Photoactivation of ^{115m}In in the 4 to 18 MeV energy range

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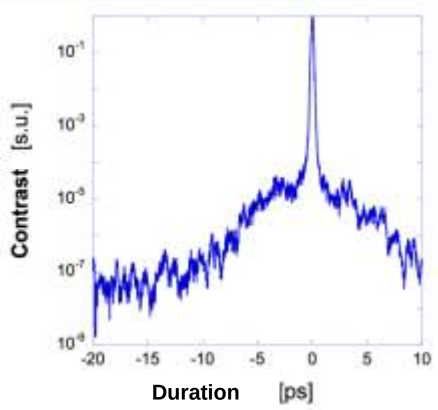
Outline

- General context
  - Laser driven particle beam acceleration
  - Nuclear activation diagnostic
- ^{115m}In photoexcitation experiment at ELSA
  - Set-up of the experiment
  - From total measured yield to (γ,γ') yield
- Comparison to theoretical calculations of the yield

Laser-driven plasma-based particle accelerators

UHI laser pulse temporal profile



- Laser :
  - CPA : pulses of 100 TW, τ~30 fs focused on a few μm

  ➪ intensities up to 10^{18}-10^{20} W.cm^{-2} : UHI lasers
  - ASE : 10^{13}-10^{15} W.cm^{-2} on target before the main pulse

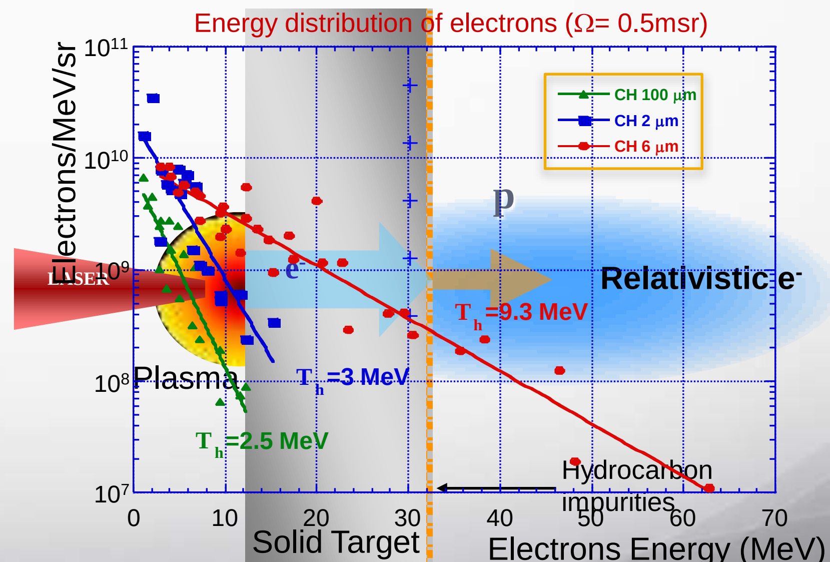
  ➪ ionization of the target : *pre*plasma

- Particle acceleration :
  - Laser-plasma interaction : plasma waves, wakefields

  ➪ acceleration of e$^-$ exiting at the rear of the target
  - Charge separation :

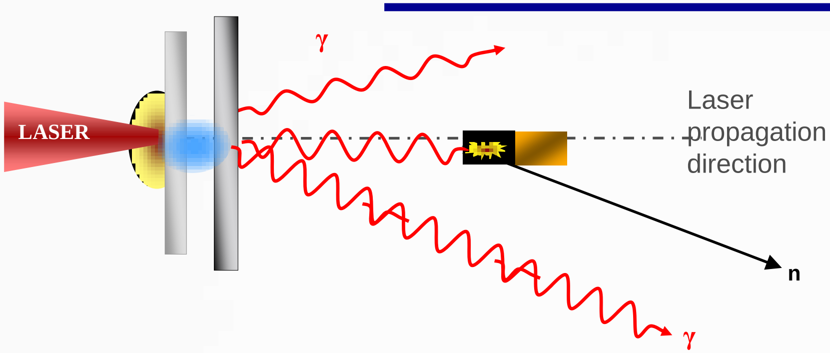
  ➪ p and ion acceleration

- Particle beam characteristics :
  - N ~ 10^{10}-10^{12} particles
  - $\tau \sim \tau_{laser}$
  - Continuous energy distribution



E. Lefebvre et al Nucl. Fusion 43 (2003)

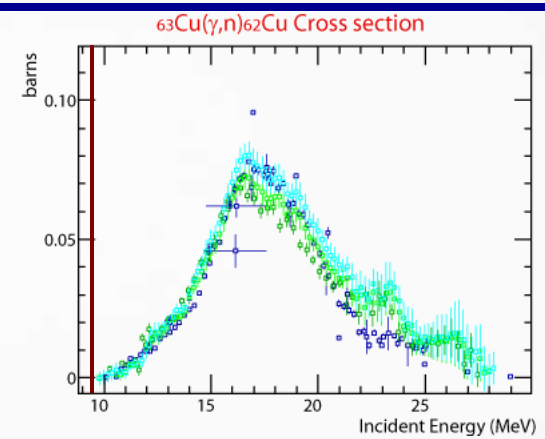
Beam characterization using nuclear activation

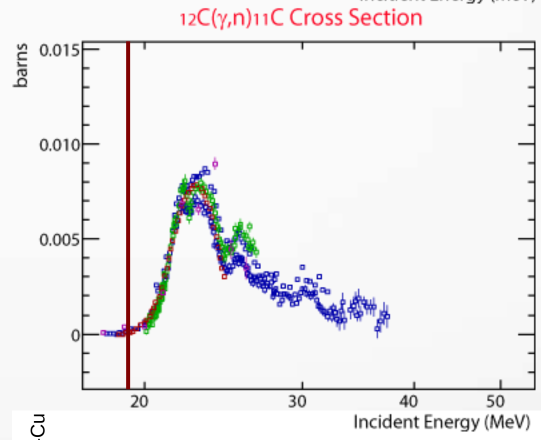


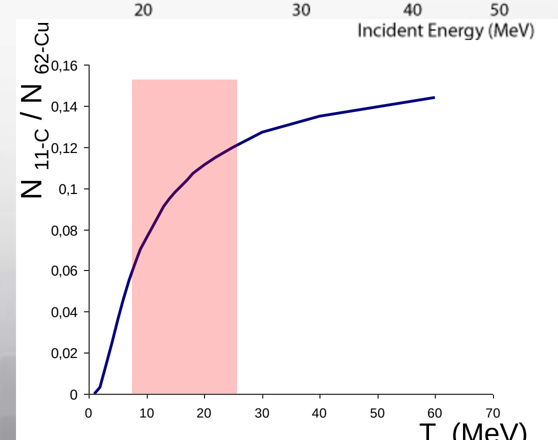
$$\frac{dN}{dE} \propto e^{-E/T_e}$$

- Electron temperature : T_e
  - e^- beam converted into γ beam
  - Nuclear activation :
    - $^{63}Cu(\gamma,n)^{62}Cu \longrightarrow \beta^+$ *$T_{1/2}$ = 9,73'* *$E_t \approx$ 9 MeV*
    - $^{12}C(\gamma,n)^{11}C \longrightarrow \beta^+$ *$T_{1/2}$ = 20,33'* *$E_t \approx$ 18 MeV*
  - Ratio of activation yields with different E_t

⇨transparent to γ with energies < 9 MeV







Why ^{115}In ?

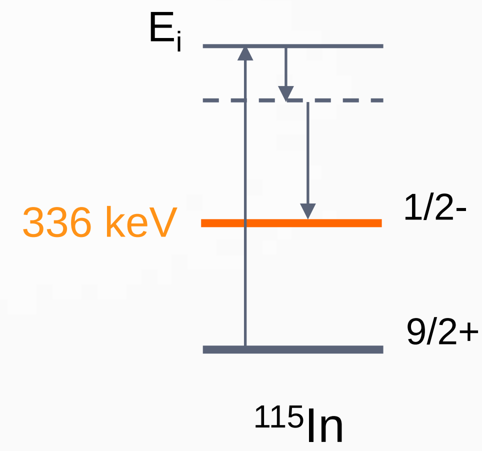
Natural In : 2 stable isotopes

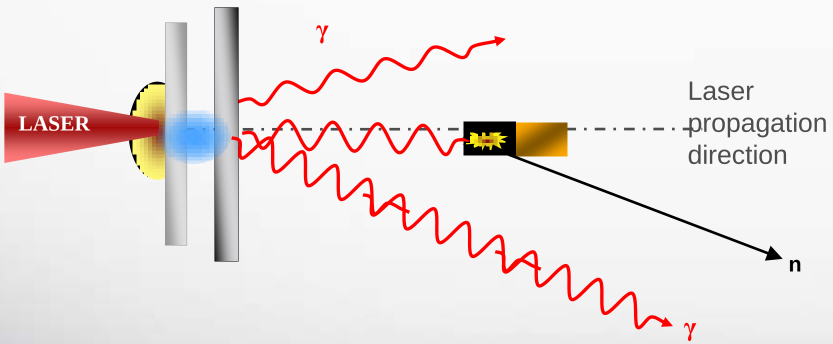
^{115}In *(95.7%)* + ^{113}In *(4.3%)*

^{115m}In isomeric state :

$T_{1/2}$ = 4.486 h

E_{γ} = 336 keV





- Accelerated electron beam
  - Photoexcitation :

    ^{115}In(γ,γ')^{115m}In ⟶ γ of 336 keV

$$N_{\rm iso} = N_{\rm gs} \int_{E_t}^{E_{\rm max}} \phi_\gamma(E_\gamma)\sigma_{\gamma,\gamma'}(E_\gamma)\ dE_\gamma$$

➪ characterization of ϕ at Eγ < 9MeV

➪ $\sigma_{\gamma\gamma'}$ cross section ?

^{115m}In photoexcitation cross section in litterature

- Measurements

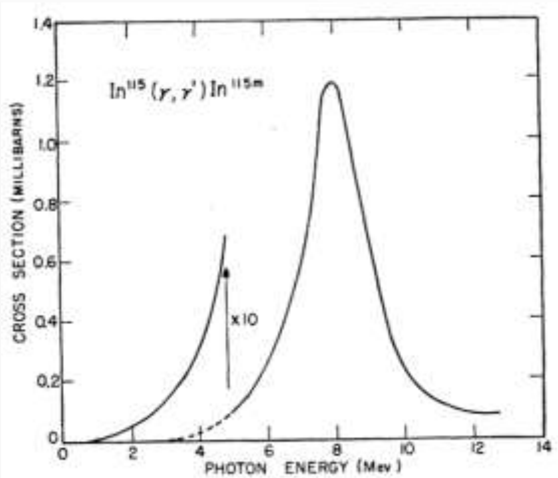


FIG. 2. Cross section for the photoexcitation of In^{115m}.

