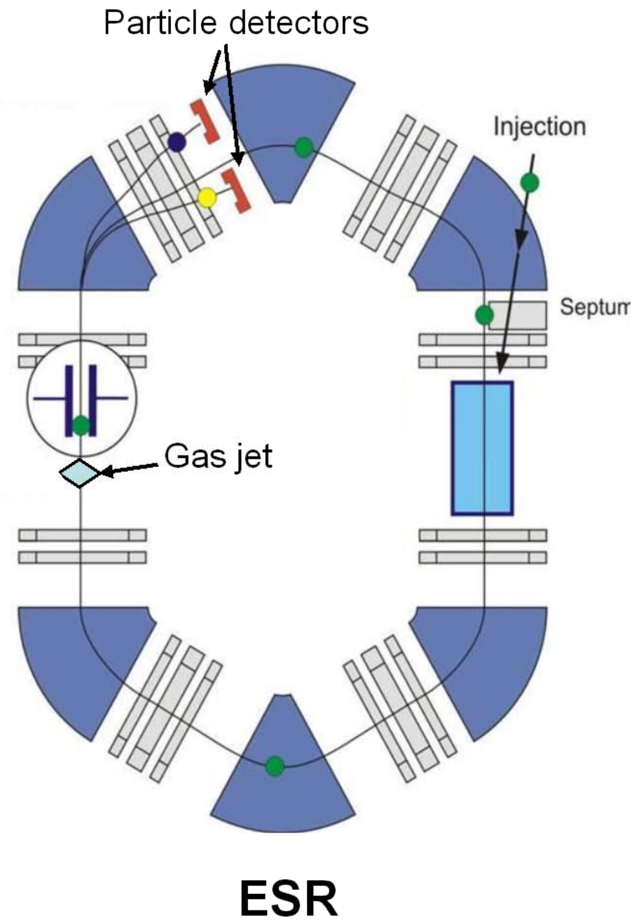
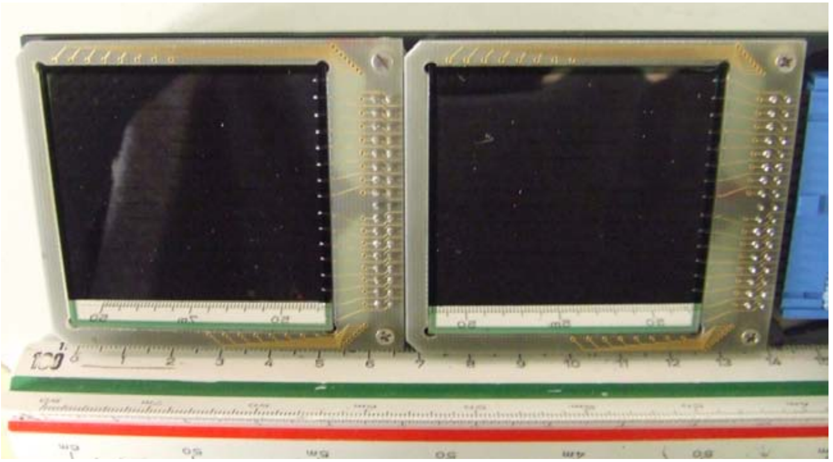
Measure ^{91}Nb(p,γ) at storage ring (*e.g.* ESR @ GSI, Germany)

