# Astrophysical production of $^{146}$Sm Isotope

**Cristiana Oprea**

**Abstract.** A possible p-process chronometer could be the $^{146}$Sm nucleus and this issue is direct related to the uncertainties of production ratio $^{146}$Sm/$^{144}$Sm observed in many meteorites and planetary bodies. One of the component of production ratios are the cross sections of type $(\alpha,\gamma)$ and $(\alpha,n)$ which are leading to the formation of $^{146}$Sm and $^{144}$Sm isotopes. The $(\alpha,\gamma)$ and $(\alpha,n)$ cross sections from the threshold up to 15-20 MeV's were obtained. We have analyzed also the contribution to the cross sections of direct and pre-equilibrium processes not only of compound processes as there are done in other papers from literature. The contribution of direct and pre-equilibrium processes becomes important with the increasing of energy.

The cross section values obtained in the present evaluations are compared with experimental data (if they exist) and give new data on $\alpha$-potentials and nuclear level densities. They could be used in the analysis of inverse reactions and for new measurements $(\alpha,\gamma)$ and $(\alpha,n)$ reactions at different facilities.

2nd WORKSHOP on Nuclear Astrophysics at the Canfranc Underground Laboratory

LSC, Canfranc Estación, SPAIN, 29 February and 1 March, 2016

# Introduction

## Considered Reactions

$^{142}Nd(\alpha,\gamma)^{146}Sm$

$Q = -\ 2.528$ MeV

$E_{threshold} = 2.6$ MeV

Properties of $^{142}Nd$ nucleus

$0^+$ - stable

abundance 27.2%

$^{143}Nd(\alpha,n)^{146}Sm$

$Q = -\ 8.652$ MeV

$E_{threshold} = 8.894$ MeV

Properties of $^{143}Nd$ nucleus

$(7/2)^-$ - stable

abundance 12.2%

Properties of $^{146}Sm$

$0^+$ long life isotope

$T_{1/2} = 3.25 \cdot 10^{25}$ s

# Introduction

**The cross sections and astrophysical rates of the following reactions were evaluated:**

$^{142}$Nd($\alpha,\gamma$)$^{146}$Sm

$^{143}$Nd($\alpha$,n)$^{146}$Sm

**Motivations**

- $\alpha$-nuclear potentials for p-process studies
- Nuclear levels density for inverse reactions
- Production of $^{146}$Sm important for astrophysics –>very long time of life
  -> $^{146}$Sm as chronometer -> discrepancy of $^{144}$Sm/$^{146}$Sm ratio
- Practically no experimental data -> proposal for new experiments

# Theoretical backgrounds

**Cross Sections (Inclusive & Exclusive ones) are calculated with Talys**

- Inclusive CS – all b particles obtained in A(a,b) reactions not only those from A(a,b)B have to be measured
- Exclusive CS –only b particles coming from A(a,b)B reactions have to be measured

**Hauser – Feshbach Formalism (HFF)**

- The evaluations have shown that the main contribution to the cross sections is given by compound processes

**Cross Section in HFF**

$$\sigma_{ab} = \pi \bar{\lambda}_a^2 \frac{T_a T_b}{\sum_c T_c} W_{ab}$$

*T* - penetrability coefficient ; T ⭘ 1

$W_{ab}$ – fluctuation correction factor

**Nuclear Potentials**

Wood – Saxon type with refinements

- With real and imaginary part
- Suggested by Talys
- Talys freeware software for nuclear reactions calculations

# Theoretical backgrounds

## Astrophysical Rate (effective stellar rate) a -> b

- calculated at temperature T taking into account various target excited states

$$N_A \langle \sigma v \rangle^*_{ab}(T) = \left(\frac{8}{\pi m}\right)^{\frac{1}{2}} \frac{N_A}{(k_B T)^{\frac{3}{2}} G(T)} \int_0^\infty \sum_\mu \frac{(2I^\mu + 1)}{(2I^0 + 1)} \sigma^\mu_{ab}(E) E \exp\left(-\frac{E + E^\mu_x}{k_B T}\right) dE$$

**Normalized Partition Function (T-dependent)**

$$G(T) = \sum_\mu \frac{2I^\mu + 1}{2I^0 + 1} \exp\left(-\frac{E^\mu_x}{k_B T}\right)$$

## Notations

*m* = mass of reduced channels (a,b,…); $k_B$ = Boltzmann constant;