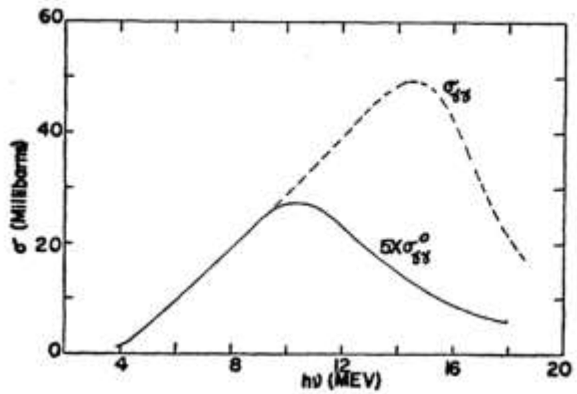
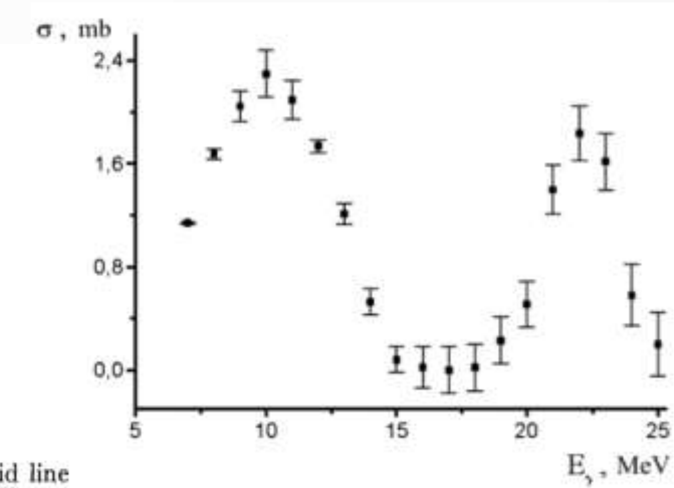


FIG. 8. Cross sections for the (γ,γ') process in In^{115}. Solid line—cross section obtained experimentally ($\sigma_{\gamma\gamma}{}^{0}$). Dotted line—ross section ($\sigma_{\gamma\gamma}$) after application of corrections (A) and (B).



J.L. Burkhardt at al Phys. Rev. 100 (1955)

J. Goldemberg and L. Katz Phys. Rev. 90 (1953)

V.S. Bokhinyuk et al Ukr. J. Phys. (2006)

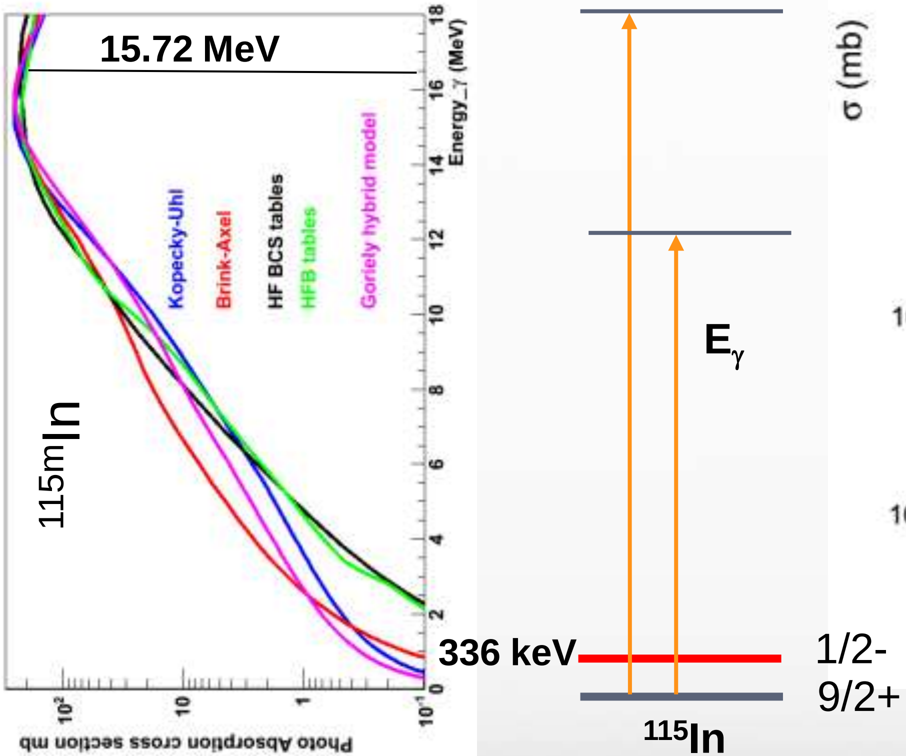
- Very few data available at E_γ > 5 MeV
- Large discrepancies

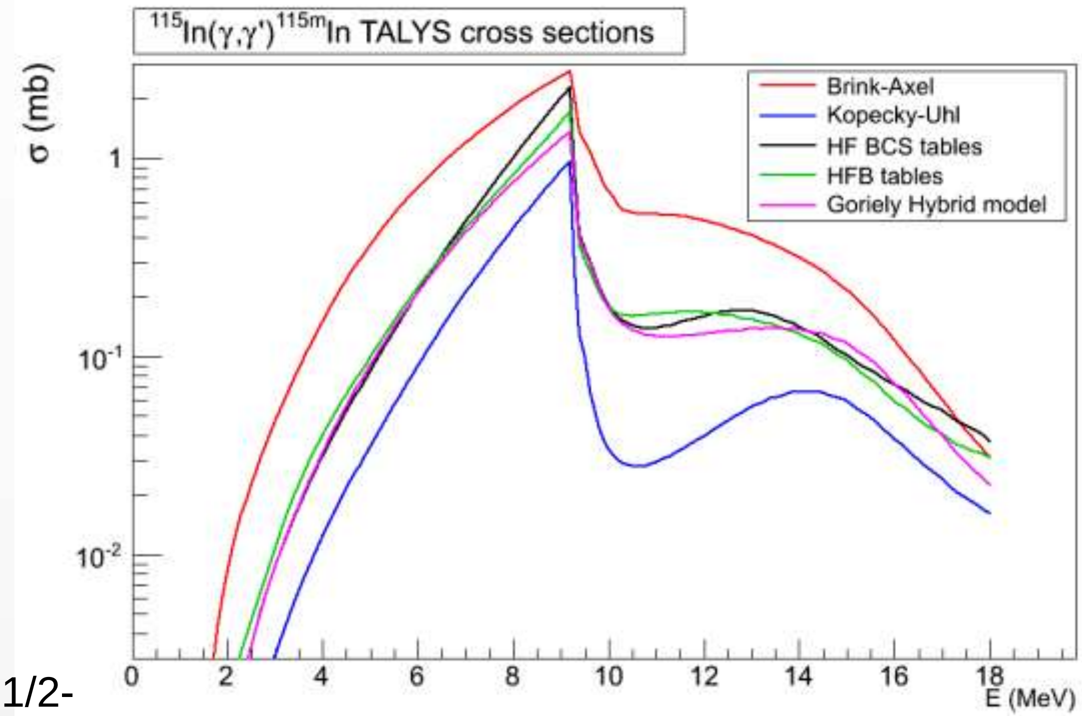
➪ need to confront to additionnal experimental data

^{115m}In photoexcitation cross section in litterature

- Theoretical calculations : TALYS

Nuclear response function to γ absorption

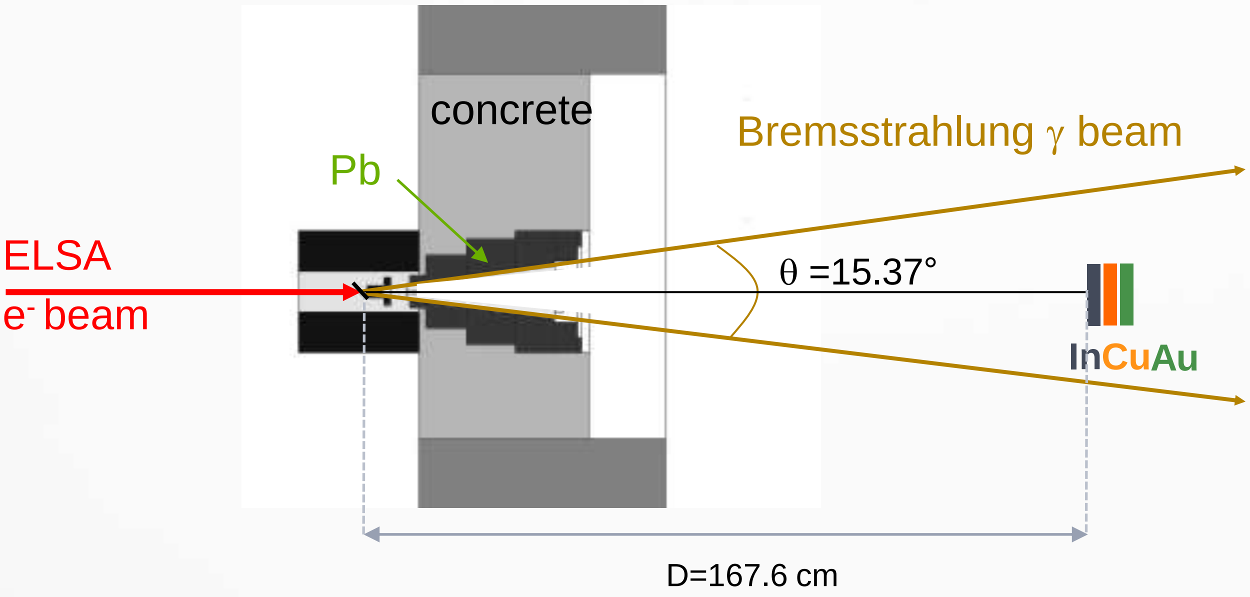


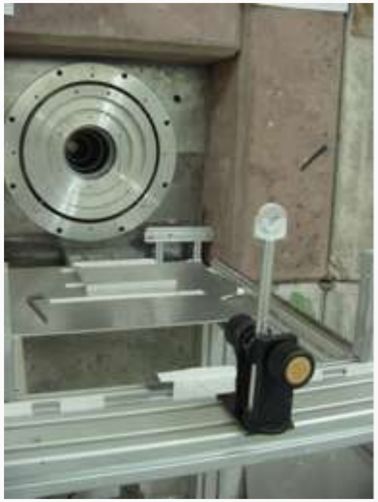


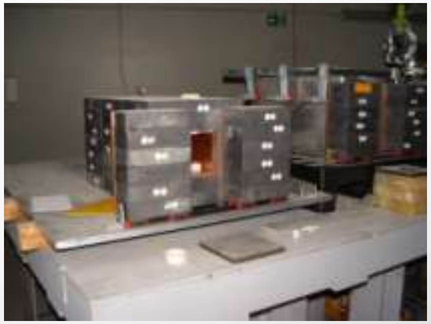
- Photoabsorption cross section based on γ strength function : parametrization or tables

