Investigation of ^{113}In(α,n) and ^{nat}In(α,n) reactions to determine the α-optical potential for astrophysical p-process

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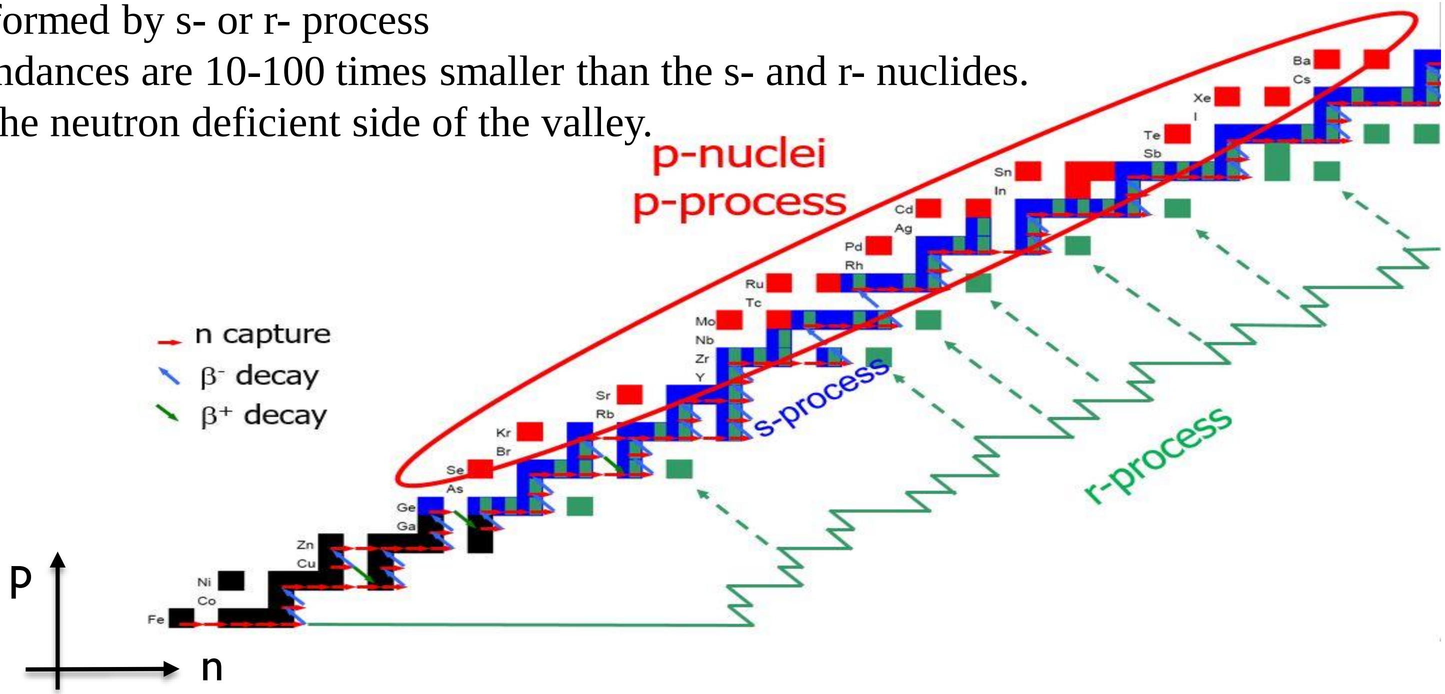
Plan of Talk

- Alpha induced reaction with p-nuclei
- Alpha optical model potential
- Sensitivity study
- Different approach : (α,n) reaction
- ^{113}In(α, γ) reaction

What Are p-nuclei

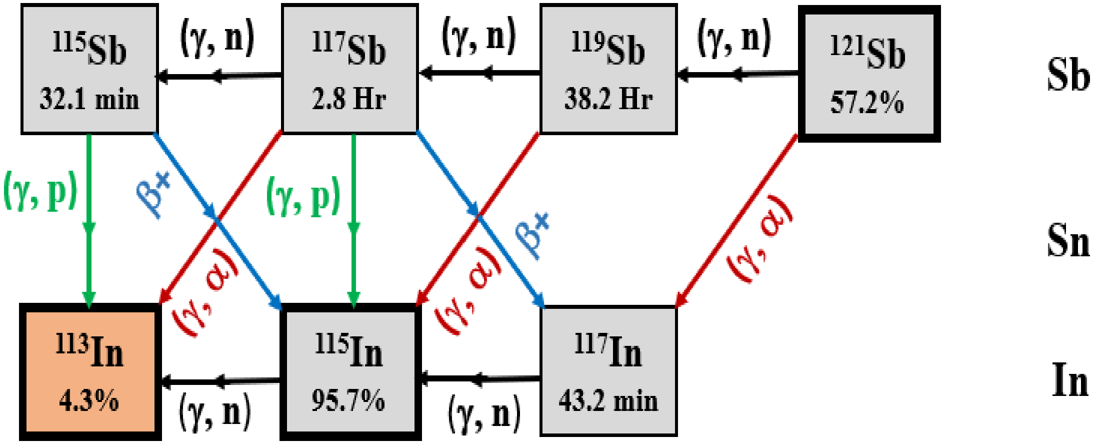
- Nuclei heavier than iron (Z>26) are produced in the stars by neutron capture and β-decay process as charged particle fusion reaction becomes more and more difficult due to the Coulomb barrier.
  - Slow neutron capture (s-process)
  - Rapid neutron capture (r- process).