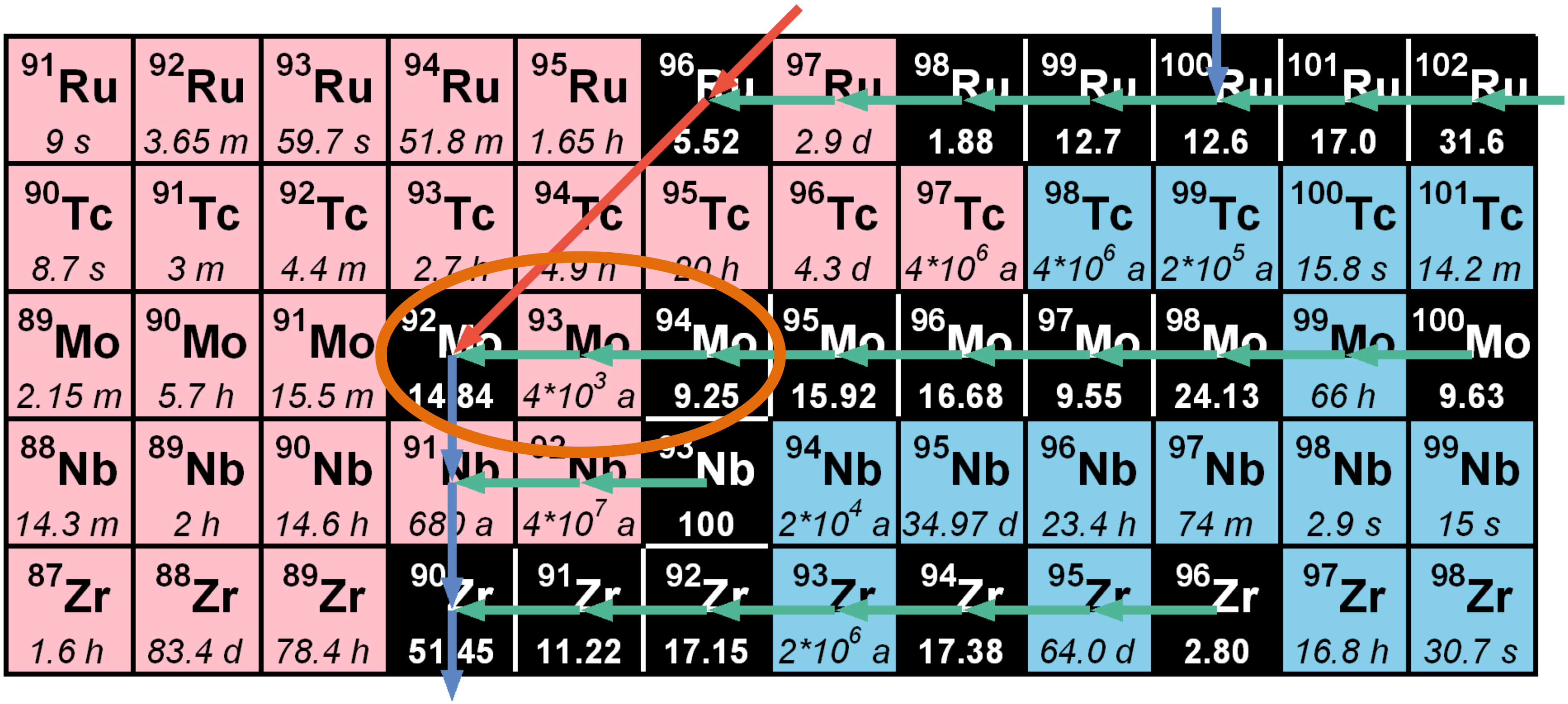


- Detection of ions with in-ring particle detectors
- Two double-sided silicon strip detectors, 4 x 4 cm^2 each
  - low background
  - high efficiency



Astrophysical motivation

Production of *p* nucleus ^{92}Mo by γ process



- Temperature: T = 2.5 · 10^9 K
- Data taken from: T. Rauscher, Phys. Rev. C **73**, 015804 (2006)