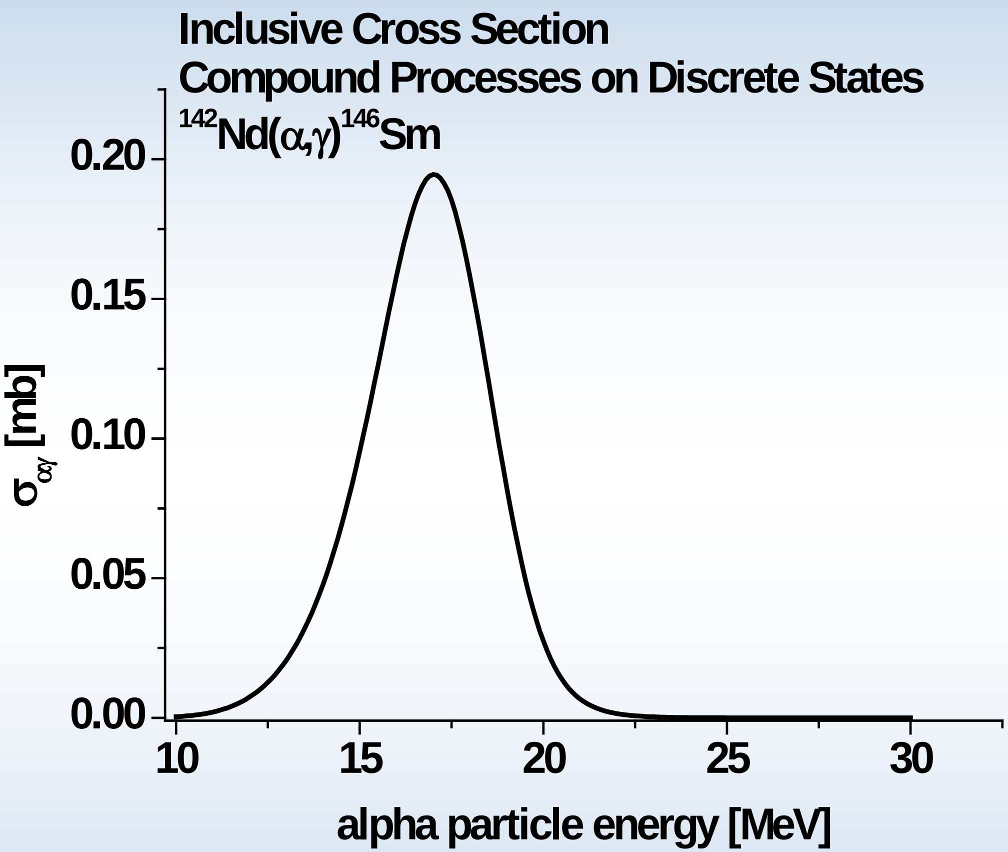
$N_A$ = Avogadro Number; - $I^\mu$, $I^0$ = spins of excited and ground states, respectively,

with corresponding excitation energy $E_x$

## Assumption

- Rates -> considering thermodynamic equilibrium
- E, $E_x$ have a Maxwell-Boltzmann distribution