- A number of naturally occurring isotopes (^{74}Se-^{196}Hg)
  - Can not be formed by s- or r- process
  - Natural abundances are 10-100 times smaller than the s- and r- nuclides.
  - Situated in the neutron deficient side of the valley.



Production of p-nuclei

- p-nuclei are formed by a sequence of photodisintegration processes in a high γ-flux scenario.
  - Pre existing s or r- seed nuclei are created proton rich isotopes via a series of (γ, n) reactions.
  - When the neutron separation energy increases, (γ, p) and (γ, α) reactions are more rapid and produced stable element with lower atomic number.



Needs for measuring alpha optical model potential (AOMP)

- Calculation for the p-process requires a huge reaction network involving about 1000 nuclei and the reaction rates are necessary input to the network reaction calculation.

- Reaction rates are derived from the reaction cross-sections.

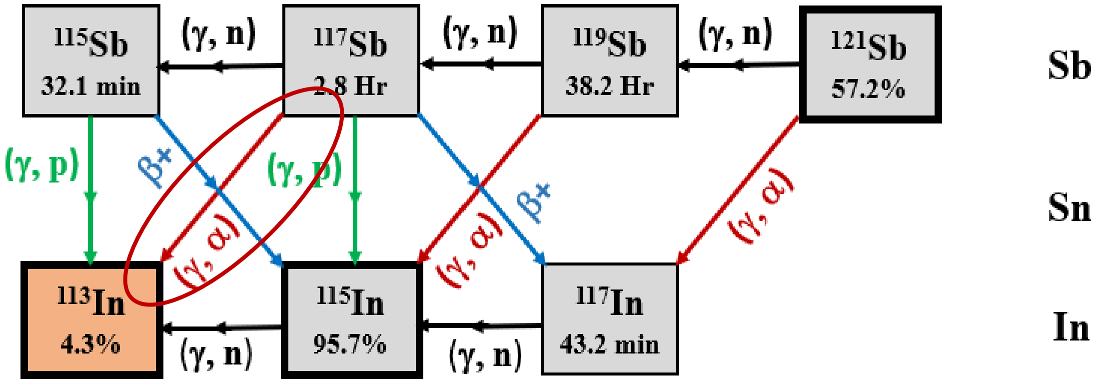
- The γ-induced reaction cross-sections can be obtained from the inverse reaction cross-section using the principle of detailed balance.

- In order to analyze measured (α,γ),(p,γ) reaction cross-sections, one has to calculate them using the statistical model for compound nuclear processes.

- One of the main Ingredient of Statistical model calculations is optical potential.

Alpha induced reaction on ^{113}In

- Maximum p-process calculation have been performed with even Z nuclei ($J^{\pi} = 0^{+}$) . ^{113}In has odd Z nuclei and non zero ground state spin($9/2^{+}$) .
- High abundant p-nuclei (4.28%)
- ^{113}In has a special importance for the study of the Cd-In-Sn region. ^{113}In is under produced in nucleosynthesis calculations of the *p* or *γ* process. ^{113}In has strong contributions from other processes.
- More accurate measured cross sections in the relevant energy range are required to find whether these discrepancies are caused by nuclear physics inputs or also problems with astrophysical models.



Limitation of elastic scattering

- α-optical potential parameters are obtained by fitting the existing alpha elastic scattering angular distribution (McFadden-Satchler).
- (α,γ) reaction cross-section are obtained at Gamow window energy region.
- Due to the dominance of Coulomb part, elastic scatterings are performed at much higher energies and extrapolated potential parameter for required energy.
- For low energy reaction , AOMP obtain form elastic scattering data are not properly explain the reaction.

Reaction cross-section : Statistical model

- Alpha induced compound nucleus cross-section for a specific outgoing channel x (x= α,p,n,γ etc.):

$$\sigma(\alpha,x) = \sum_J \underset{\downarrow}{\sigma(E_c,J)}\,\underset{\downarrow}{P(E_c,J;x)}$$

Compound nucleus formation cross-section

Decay probability

- Decay probability : $P(E_c,J;x) = \frac{T_x}{\sum T_i}$
- Above neutron threshold (for low energy reaction) neutron decay dominates

$$P(E_c,J;x) \;\approx 1$$

$$\sigma(\alpha,n) \sim \sum_J \sigma(E_c,J) \approx \sum_J \pi ƛ_\alpha^2 T_l(\alpha)$$

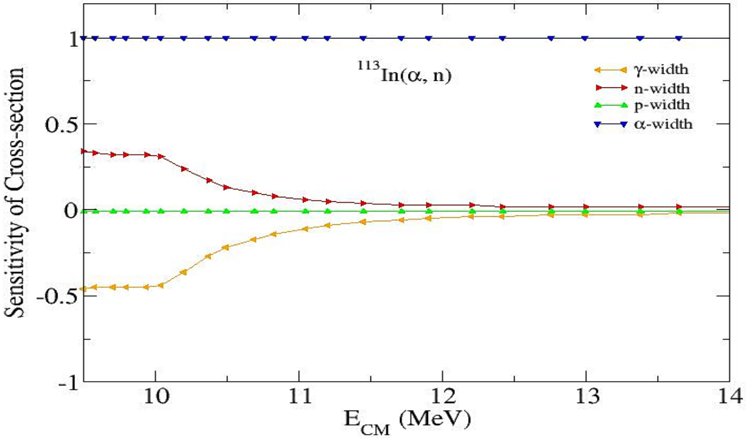
$T_l\ (\alpha)$: Transmission coefficient for entrance channel.