Measurements in inverse kinematics

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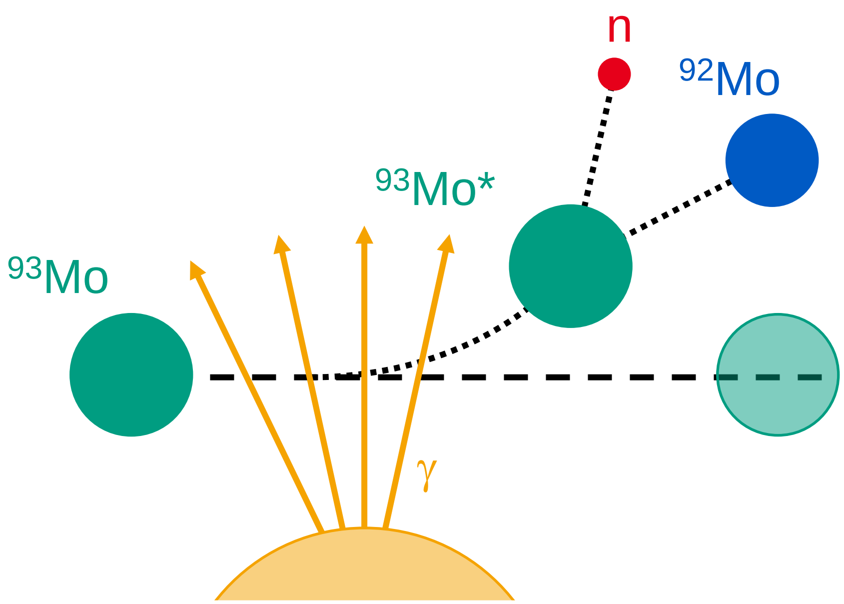
Coulomb dissociation in inverse kinematics @ LAND/R³B



- CD cross section of $Pb(^{93,94}Mo,^{92,93}Mo+n)Pb$ yields cross section of $^{93,94}Mo(\gamma,n)^{92,93}Mo$
- Kinematically complete measurement needed
- Detection of all reaction products with energy information