➪need for experimental data to test the models

Set up of the experiment

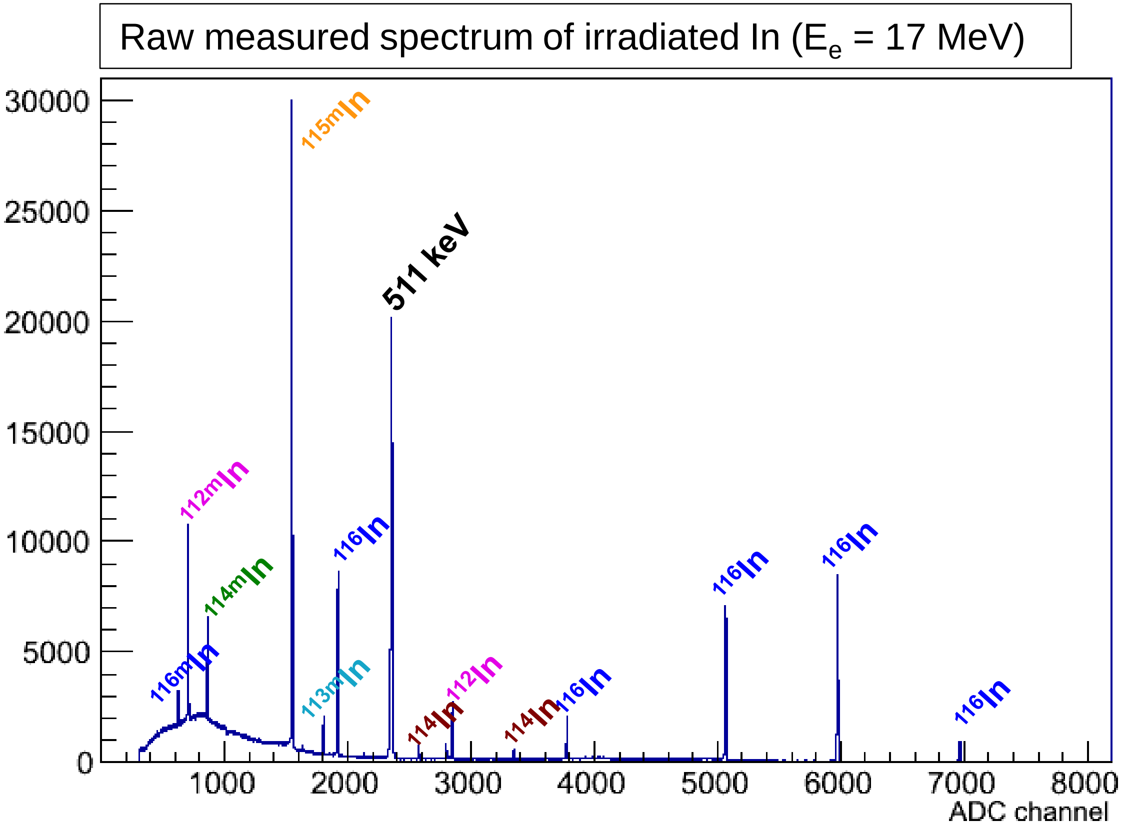






- ELSA : monoenergetic e^- beam $\longrightarrow$ γ beam
  - E_e from 4 to 18 MeV
  - I from 1.7 to 3.3 μA
- Irradiation of three samples :
  - Natural In : ^{113}In and ^{115}In
  - Pure ^{197}Au
  - Natural Cu : ^{63}Cu and ^{65}Cu

Measured spectrum of irradiated In



(γ,γ')+(n,n')

^{115}In (γ,γ)^{115m}In : 336 *$T_{1/2}$=4.486h*

^{113}In (γ,γ') ^{113m}In : 390 *$T_{1/2}$=99.51'*

(γ,n)

^{115}In (γ,n) ^{114m}In : 190 *$T_{1/2}$=49.51d*

^{113}In (γ,n) ^{112m}In : 155 *$T_{1/2}$=20.56'*

^{113} In (γ,n) ^{112}In : *$T_{1/2}$=14.97'*

$\beta^+ \rightarrow ^{112}$Cd* : 617, 606, 1235.5

(n,γ)

^{115}In (n,γ) ^{116m}In : 127 *$T_{1/2}$=54.29'*

^{115}In (n,γ) ^{116}In : *$T_{1/2}$=14.10"*

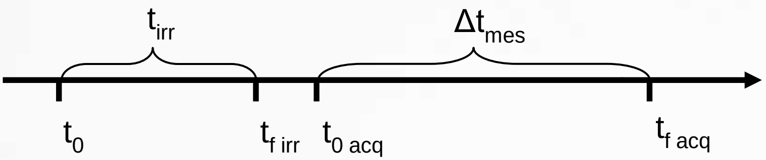
$\beta^- \rightarrow ^{116}$Sn* : 1507, 1293, 1097, 818, 463, 416.8

^{113}In (n,γ) ^{114}In : *$T_{1/2}$=71.9"*

$\beta^+ \rightarrow ^{114}$Cd* : 558, 725

➪ All γ rays are identified

Measured ^{115m}In production yield



- Measured yield of ^{115m}In per μC and per sample :

$$Y = \frac{\Delta t_{irr}}{Q}\frac{\lambda}{1-e^{-\lambda\Delta t_{irr}}}e^{\lambda(t_{0_{acq}}-t_{f_{irr}})}\frac{N_{\gamma}-N_{bdf}}{\Gamma\epsilon(1-e^{-\lambda\Delta t_{mes}})}$$

Ge detector efficiency

- Point source efficiency
  - ^{152}Eu point source measurements: $\epsilon = \frac{N_{\gamma}^{\text{meas}}}{N_{\gamma}^{\text{desint}}}$

    121,244,344,780,964,1112,1407 keV
  - Monte Carlo simulation :
    - *geometry : detector X-ray images*
    - *calculated spectrum of detected γ*
  - Comparison ε_{meas} vs ε_{simu}

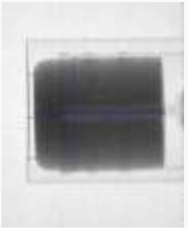
  ➪ validation of the geometry

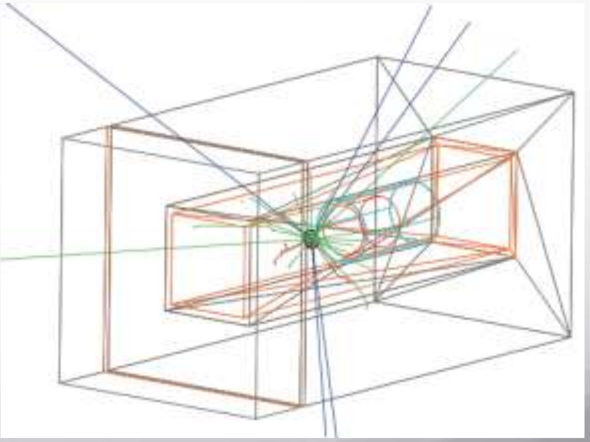
- Extended source efficiency
  - Monte Carlo simulation