(α,n) cross-section is solely dependent on the α-optical potential.

- Fitting the (α,n) reaction cross-section data to modify the AOMP parameters for lower energies.
- The HF calculations are carried out using the statistical model code TALYS in version 1.96

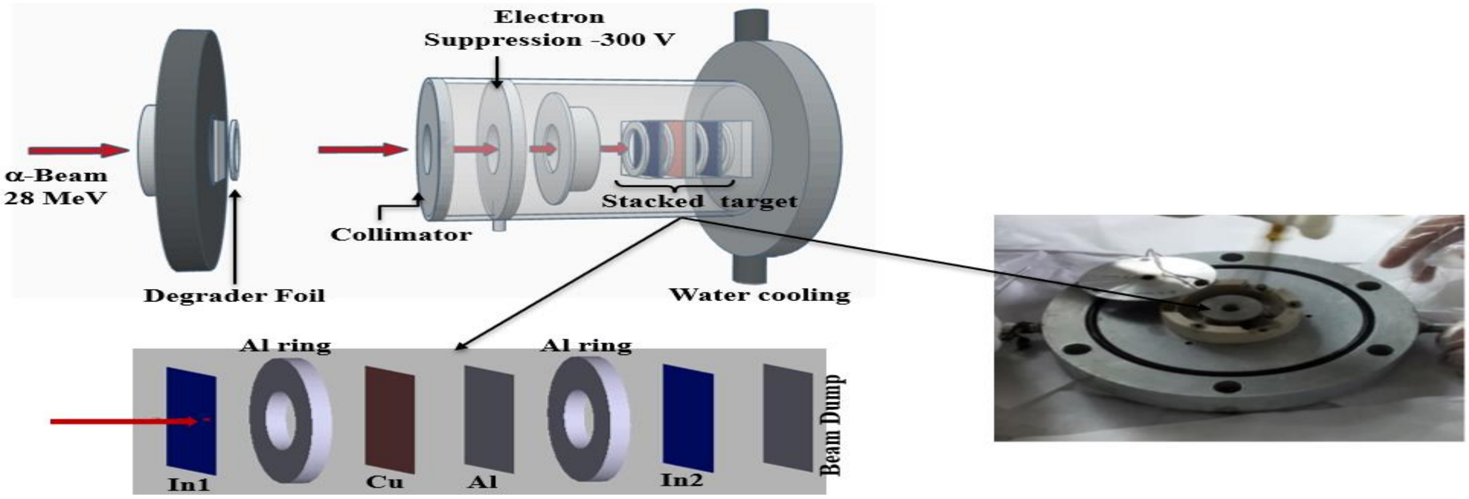
Sensitivities of Cross-section

- In Hauser-Feshbach model calculation, reaction cross-sections are computed from the transmission coefficients that are correlated with the average width parameters
- Sensitivities of cross-section (σ) with variation of width (w):
- $S = \frac{\frac{d\sigma}{\sigma}}{\frac{dw}{w}}$ Ref : T. Rauscher, Ap. J. Suppl. 201, (2012) 26.
  - S = 0 : No change in cross-section by changing the width.
  - S = ±1 : Cross-section is changed by same factor as the width changes.



Activation Measurement @ VECC:

- α-beam energy = 28 MeV
- Target :
  - Enrich ^{113}In (93.1% ^{113}In , 6.9% ^{115}In) / Al Backing
    (Thickness In : 0.078 μm (56 μm/cm^{2}) / Al : 2.71 μm)
  - ^{nat}In (4.3% ^{113}In , 95.7% ^{115}In) / Al Backing
    (Thickness In : 0.12 μm (85μm/cm^{2}) / Al : 2.71 μm)
- Reaction : ^{113}In(α,n), Energy : 9.9 -17.8 MeV
- Monitor foil : ^{nat}Cu (Thickness 7 μm)



Modified McFadden-Satchler (McF) potential:

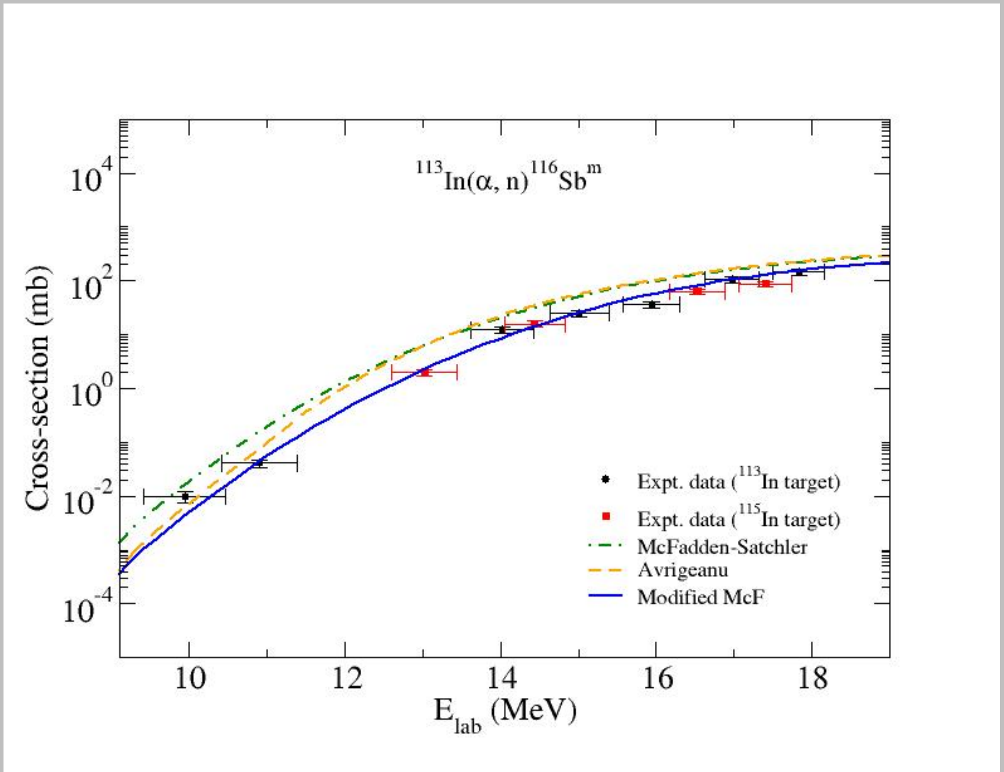
- Modified McF potential parameter set :

Real Potential parameter	Imaginary potential parameter
$V_0 = \frac{185}{1+\exp(\frac{0.9E_{cu}-E_{cm}}{a_c})}$ MeV	$W_0 = \frac{25}{1+\exp(\frac{0.9E_{cu}-E_{cm}}{a_c})}$ MeV
r_v = 1.4 fm	r_w = 1.4 fm
a_v = 0.52 fm	a_w = 0.52 fm
r_c = 1.3 fm	

Energy diffusivity : a_c = 10 MeV
E_{cu} = Coulomb barrier

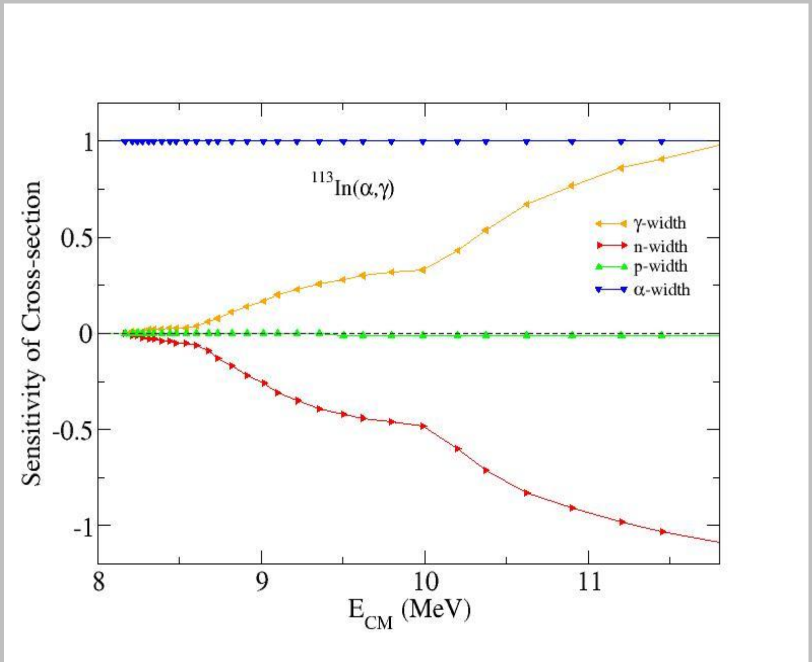
Ref : 1. Astron. Astrophys. 333, (1998) 1112
2. D. Basak, C. Basu, Eur. Phys. J. A 58 (2022) 150