Measurements in inverse kinematics

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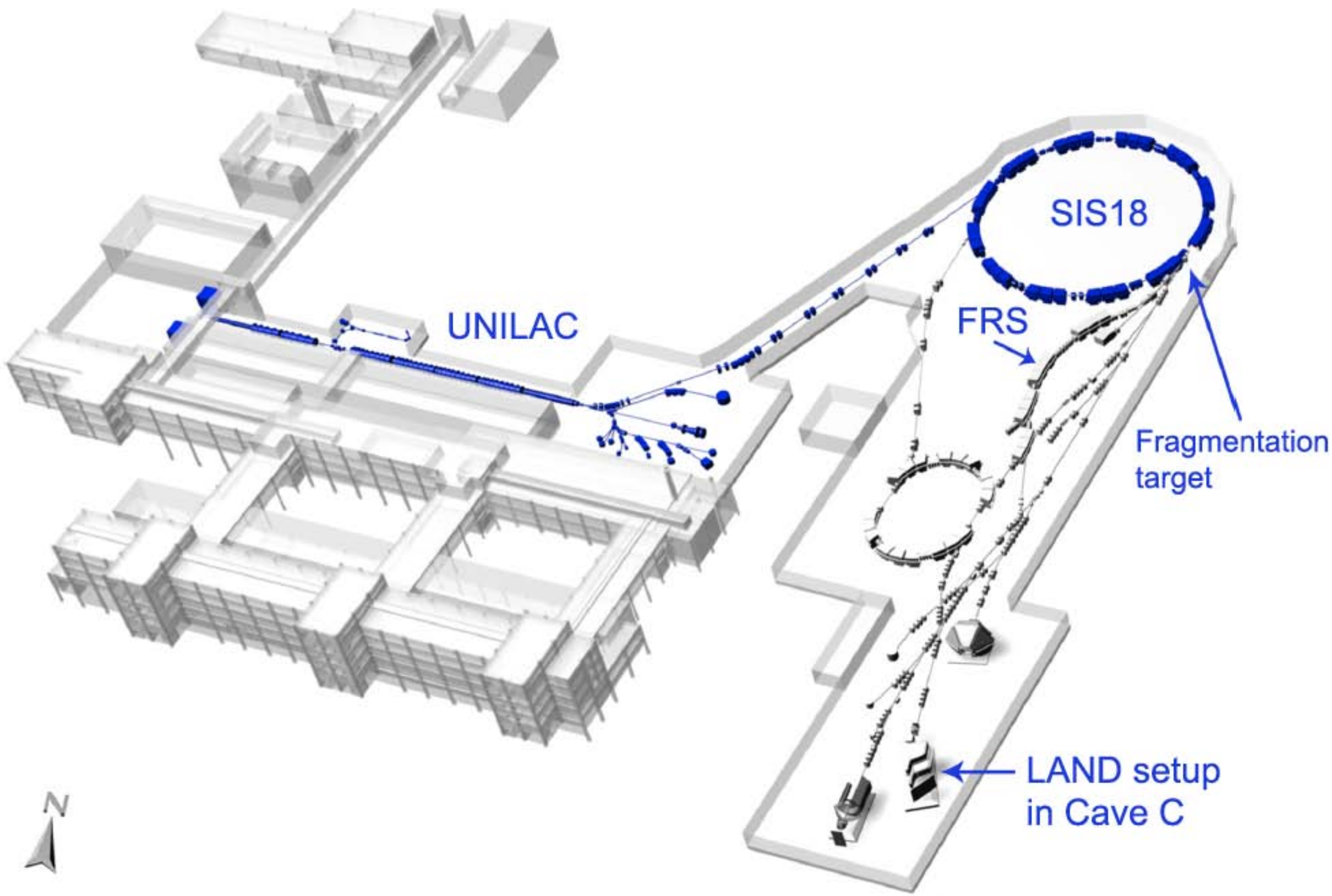