  ➪ ε = 0.88 to 1.87 % depending on E_{γ}

Ge planar : Au

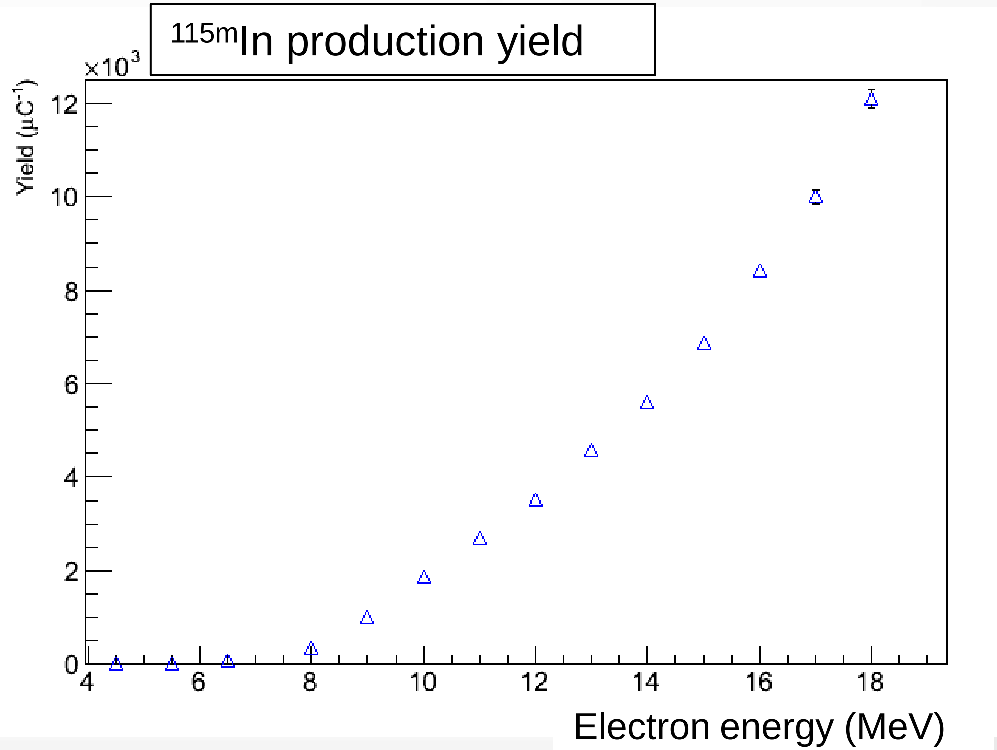
Ge coaxial : In

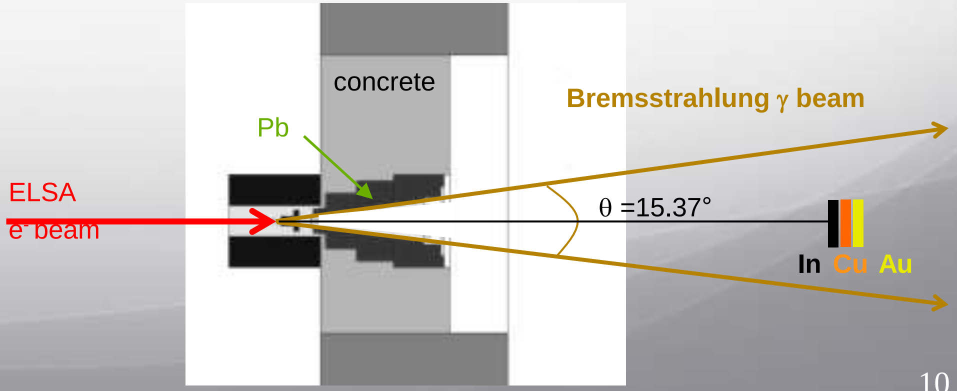




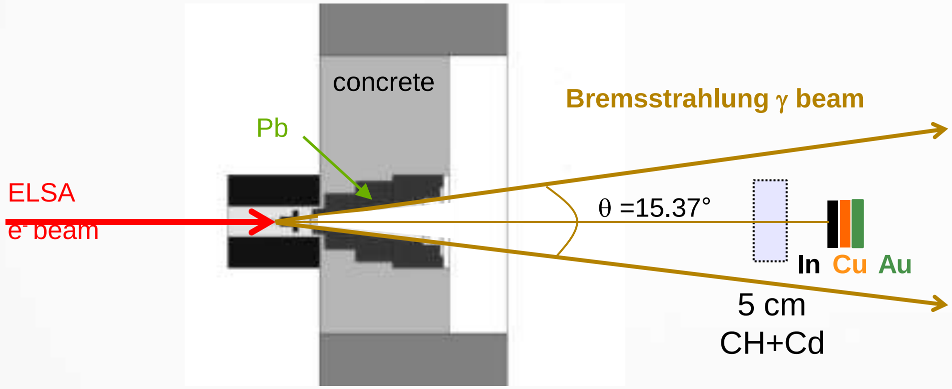
Measured ^{115m}In production yield

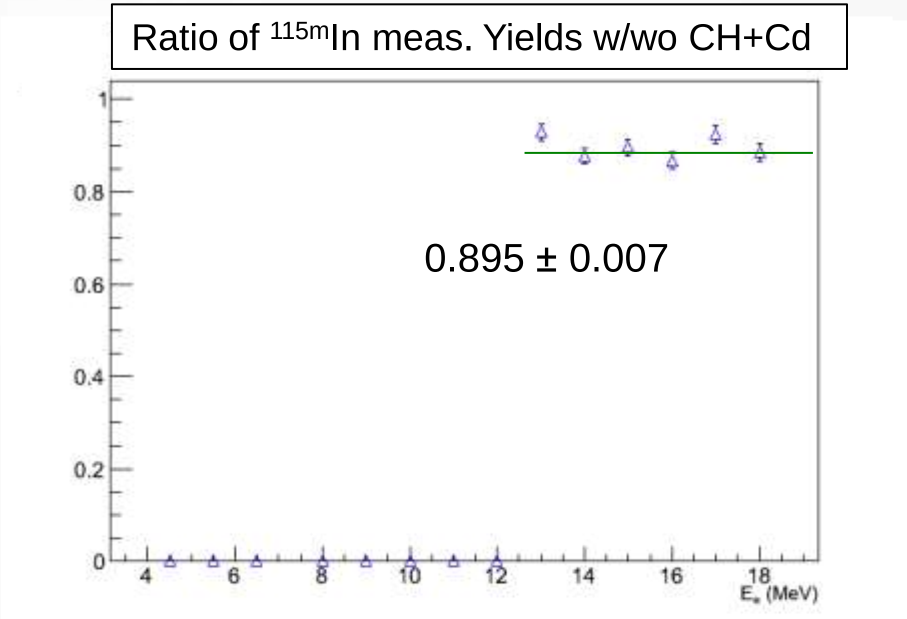
- Total (γ,γ')+(n,n') contributions
- Sources of fast neutrons :
  - ELSA collimators
  - Au sample : 1 source
    - $^{197}Au(\gamma,n)^{196}Au$
  - Cu sample : 2 sources
    - $^{63}Cu(\gamma,n)^{62}Cu$
    - $^{65}Cu(\gamma,n)^{64}Cu$
  - In sample : 4 sources
    - $^{115}In(\gamma,n)^{114m}In$ and $^{115}In(\gamma,n)^{114}In$
    - $^{113}In(\gamma,n)^{112m}In$ and $^{113}In(\gamma,n)^{112}In$

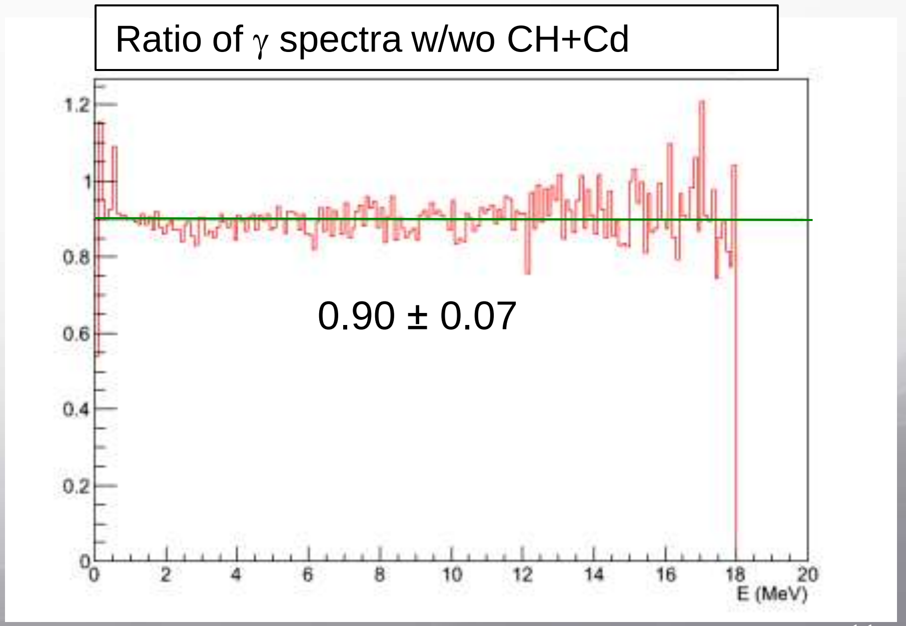




n flux from ELSA







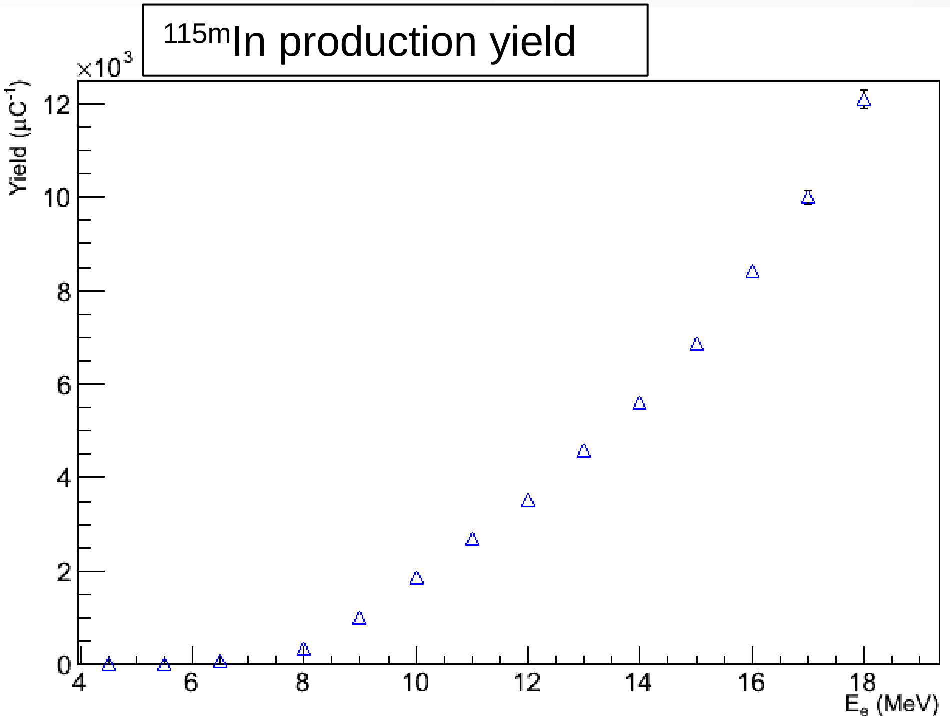
- Irradiations E_e = 18-12 MeV doubled :
  - with and without 5 cm CH + 0.8 mm Cd
- Monte Carlo simulation of γ beam on In
  - with and without CH+Cd
- Ratios w/wo CH+Cd are equal :

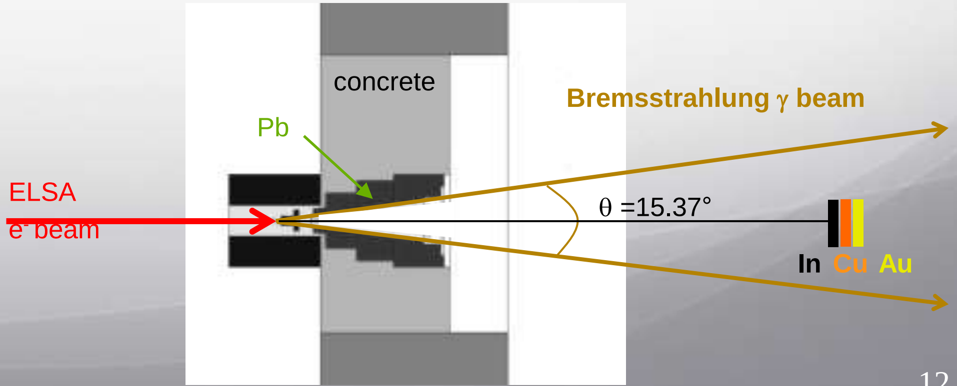
No other significant contribution to the measured ^{115m}In yield than (γ,γ') from ELSA.

➪ ELSA n flux negligible

^{115m}In production yield

- Total (γ,γ')+(n,n') contributions
- Sources of (γ,n) neutrons :
  - ELSA collimators
  - Au sample : 1 source
    - $^{197}Au(\gamma,n)^{196}Au$
  - Cu sample : 2 sources
    - $^{63}Cu(\gamma,n)^{62}Cu$
    - $^{65}Cu(\gamma,n)^{64}Cu$
  - In sample : 4 sources
    - $^{115}In(\gamma,n)^{114m}In$ and $^{115}In(\gamma,n)^{114}In$
    - $^{113}In(\gamma,n)^{112m}In$ and $^{113}In(\gamma,n)^{112}In$

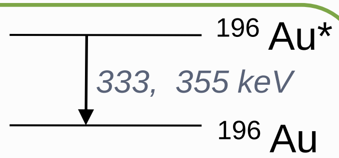


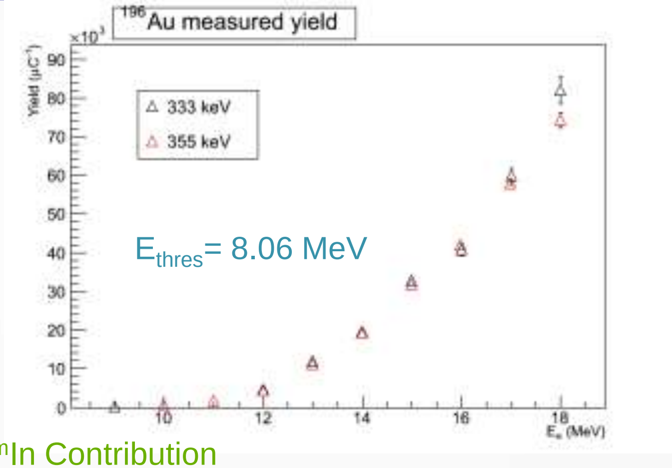


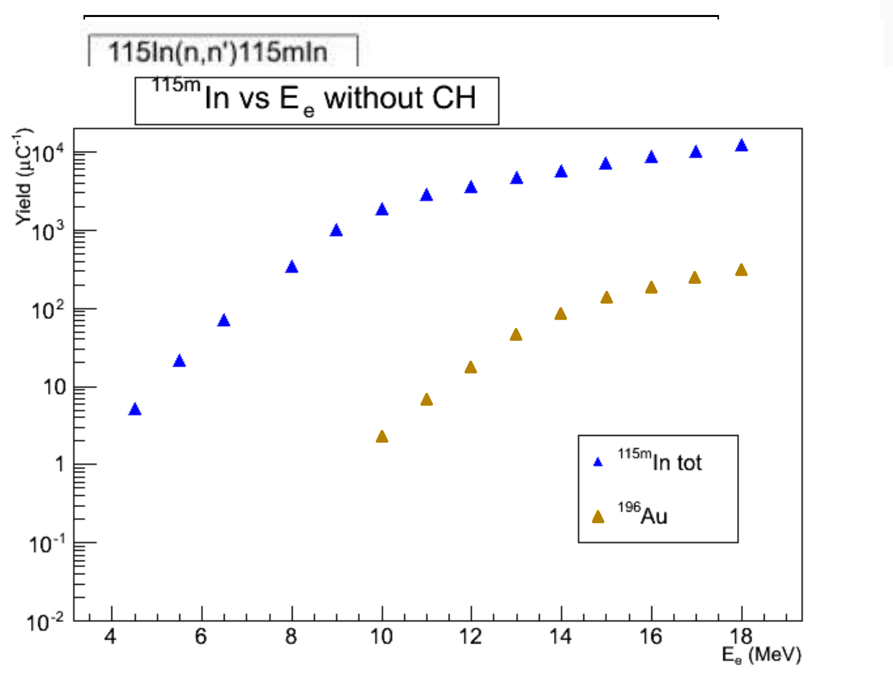
$^{115}In(n,n')^{115m}In$ yield from $^{197}Au(\gamma,n)^{196}Au$ fast neutrons