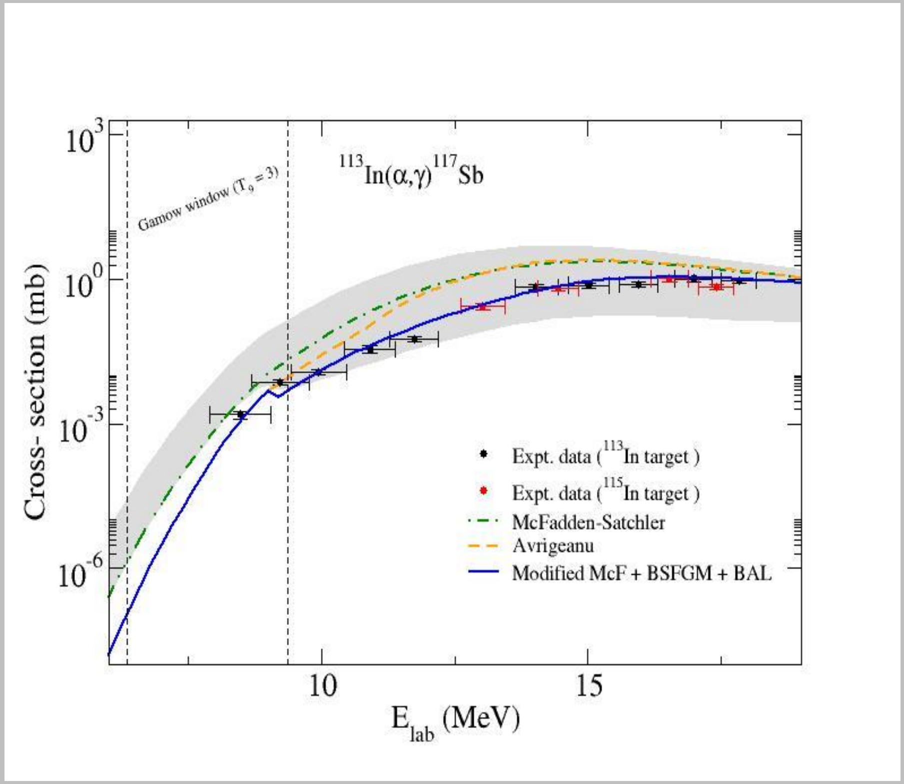
^{113}In(α,n) Reaction



Potential	χ^2/N
McFadden-Satchler	94.46
Avrigeanu	83.21
Modified McF	4.58

^{113}In(α,γ) Reaction





Conclusion

- (α,n) reactions for p-nuclei ^{113}In is mainly dependent on the α-width, other width contributions are negligible .
  - McF potential with both real and imaginary depth modified adequately explains the results.
  - Modified potential defines α–width with significant accuracy.
- Neutron and gamma width also contribute to the ^{113}In(α,γ) reaction cross-section
  - The modified potential provide a satisfactory representation of the (α,γ) reaction cross-section with suitable level density(Back-shifted Fermi gas Model) and γ-ray strength function (Brink-Axel Lorentzian).

Thank You

α-optical potential

- α-optical Potential form for Present System :

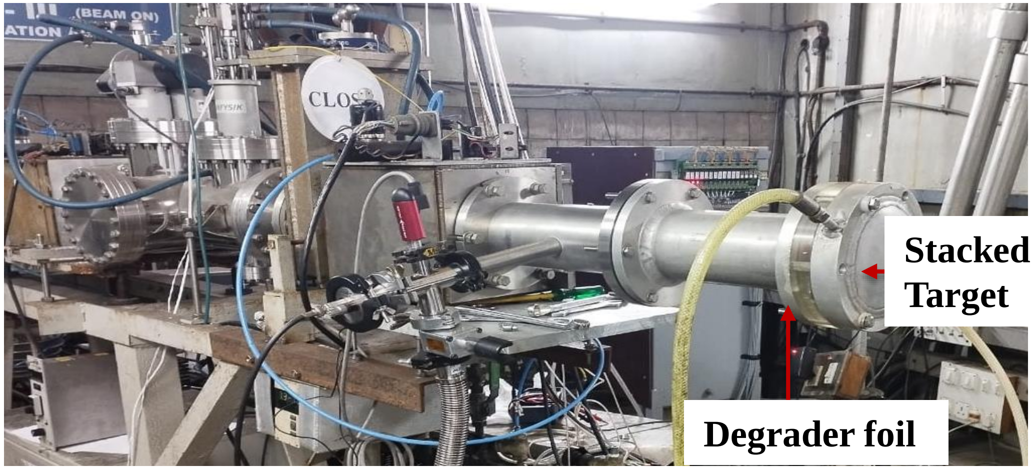
$$U(r) = V_C(r) + V_N(r)$$

$$\underset{\text{Coulomb potential}}{\downarrow} \qquad \underset{\text{Nuclear potential}}{\downarrow}$$

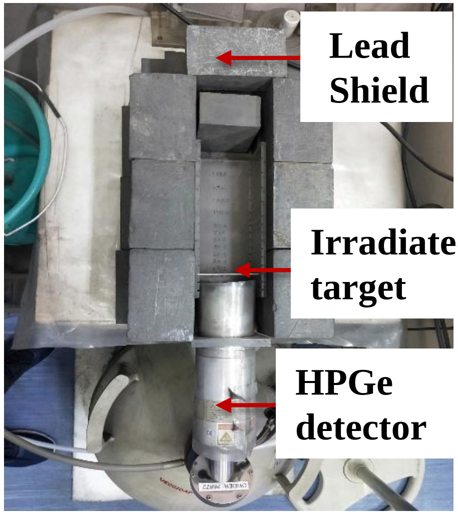
$$V_N(r) = \frac{-V_0}{1 + exp\left(\frac{r - r_v A_T^{1/3}}{a_v}\right)} + i\frac{-W_0}{1 + exp\left(\frac{r - r_w A_T^{1/3}}{a_w}\right)}$$

- V_0,W_0= Real and Imaginary potential strength
- r_i,a_i= Radii and diffusivities. (i=v,w)

Experimental Setup



- Performed at K-130 cyclotron (channel 1) in VECC , Kolkata
- Irradiation time ~3-12 Hr
- Current = 250-300 nA