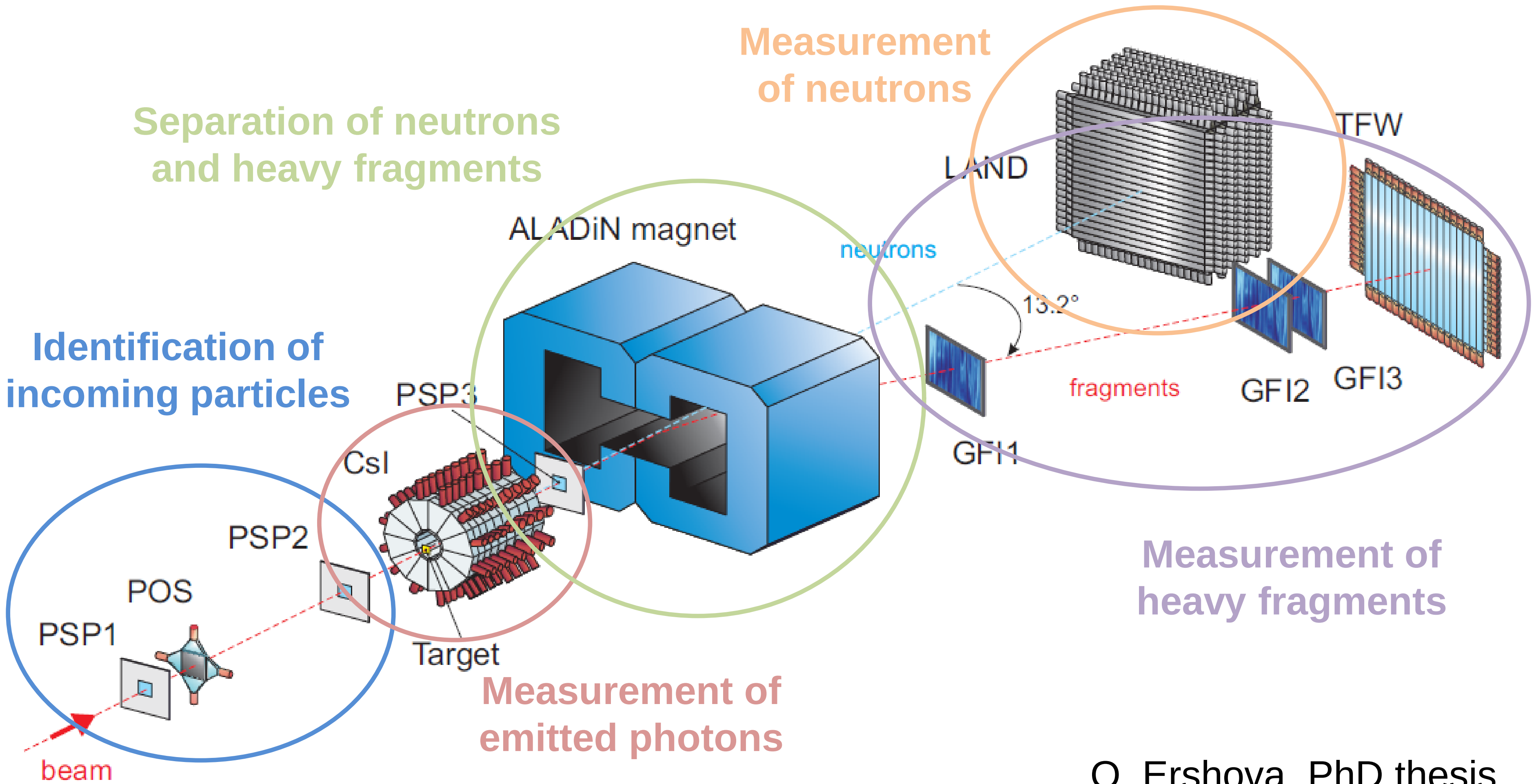
Coulomb dissociation @ LAND/R³B, GSI, Germany