Measured yield of ^{196}Au

- **Au** : ^{197}Au 100%
  - $^{197}Au(\gamma,n)^{196}Au^* \longrightarrow \gamma_{333}, \gamma_{355}$
  - $$Y = \frac{\Delta t_{irr}}{Q} \frac{\lambda}{1-e^{-\lambda \Delta t_{irr}}} e^{\lambda(t_{0_{acq}} - t_{f_{irr}})} \frac{N_\gamma - N_{bdf}}{\Gamma \epsilon (1-e^{-\lambda \Delta t_{mes}})}$$
  - n yield = ^{196}Au yield







$^{155}In(n,n')^{115m}In$ Contribution

- Probability of $^{115}In(n,n')^{115m}In$ interaction :

$$p = \frac{1}{N_n^{tot}} \int_{R_{min}}^{R_{max}} \frac{dN_n}{dr} (1 - \mathrm{e}^{-N_{gs}\ \sigma_{nn'} r})\ dr$$

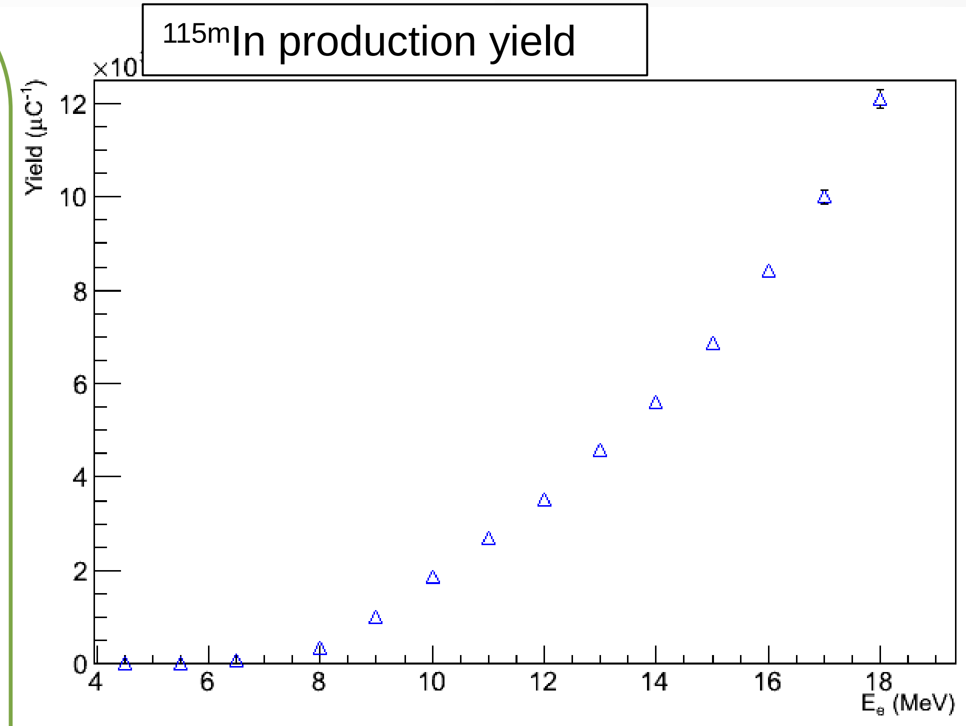
  - Neutrons' range in In sample : Monte Carlo
  - $^{115}In(n,n')^{115m}In$ cross section : constant

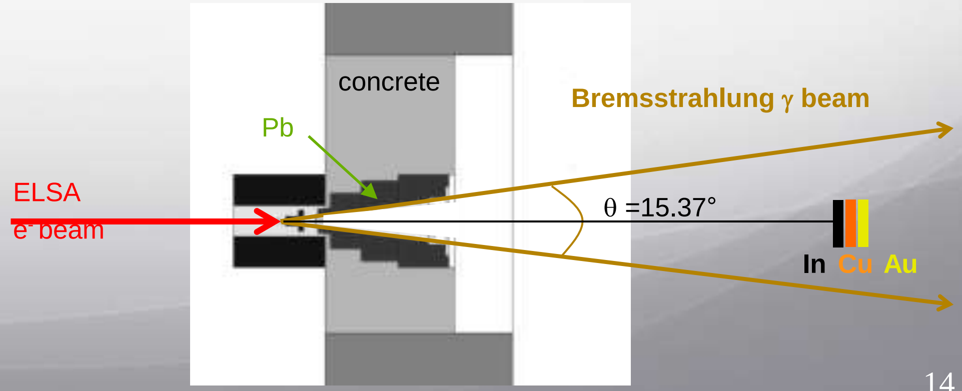
p_{Au}= 0.42 ± 0.02 %

18 MeV	Y (μC^{-1})	%
total	12100	100
^{196}Au contrib.	310	2.6

^{115m}In production yield

- Total (γ,γ')+(n,n') contributions
- Sources of (γ,n) neutrons :
  - ELSA collimators
  - Au sample : 1 source
    - $^{197}Au(\gamma,n)^{196}Au$
  - Cu sample : 2 sources
    - $^{63}Cu(\gamma,n)^{62}Cu$
    - $^{65}Cu(\gamma,n)^{64}Cu$
  - In sample : 4 sources
    - $^{115}In(\gamma,n)^{114m}In$ and $^{115}In(\gamma,n)^{114}In$
    - $^{113}In(\gamma,n)^{112m}In$ and $^{113}In(\gamma,n)^{112}In$

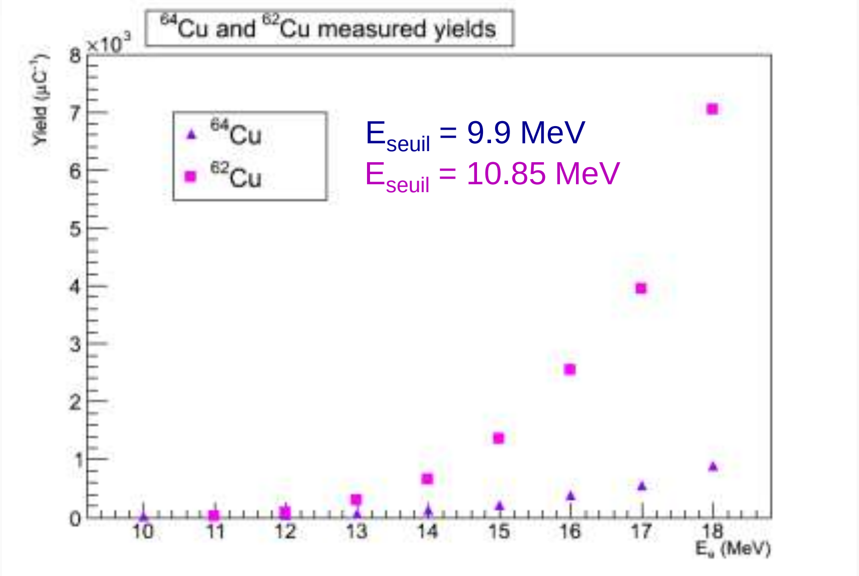


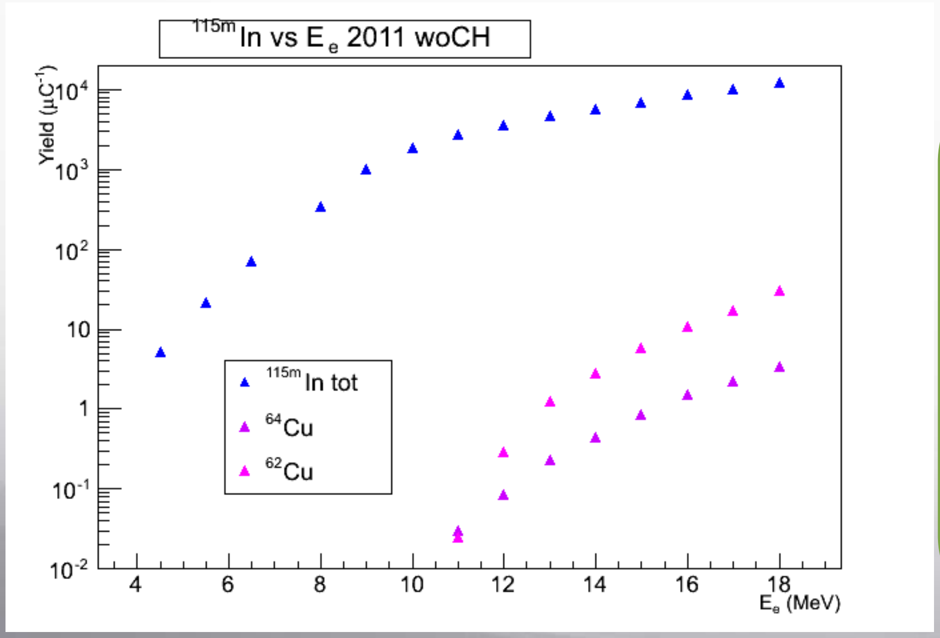


^{115}In(n,n')^{115m}In yield from (γ,n) on Cu

Measured yield of ^{64}Cu and ^{62}Cu

- **Cu** : ^{65}Cu 30.8% + ^{63}Cu 69.2%
  - $^{65}Cu(\gamma,n)^{64}Cu \longrightarrow \beta^{+}$
  - $^{63}Cu(\gamma,n)^{62}Cu \longrightarrow \beta^{+}$





^{155}In(n,n')^{115m}In Contribution

- Probability of ^{115}In(n,n')^{115m}In interaction :

$$p_{Cu}=p_{Au}= 0.42 \pm 0.02\ \%$$

18 MeV	**Y (μC^{-1})**	**%**
total	12100	100
^{62}Cu contrib.	30	0.2
^{64}Cu contrib.	4	0.03

^{115m}In production yield

- Total (γ,γ')+(n,n') contributions
- Sources of (γ,n) neutrons :
  - ELSA collimators
  - Au sample : 1 source

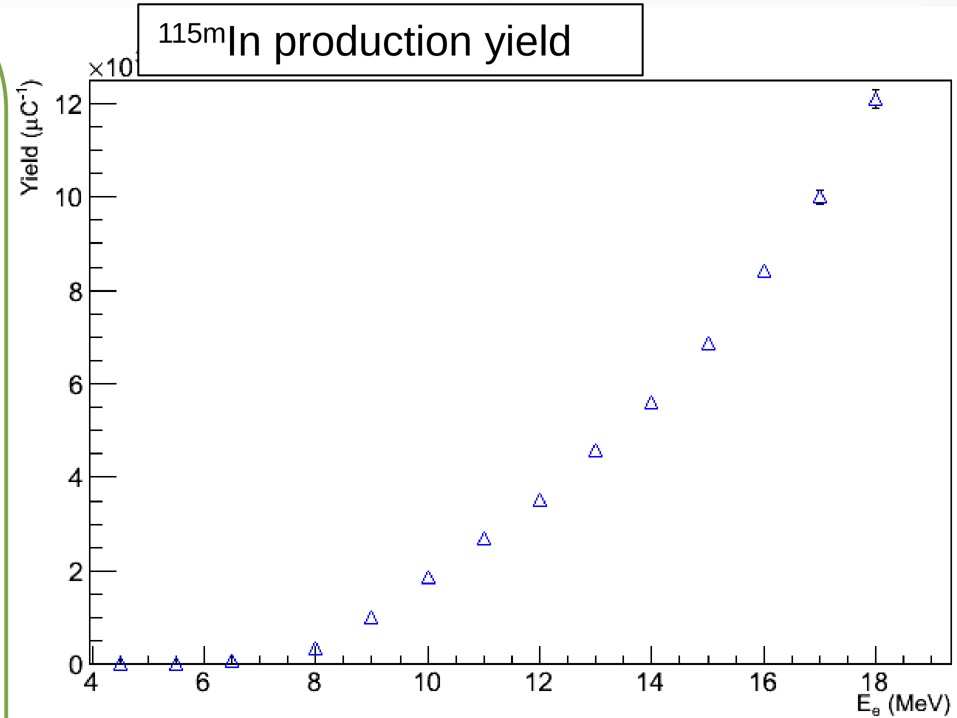
    $^{197}Au(\gamma,n)^{196}Au$
  - Cu sample : 2 sources