# Results. Inclusive CS. $^{142}Nd(\alpha,\gamma)$ Reaction



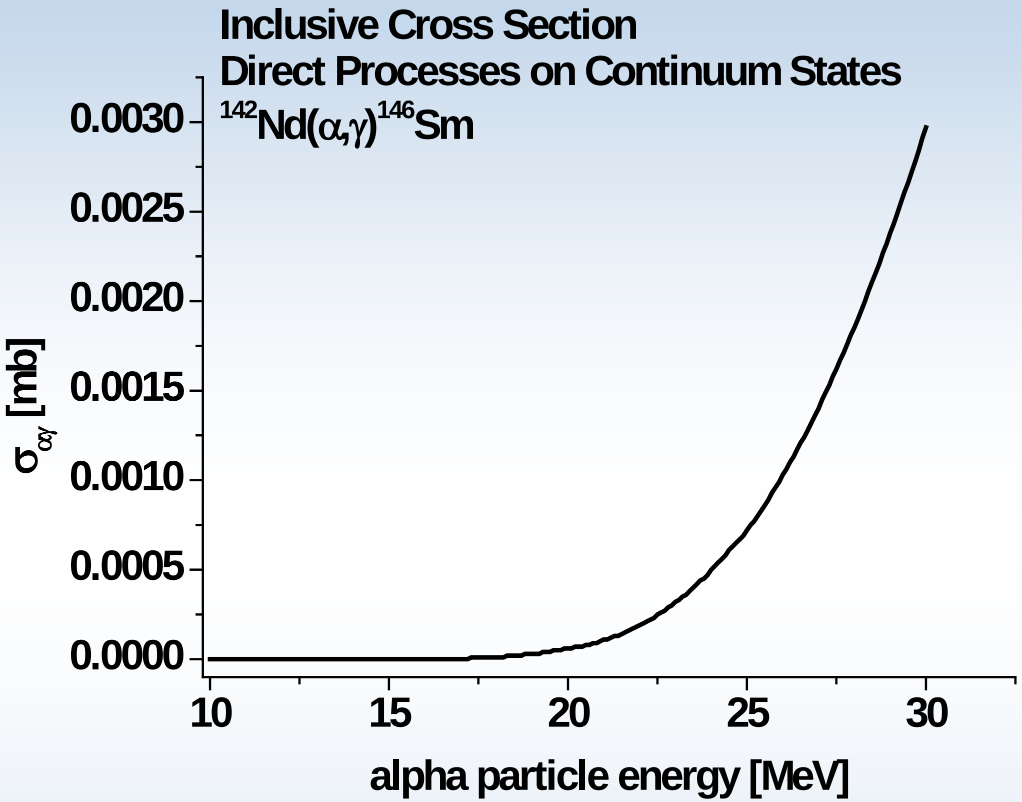

**Inclusive CS**

- Measured $\gamma$'s from other channels like $(\gamma,n)$, $(\gamma,2n)$, $(\gamma,p)$,…..
- Typical shape of the CS
- Low value of the CS