O. Ershova, PhD thesis, Goethe-University Frankfurt

Measurements in inverse kinematics

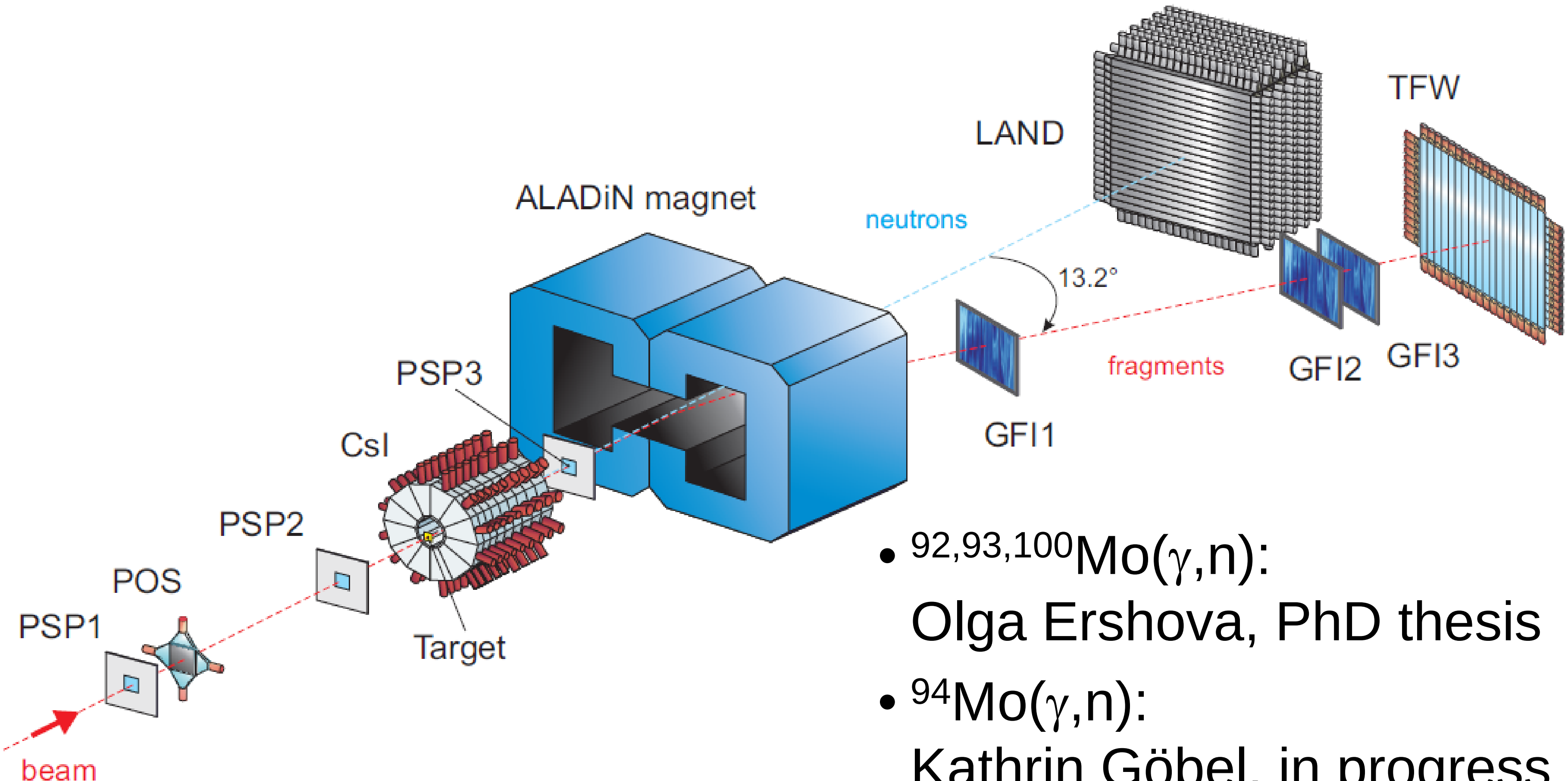
Coulomb dissociation @ LAND/R³B, GSI, Germany



O. Ershova, PhD thesis

Measurements in inverse kinematics

Coulomb dissociation @ LAND/R³B, GSI, Germany



- ^{92,93,100}Mo(γ,n): Olga Ershova, PhD thesis
- ^{94}Mo(γ,n): Kathrin Göbel, in progress

Summary & Outlook

- Production of ^{92}Mo by proton-capture reactions and γ process
- Measurements of key reactions:
  - ^{94}Mo(γ,n)^{93}Mo and ^{93}Mo(γ,n)^{92}Mo @ LAND/R^{3}B, GSI
  - ^{90}Zr(p,γ)^{91}Nb and ^{91}Nb(p,γ)^{92}Mo @ FRANZ and ESR, GSI
- Missing reactions:
  - ^{92}Mo(γ,p)^{91}Nb $\rightarrow$ use data on inverse reaction ^{91}Nb(p,γ)
  - ^{96}Ru(γ,α)^{92}Mo $\rightarrow$ measure inverse reaction ^{92}Mo(α,γ) in standard and/or inverse kinematics

$\rightarrow$ Determine dominant production mechanism and astrophysical site

Summary & Outlook

- Find key reactions to probe astrophysical network or model calculations → networking activity ATHENA

- Beam diagnostics and beam transport close to the space charge limit

- Detection systems capable for highest count rates
- Data processing, storage, and analysis

- Development of high power targets
- Development of efficient production mechanism for targets

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- **E062 collaboration** (^{96}Ru(p,γ) @ ESR, GSI)
- **S295 collaboration** (^{92,93,94,100}Mo(γ,n) @ LAND/R^{3}B, GSI)
- **D. Schumann, PSI, Villingen, Switzerland**
- **M. Wiescher, University of Notre Dame, Indiana, U.S.A.**