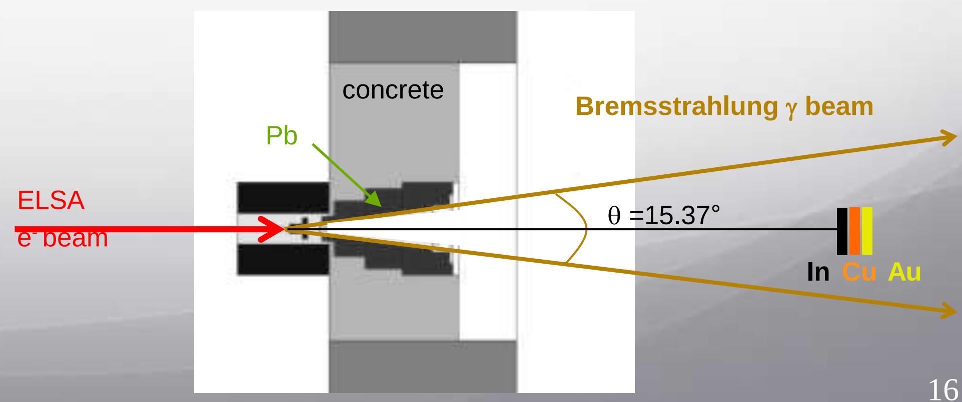
    $^{63}Cu(\gamma,n)^{62}Cu$

    $^{65}Cu(\gamma,n)^{64}Cu$
  - In sample : 4 sources

    $^{115}In(\gamma,n)^{114m}In$ and $^{115}In(\gamma,n)^{114}In$

    $^{113}In(\gamma,n)^{112m}In$ and $^{113}In(\gamma,n)^{112}In$

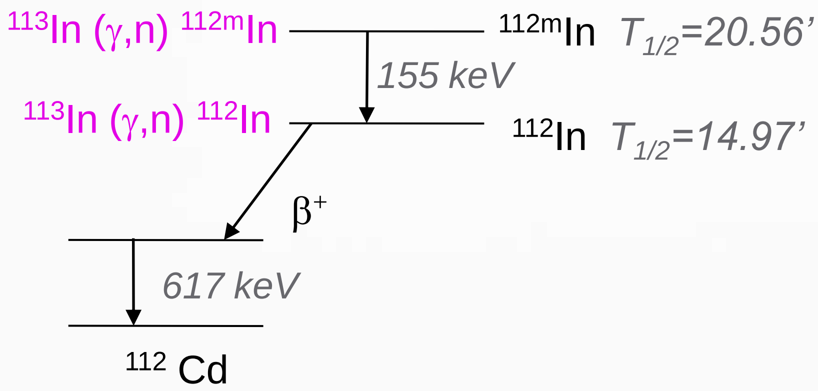




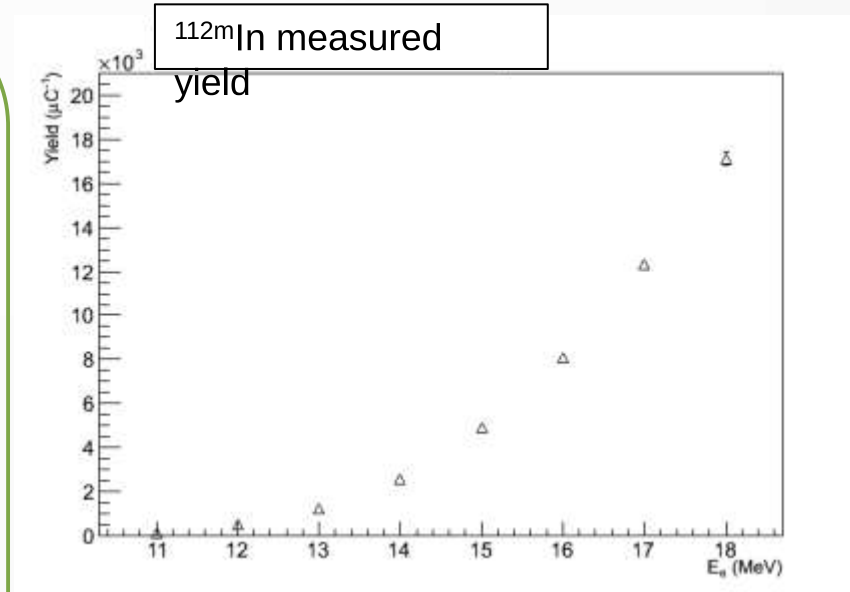
$^{113}In(\gamma,n)^{112}In$ and $^{113}In(\gamma,n)^{112m}In$ Yields

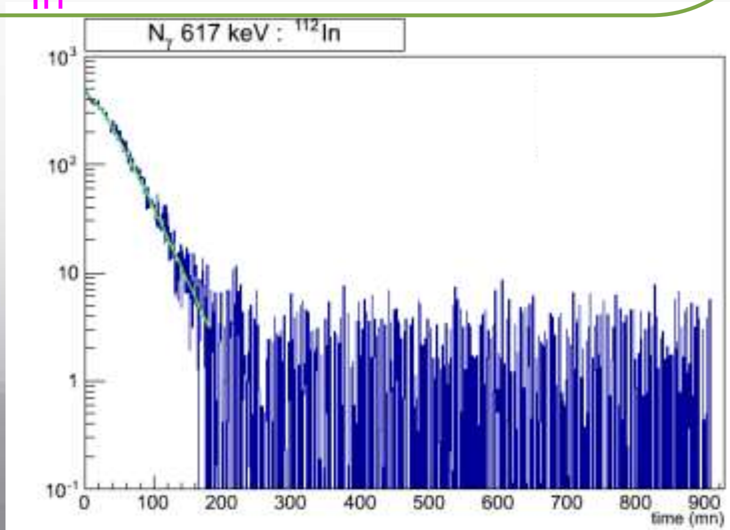
Measured yields of ^{112}In and ^{112m}In

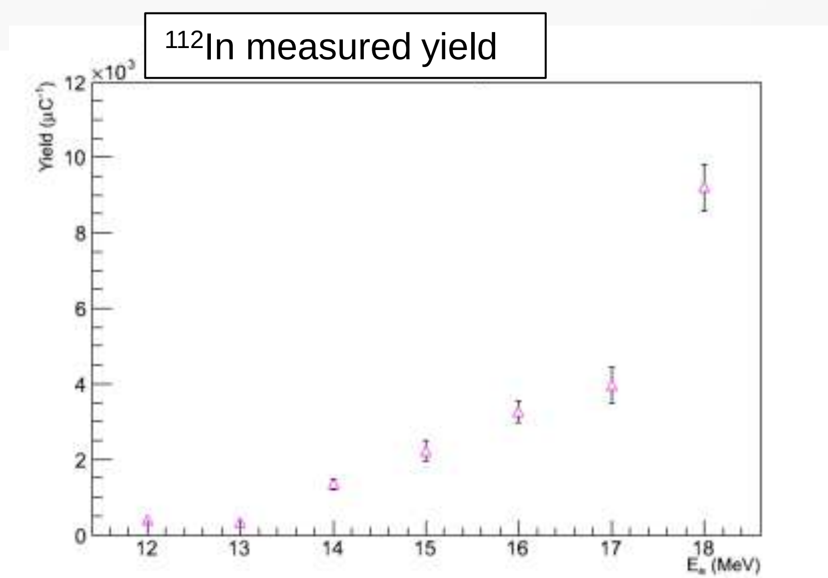
- **In** : ^{113}In 4.3%



- $^{113}In(\gamma,n)^{112m}In \longrightarrow \gamma_{155}$
- $^{113}In(\gamma,n)^{112}In$: fit of 617 keV decay with 2 parameters : (γ,n) prod. yield of ^{112}In and ^{112m}In



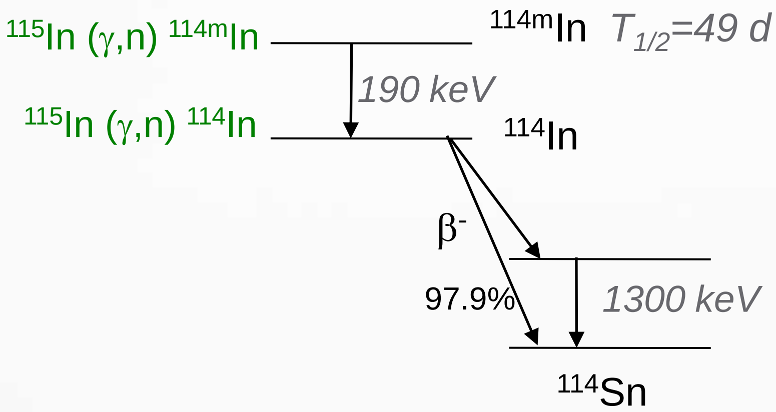




$^{115}In(\gamma,n)^{114}In$ and $^{115}In(\gamma,n)^{114m}In$ Yields

Measured yields of ^{114}In and ^{114m}In

- **In** : ^{115}In 95.7%



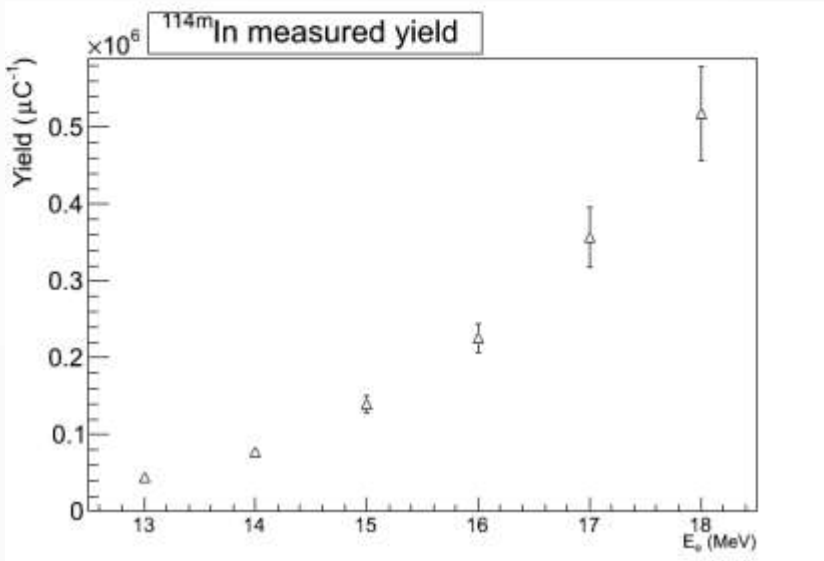
- $^{115}In(\gamma,n)^{114m}In \longrightarrow \gamma_{190}$
- $^{115}In(\gamma,n)^{114}In$: calculation using σ_{TALYS}