**Inclusive CS of Direct Processes on Discrete States**

- with one order of magnitude lower
- they are not represented
- The same shape

# Results. Inclusive CS. $^{142}$Nd($\alpha,\gamma$) Reaction

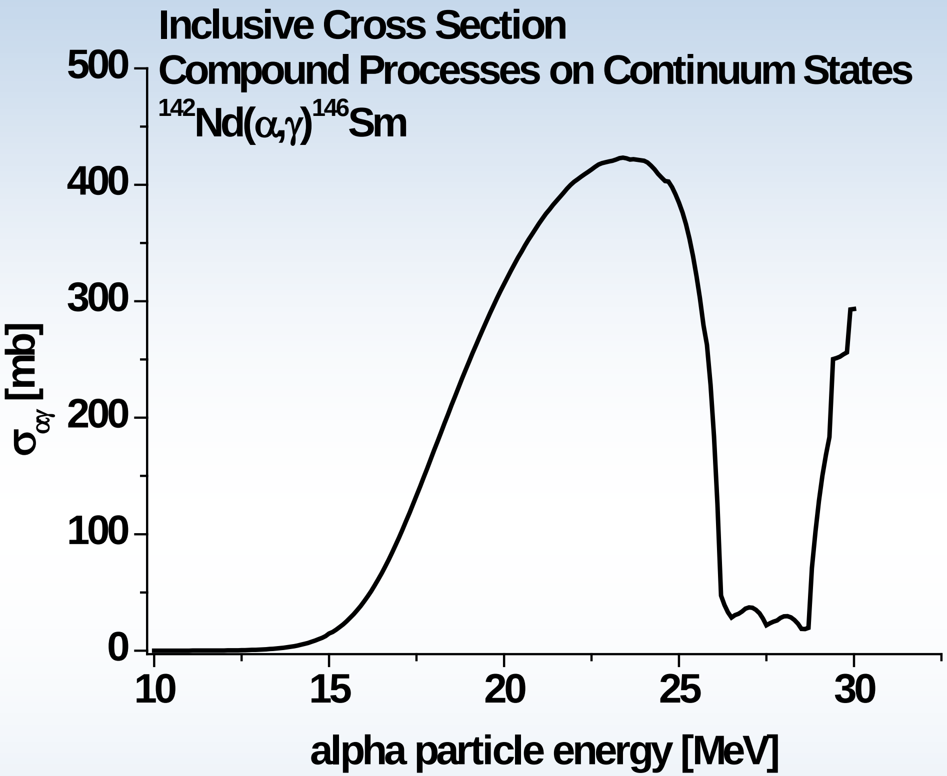



**Like in the case of Discrete States**

- The contribution to the cross section is very low

- In the analyzed energy interval the CS is increasing with energy

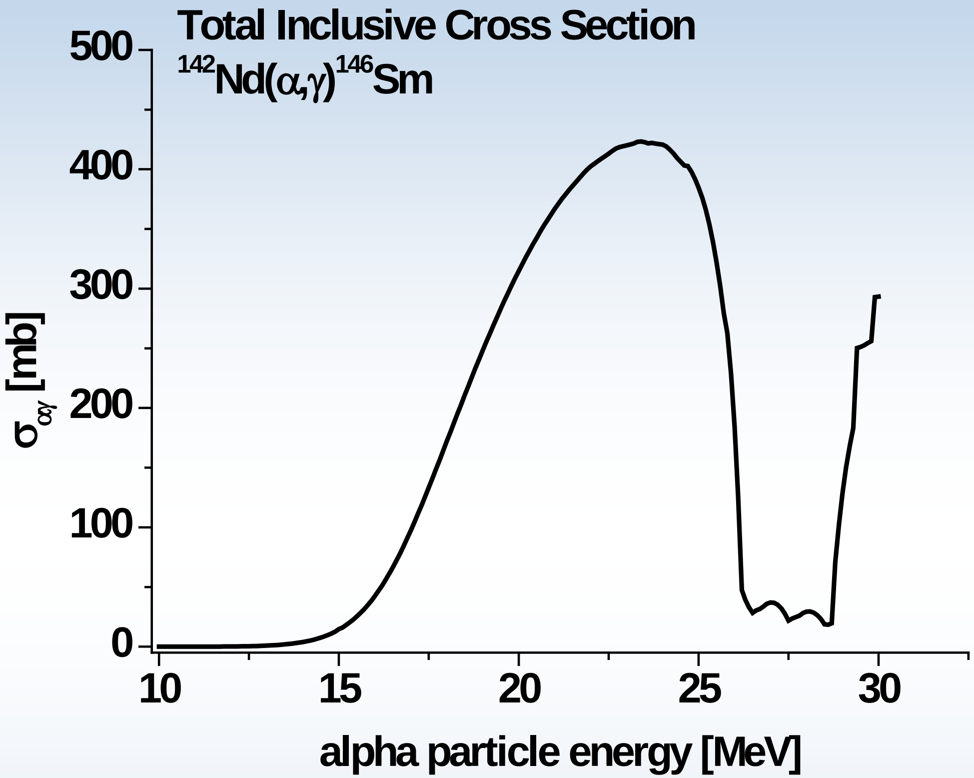
# Results. Inclusive CS. $^{142}Nd(\alpha,\gamma)$ Reaction




## Inclusive CS

- Much greater than the CS on discrete states
- The Compound Processes are dominant
- Other processes can be neglected
- CS of the Compound Processes are evaluated using the HF formalism and the Statistical Model of Nuclear Reactions => suitable for astrophysical rates calculation
- The high energy part is interesting