- Distance between detector window and target is = 12.5 mm

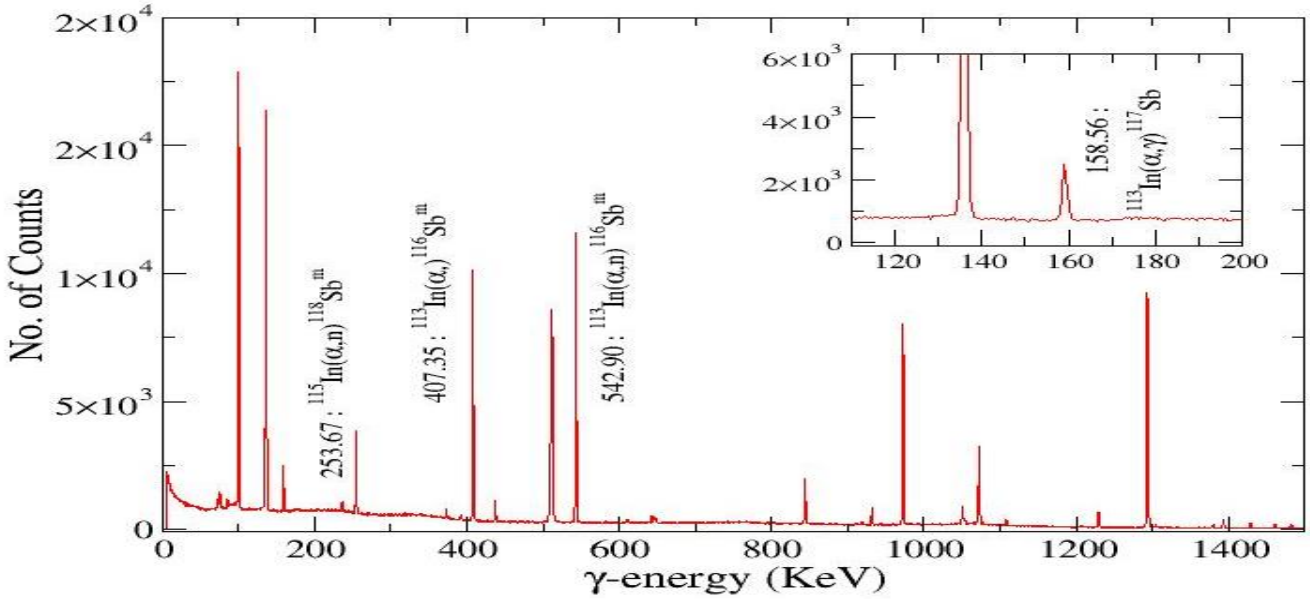
Sensitivities of Cross-section

- In Hauser-Feshbach model calculation, reaction cross-sections are computed from the transmission coefficients that are correlated with the average width parameters
- Sensitivities of cross-section (σ) with variation of width (w):
- $$S = \frac{\frac{d\sigma}{\sigma}}{\frac{dw}{w}}$$ Ref : T. Rauscher, Ap. J. Suppl. 201, (2012) 26.
  - S = 0 : No change in cross-section by changing the width.
  - S = ±1 : Cross-section is changed by same factor as the width changes.

Results

Reaction	Product	Half Life (Hr)	γ-energy (KeV)	Relative Intensity (%)
^{113}In(α,n)	^{116}Sb^{m}	1.01	407.35	38.8
			542.9	52
^{113}In(α,γ)	^{117}Sb	2.8	158.56	85.9

Ref : Nuclear Data Sheets 137, 1 (2016)