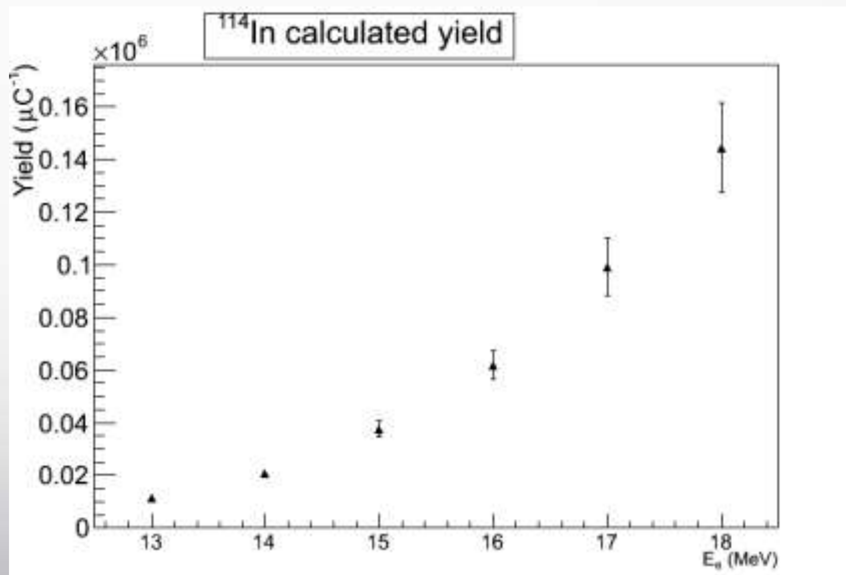
➪ validation on ^{113}In

$$Y_{A-1} = N_A \int_{E_{\rm th}}^{E_{\rm max}} \phi(E_\gamma)\sigma_{\gamma,n}(E_\gamma)\, dE_\gamma$$

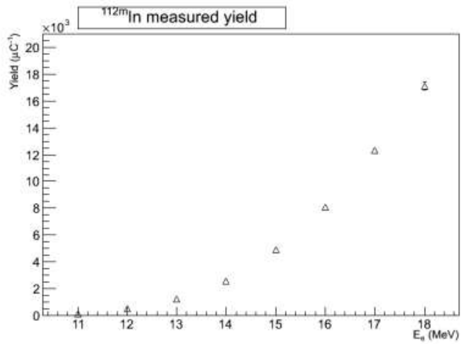
$$\frac{Y_{\rm iso}^{\rm TALYS}}{Y_{\rm gs}^{\rm TALYS}} = \frac{Y_{\rm iso}^{\rm meas}}{Y_{\rm gs}^{\rm meas}}$$

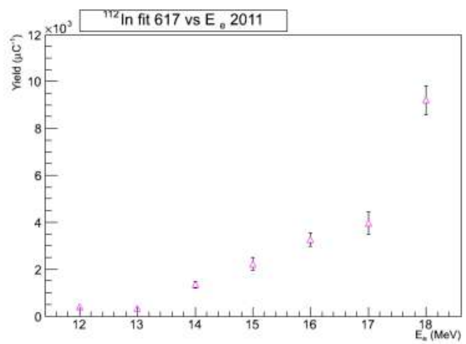
➪ application to ^{115}In : $Y_{\rm gs} = Y_{\rm iso}^{\rm meas} \dfrac{Y_{\rm gs}^{\rm TALYS}}{Y_{\rm iso}^{\rm TALYS}}$

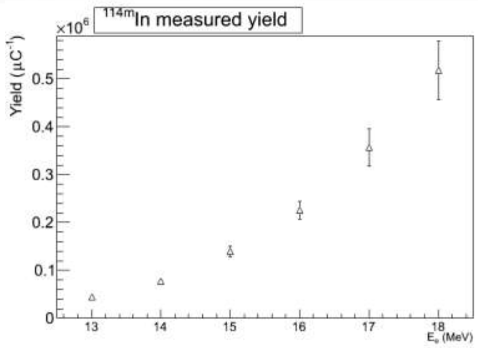


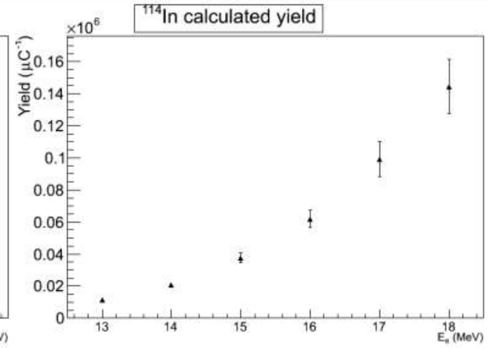


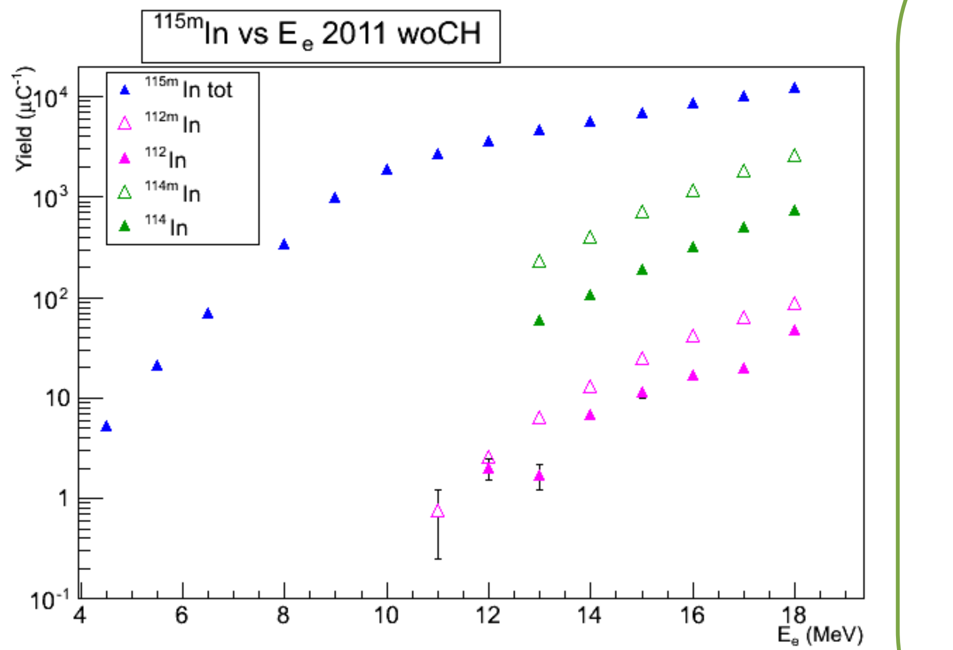
^{115}In(n,n')^{115m}In yield from (γ,n) on In











^{115}In(n,n')^{115m}In Contribution

- Probability of ^{115}In(n,n')^{115m}In interaction :

$$p = \frac{1}{N_n^{tot}} \int_{R_{\min}}^{R_{\max}} \frac{dN_n}{dr}\left(1 - e^{-N_{gs}\ \sigma_{nn'} r}\right)\, dr$$

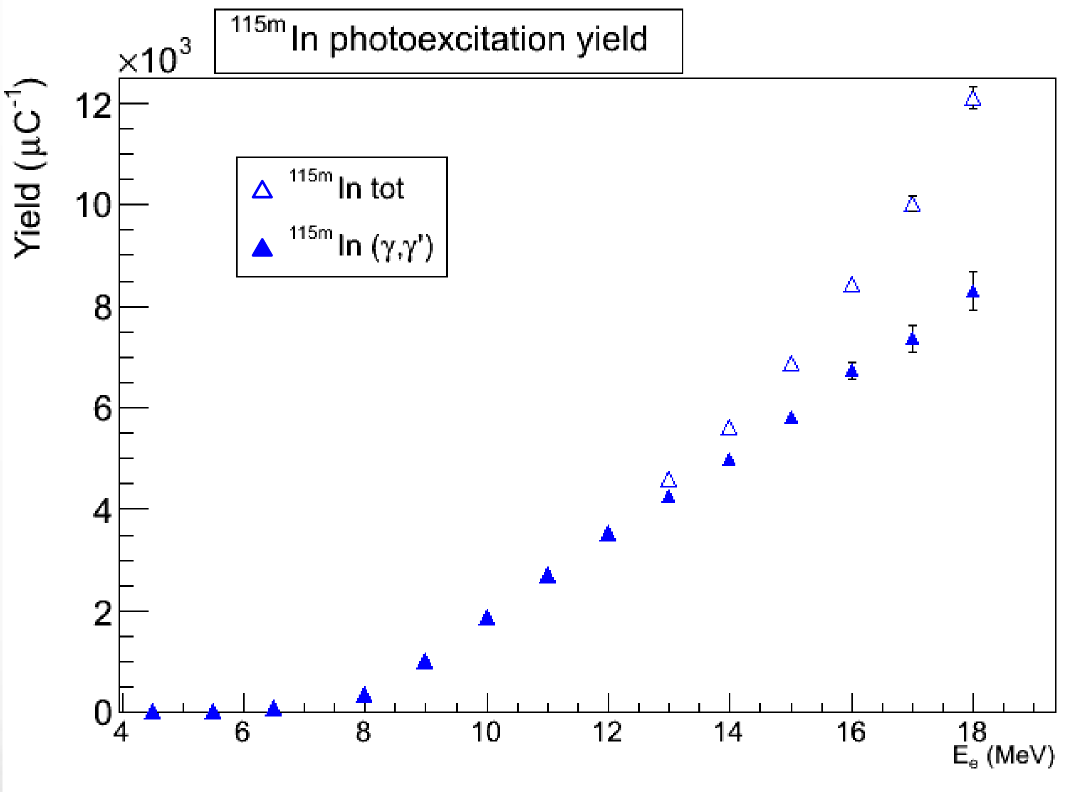
- Neutrons' range in In sample : Monte Carlo
- ^{115}In(n,n')^{115m}In cross section : 319.9 ± 0.9 mb

p_{In}= 0.50 ± 0.02 %

18 MeV	µC^{-1}	**%**
Y total	12100	100
^{112m}In contrib.	86	0.7
^{112}In contrib.	46	0.4
^{114m}In contrib.	2610	**21.6**
^{114}In contrib.	1396	**11.5**