# Results. Total Inclusive CS. $^{142}Nd(\alpha,\gamma)$ Reaction

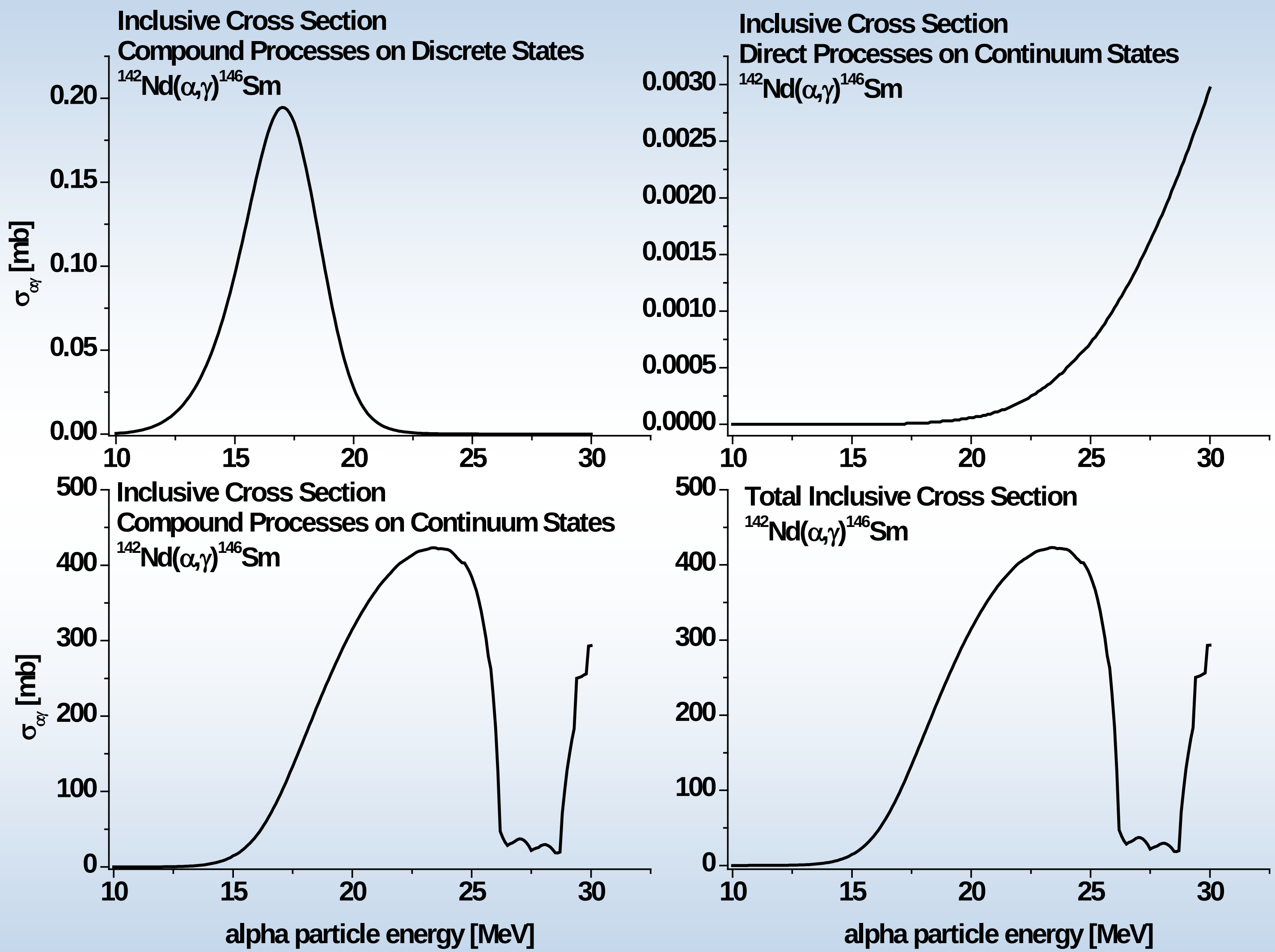



**Inclusive CS**

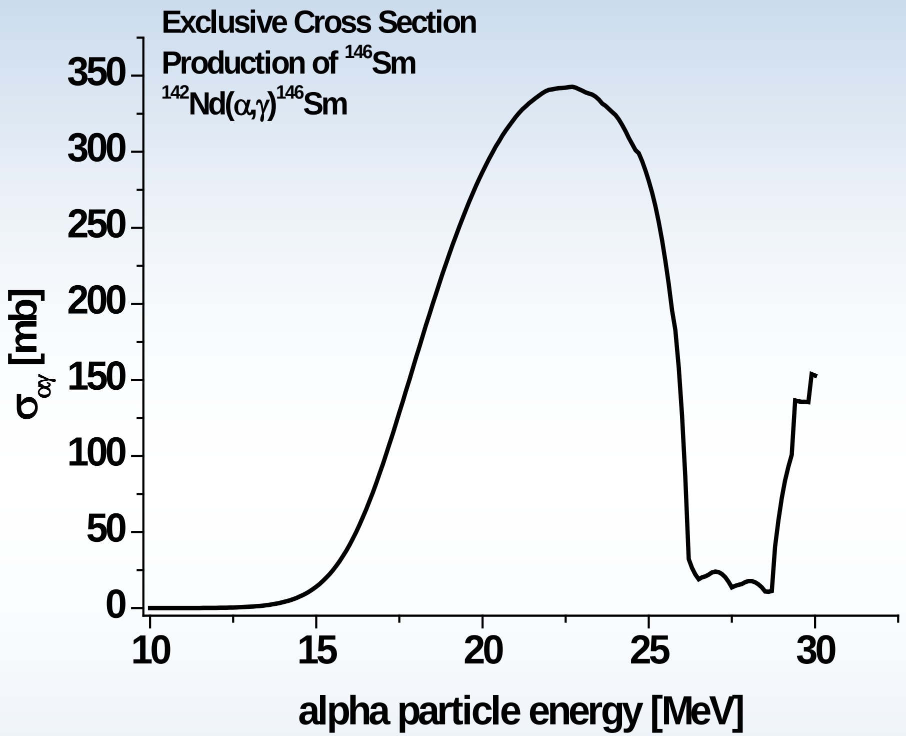
- Contribution of all processes with discrete and continuum states

- Compound processes are dominant

# Results. Inclusive CS. $^{142}Nd(\alpha,\gamma)$ Reaction. All Figures



# Results. Exclusive CS. $^{142}Nd(\alpha,\gamma)^{146}Sm$ Reaction




**Exclusive CS**

- Only $\gamma$'s from $^{142}Nd(\alpha,\gamma)^{146}Sm$ reaction have to be measured