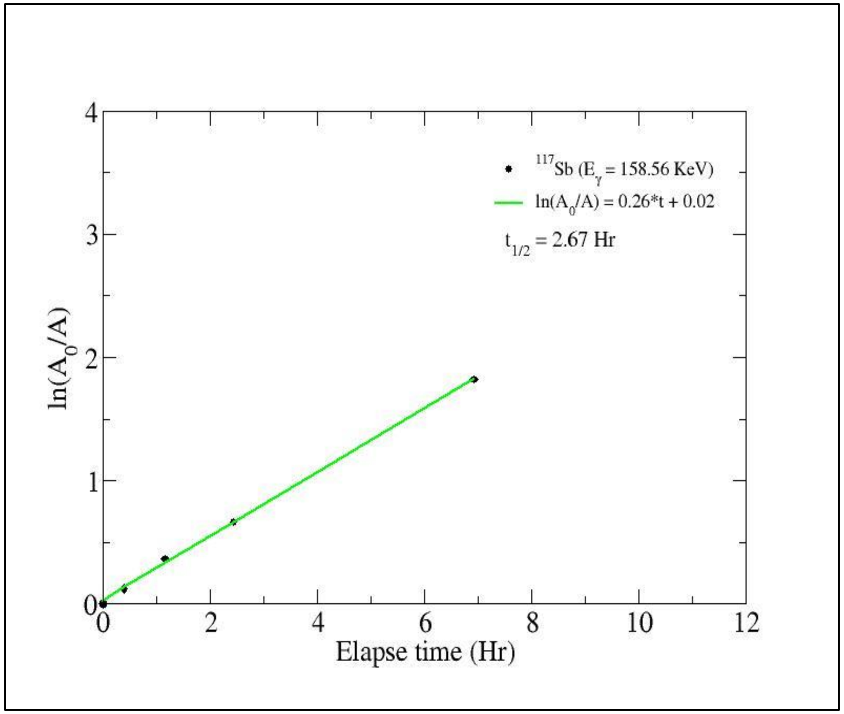


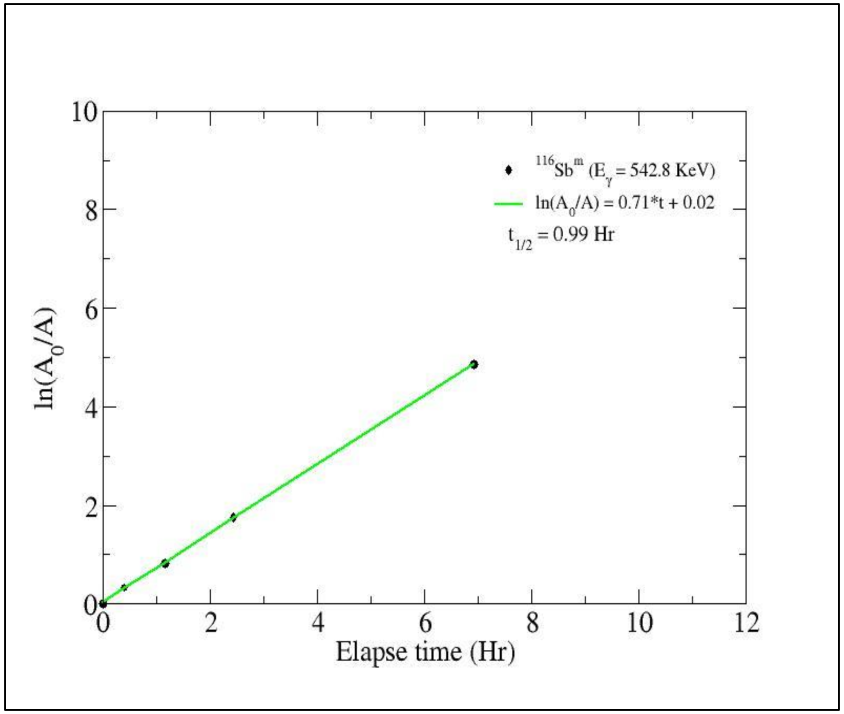
E ~ 15.94±0.36MeV

t_{irrad} ~ 3 Hr

$t_{waiting}$ ~ 1.2 Hr

Half Life Estimation





Half life : ^{117}Sb : 2.8 Hr
^{116}Sb^m : 1.01 Hr

α– induced reaction cross-section

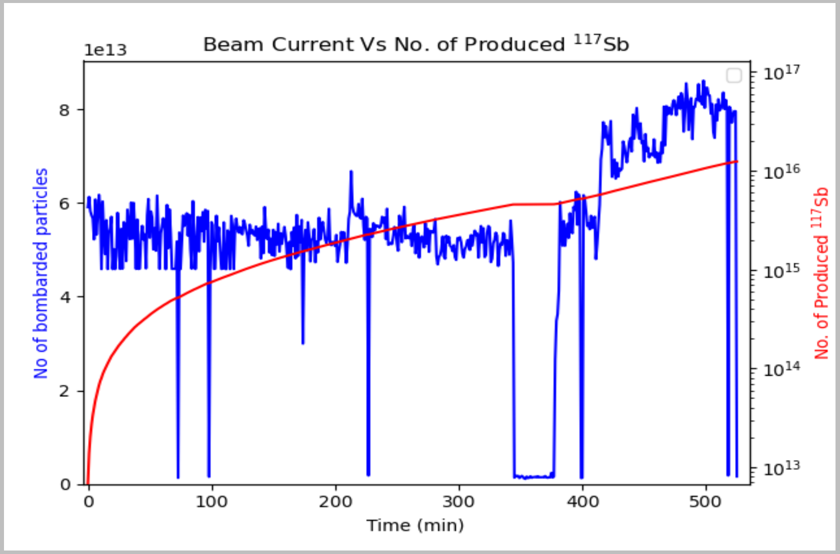
$$N_{Prod} = \frac{A}{\varepsilon\eta e^{-\lambda t_w}(1 - e^{-\lambda t_c})}$$

A = Peak Area
ε = Efficiency of the detector at given γ-energy
η = Relative intensity of the transition
t_w = cooling time, t_c = counting time