^{115m}In photoexcitation production yield

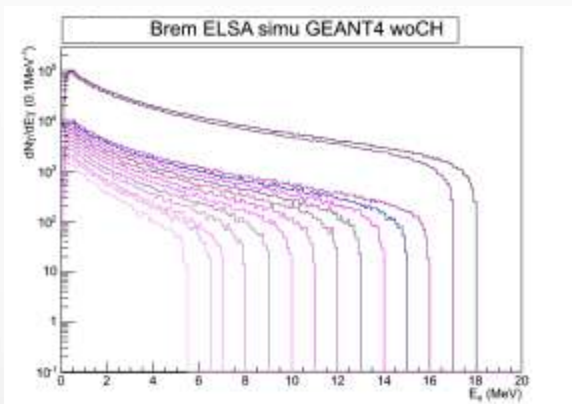
- Total (γ,γ')+~~(n,n') contributions~~
- ~~Sources of (γ,n) neutrons :~~
  - ~~ELSA collimators~~
  - ~~Au sample : 1 source~~
    - ~~$^{197}Au(\gamma,n)^{196}Au$~~
  - ~~Cu sample : 2 sources~~
    - ~~$^{63}Cu(\gamma,n)^{62}Cu$~~
    - ~~$^{65}Cu(\gamma,n)^{64}Cu$~~
  - ~~In sample : 4 sources~~
    - ~~$^{115}In(\gamma,n)^{114m}In$ and $^{115}In(\gamma,n)^{114}In$~~
    - ~~$^{113}In(\gamma,n)^{112m}In$ and $^{113}In(\gamma,n)^{112}In$~~
  - ➪ Have all been corrected



$$Y_{calc}(E_e) = \frac{1}{e10^6 N_e} \frac{m_{vol} N_A \epsilon_{tgt}}{M_{at}} \int_{E_s}^{E_e} \frac{dN_\gamma}{dE_\gamma}(E_\gamma, E_e)\, \sigma(E_\gamma)\, dE_\gamma$$

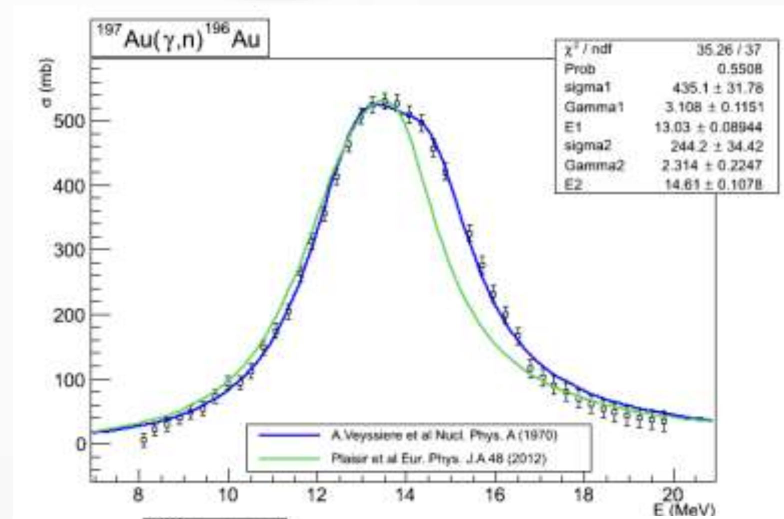
Validation of γ distributions

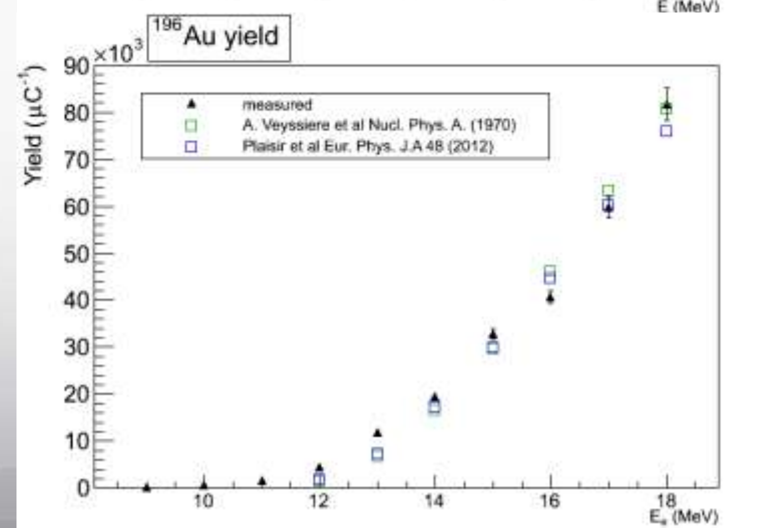
- Calculated bremsstrahlung spectra
  - Detailed Monte Carlo simulation



- Comparaison between measured and calculated yields of ^{63}**Cu** and ^{196}**Au**
  - Uncertainties < marker.

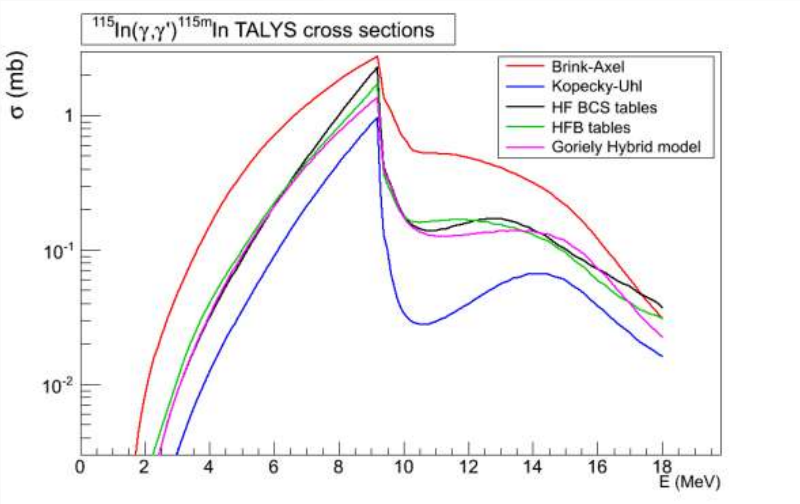
➪ γ spectra validated

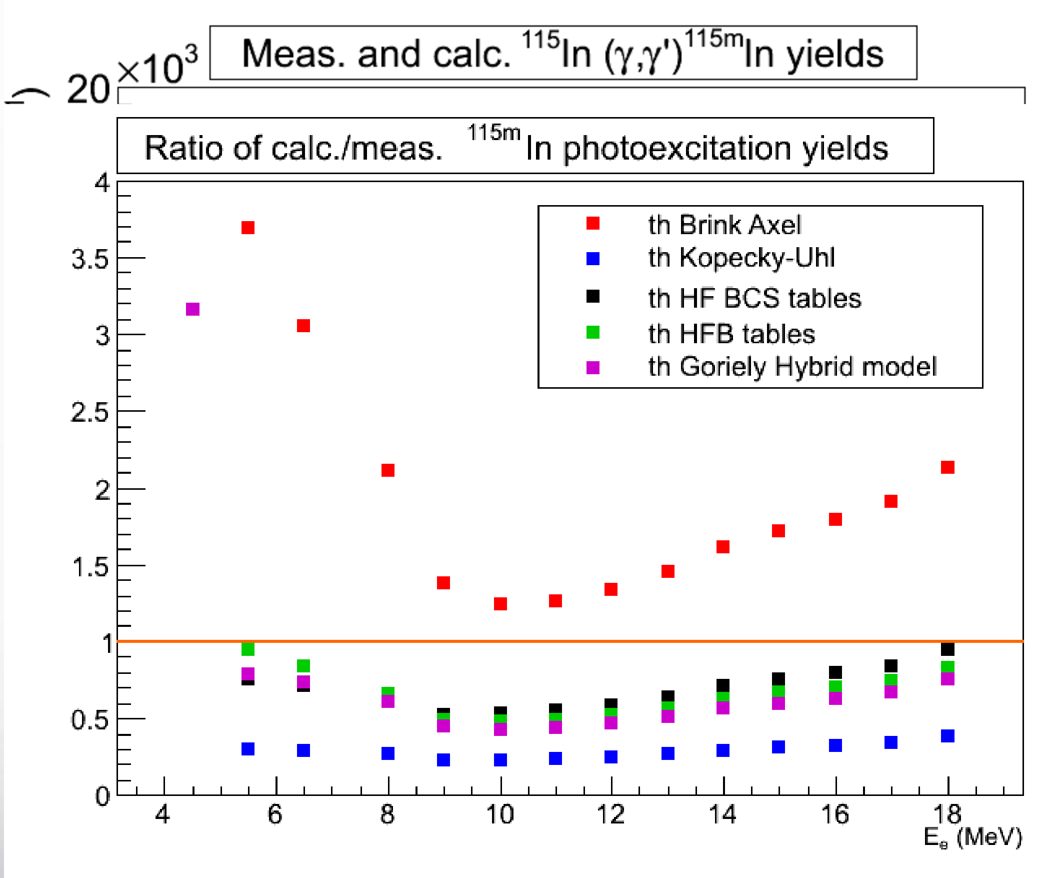




Testing theoretical calculations

$$Y_{calc}(E_e) = \frac{1}{e10^6 N_e} \frac{m_{vol} N_A \epsilon_{tgt}}{M_{at}} \int_{E_s}^{E_e} \frac{dN_\gamma}{dE_\gamma}(E_\gamma, E_e)\, \sigma(E_\gamma)\, dE_\gamma$$





- Brink-Axel > Measurement
- All other models underestimate our results

- New experimental photoexcitation yields of ^{115m}In
  - All (n,n') contributions have been corrected
- Comparison with available models
  - All the γ strength models tried in TALYS fail to reproduce our results

Perspectives

- ^{113}In(γ,n)^{112m}In is to be extracted from our data
- New calculations underway :
  - Self consistent QRPA + blocking with the Gogny force

S. Péru and H. Goutte Phys. Rev. C ***77*** *(2008)*

S.Péru et al Phys. Rev. C ***83*** *(2011)*

- First measurement of ^{115m}In photoexcited by γ beam produced at laser installation ELFIE (Palaiseau, France) :

April 2013

Thank you.

^{115}In potential used for TALYS calculation

- ^{115}In : slightly deformed
  - Morillon and Romain potential

    PRC 70 014601 (2204)

  Rather than the Delaroche spherical potential.

^{113}In(γ,n)^{112m}In cross section

- Méthode de minimisation de χ^2 entre Y_{calc} et Y_{mes} avec une forme analytique de la section efficace
- Comparaison à la littérature et aux calculs TALYS

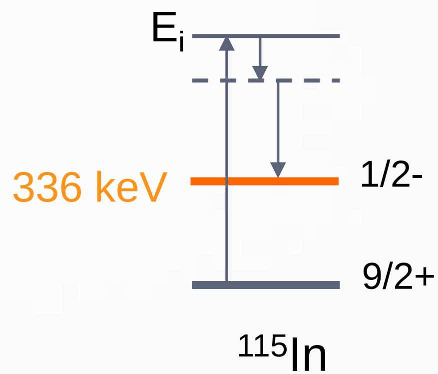
Natural In : 2 stable isotopes

^{115}In (95.7%) + ^{113}In (4.3%)

^{115m}In isomeric state :

$T_{1/2}$ = 4.486 h

E_g = 336 keV



- Neutron yields in ICF experiments :
  - DD fusion : D + D $\longrightarrow$ He + n

    10^9 to 10^{14} n of 2.45 MeV
  - Inelastic n scattering :

    ^{115}In(n,n')^{115m}In : γ of 336 keV

$$N_{\rm iso} = N_{\rm gs} \int_{E_t}^{E_{\rm max}} \phi_n(E_n)\sigma_{n,n'}(E_n)\ dE_n$$

➪ characterization of ICF performance

- Contribution of ^{115}In(γ,γ')^{115m}In to the total number of measured 336 keV γ

➪ $\sigma_{\gamma\gamma'}$ cross section ?