- Good CS of $^{146}Sm$ production suitable for measurement

- The interesting high energy part is shown

# Results. Talys Standard Input. $^{142}Nd(\alpha,\gamma)^{146}Sm$ Reaction

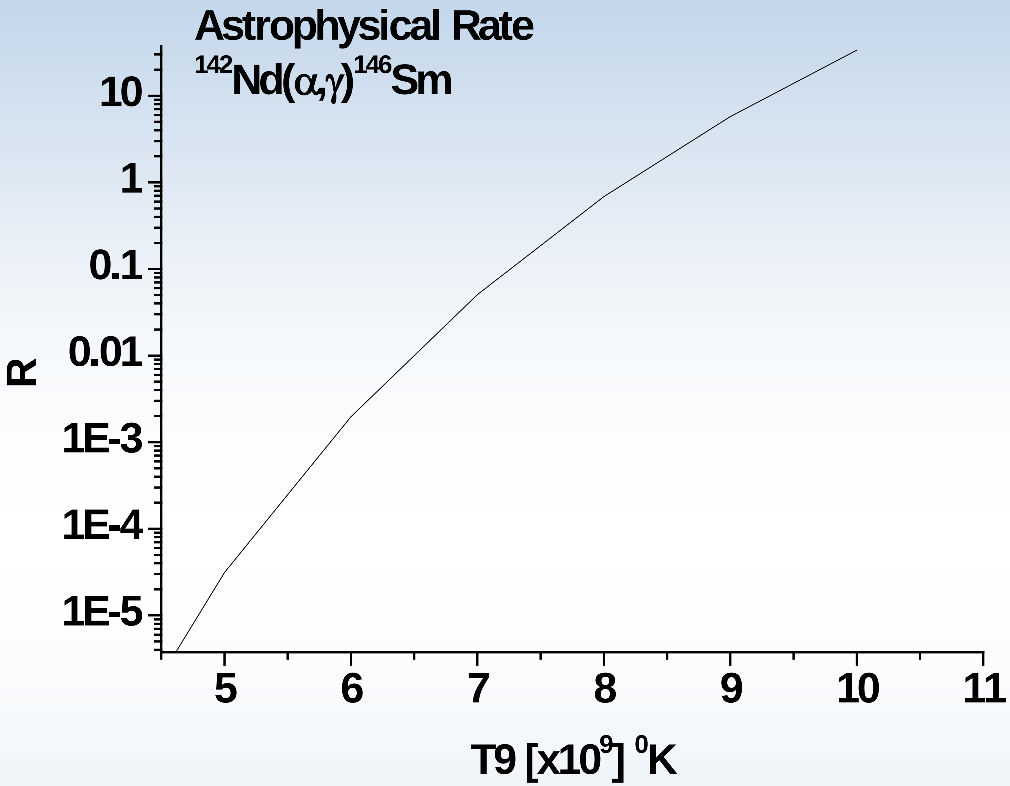
**TALYS**

-Nuclear reactions mechanisms (compound, direct, preequilibrium), nuclear structure data, fission processes implemented in Talys were used
- Incident energies of n,p,d,t,$\alpha$,$\gamma$ up to 1000 MeV (includes relativistic nuclear physics evaluations)

**Potentials and other parameters – Standard Talys Input**

- Wood – Saxon type
  Real Part $V_0$ = 250 MeV; Imaginary Part $W_0$ = 0.16 MeV
- Nuclear Radius of type $R=R_0 \cdot A^{1/3}$ [fm]
- Levels Density – simple Fermi gas model
- Other parameters