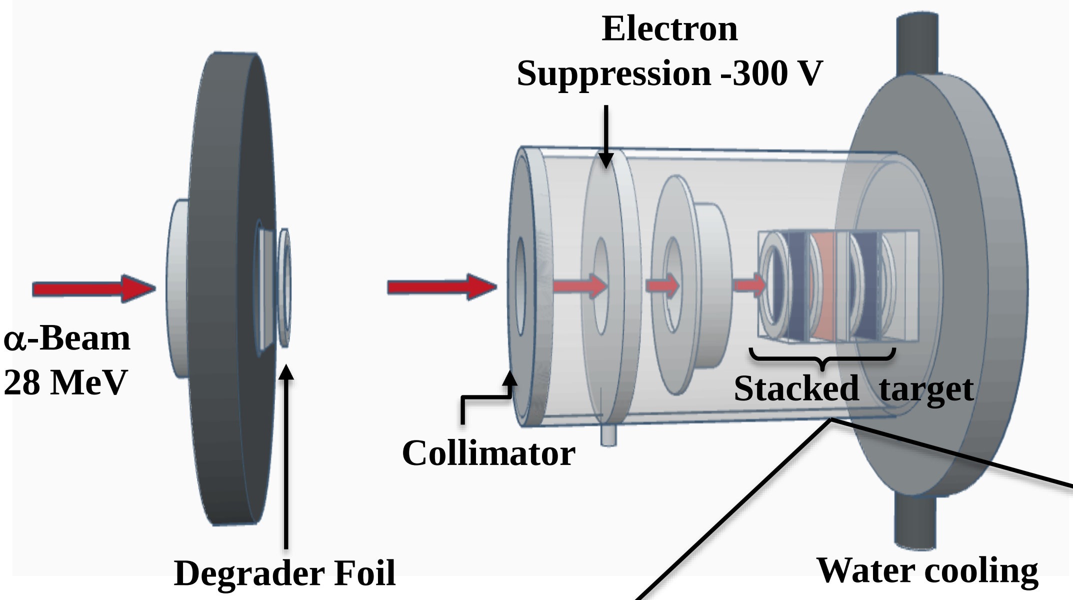
Cross-section of a given reaction is

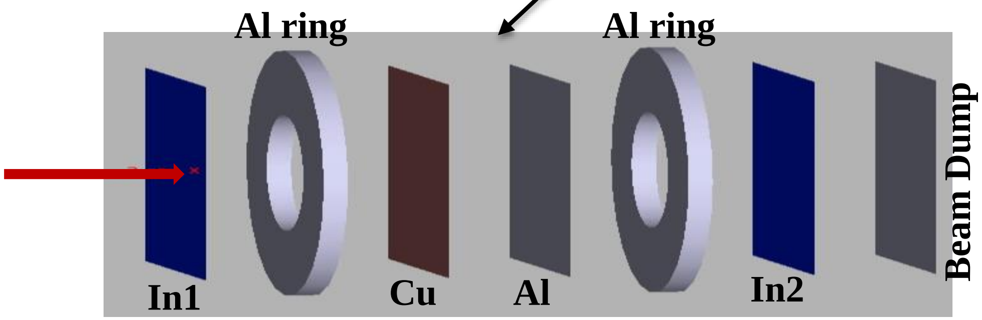
$$\sigma_{reac} = \frac{N_{Prod}}{N_A \sum_{i=1}^{N} \phi_{b,i} \frac{1 - e^{-\lambda\Delta t}}{\lambda} e^{-\lambda\Delta t(N-i)}}$$

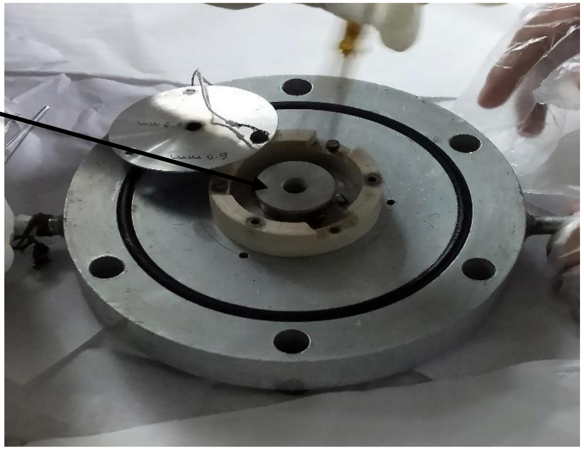
N_A = Surface density of the target(atoms/cm^2)
$\phi_{b,i}$ = Number of bombarded α-particle per sec in the i^{th} time period.
t_i = Irradiation time (divided into N short intervals Δt = 1 min)



Stacked target







Principle of detailed balance

- X + x ⟷ Y + y

$$\frac{\sigma_{YX}}{\sigma_{XY}} = \frac{P_x^2\ (2I_x+1)(2I_X+1)}{p_y^2(2I_y+1)(2I_Y+1)}$$

- Decay probability : $P(E_c,J;x) = \frac{R(E_c,J;x)dE}{R(E_c,J)dE}$
- Total decay rate : $R(E_c,J) = R_p(E_c,J) + R_\gamma(E_c,J)$
- Decay rates for particles : $R_p(E_c,J)dE = \sum_x \sum_{j,s} \int_{\varepsilon=0}^{E_c-S_x} R_x(E_c,J;U,j,s)d\varepsilon$

$$R_x(E_c,J;U,j)dE = \frac{1}{h}\sum_{S=|j-s|}^{j+s} \sum_{l=J-S}^{J+S} T_l(\varepsilon)\left[\frac{\rho(U,j)}{\rho(E_c,J)}\right] dE$$

$\varepsilon = E_c - U - S_x$, S_x = Separation energy of particle x

- Decay rate of γ-channel : $R_\gamma(E_c,J)dE = \sum_\lambda \sum_j \int_{\varepsilon=0}^{E_c} R_\lambda(E_c,J;U,j)d\varepsilon$

$$R_\gamma(E_c,J;U,j)dE = [c_\lambda(\varepsilon)][\varepsilon^{2\lambda+1}]\left[\frac{\rho(U,j)}{\rho(E_c,J)}\right] dE$$

$\varepsilon = E_c - U$, $\vec{J} = \vec{\lambda} + \vec{j}$, λ= Multipolarity of γ-ray

Cont…

- Above neutron threshold (for low energy reaction) neutron decay dominates

$$P(E_c, J; x) \approx 1$$

$$\sigma(\alpha, n) \sim \sum_J \sigma(E_c, J) \approx \sum_J \pi \lambda\!\!\!^{-2}_{\alpha} T_l(\alpha)$$

$T_l\ (\alpha)$: Transmission coefficient for entrance channel.

Cross-section is solely dependent on the α-optical potential.

- But (α,γ) reaction cross-section are depends on
  - Entrance channel optical potential
  - Level densities (ρ)
  - γ-ray strength function (C_λ)
- Knowing about (α,γ) reaction rate from reaction cross-section is important for p-process study.
- Nuclear input parameters (AOMP , LD, γSF) have to known experimentally or predicted by a model.