# Results. Astrophysical Rate. $^{142}Nd(\alpha,\gamma)^{146}Sm$ Reaction



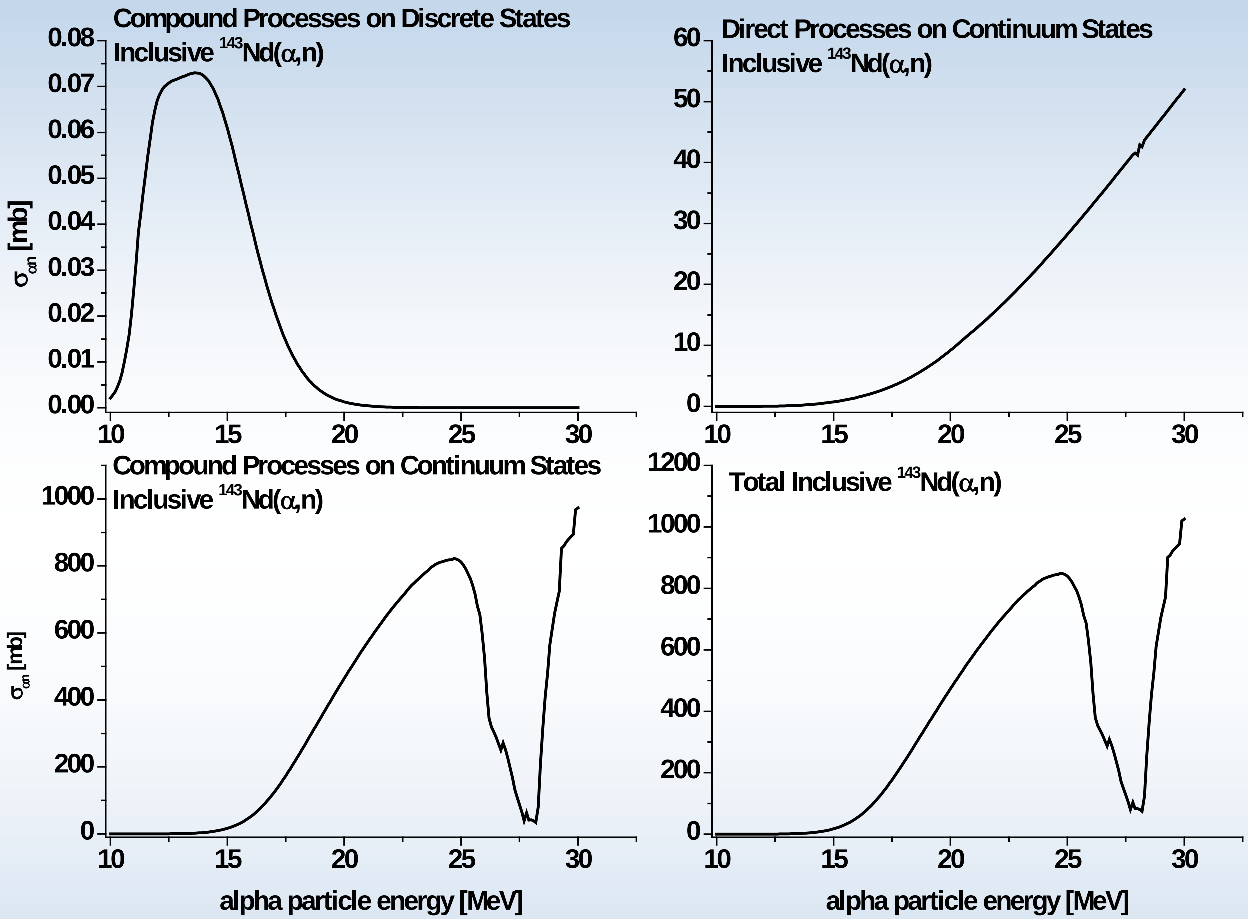

**Rate**

- Calculated by using the standard input of Talys

- Taking into account various excited states of target nucleus

$$N_A\langle\sigma v\rangle^*_{ab}(T)=\left(\frac{8}{\pi m}\right)^{\frac{1}{2}}\frac{N_A}{(k_BT)^{\frac{3}{2}}G(T)}\int_0^\infty\sum_\mu\frac{(2I^\mu+1)}{(2I^0+1)}\sigma^\mu_{ab}(E)E\exp\left(-\frac{E+E^\mu_x}{k_BT}\right)dE$$

# Results. $^{143}Nd(\alpha,n)^{146}Sm$ Reaction. Inclusive Cross Section



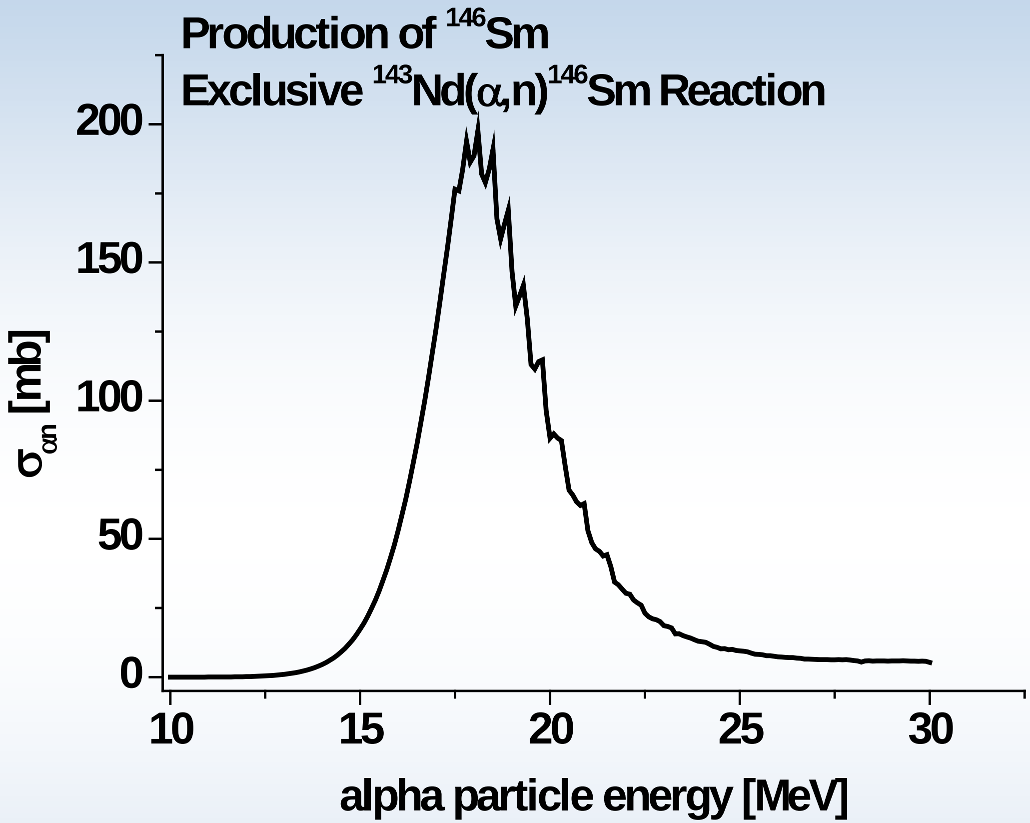

- This second reaction is also a source of $^{146}Sm$ production

- Compound Processes are dominant

- Direct Processes give their contribution to the cross section

- The same behavior at energy higher than 25 MeV

# Results. $^{143}Nd(\alpha,n)^{146}Sm$ Reaction. Exclusive Cross Section




**$^{146}Sm$ production**

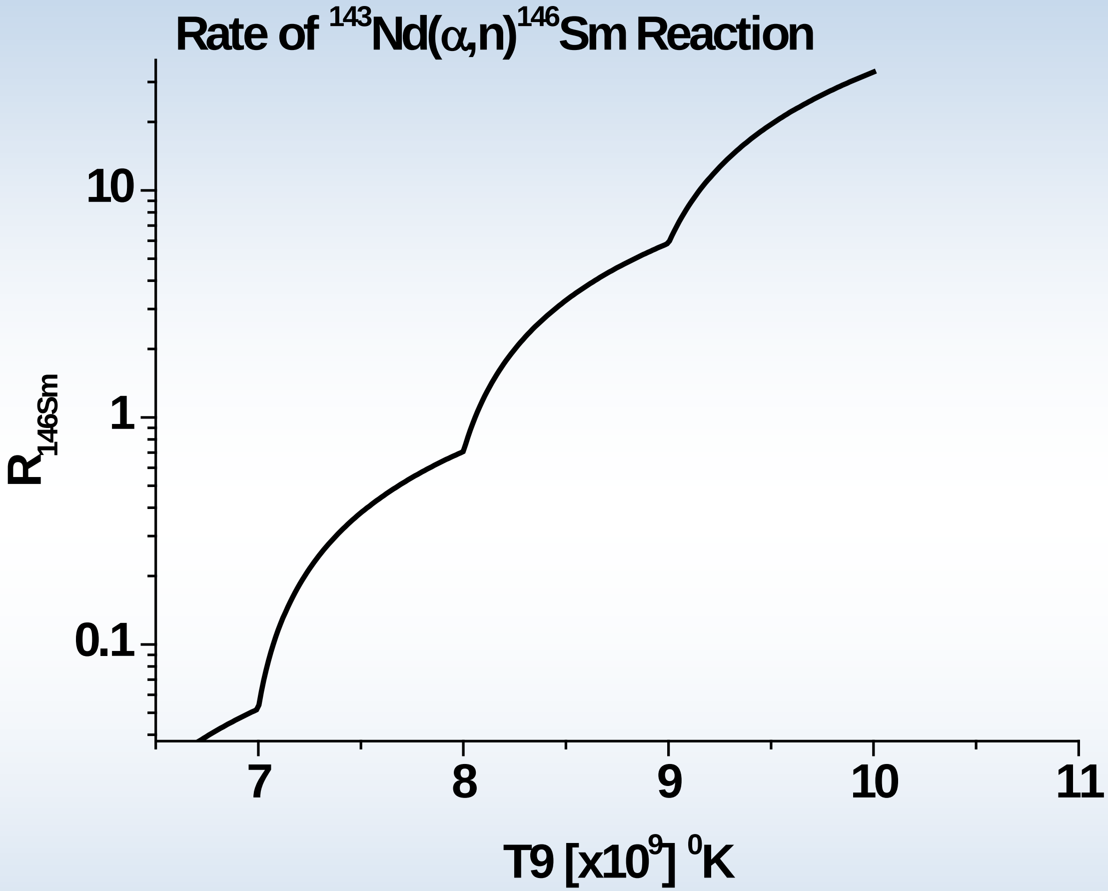
- Exclusive CS is sensibly lower in comparison with Inclusive CS

- Difference between Inclusive and Exclusive CS -> separation between background and necessary signal in the experiment

- HF formalism and SM of Nuclear Reactions -> for CS calculations

-CS calculation -> Astrophysical Rates

# Results. $^{143}Nd(\alpha,n)^{146}Sm$ Reaction. Astrophysical Rates



# Conclusions

Cross sections were evaluated by Talys

- possibility to calculate inclusive and exclusive cross sections was used

**Analyzed Reactions** – $^{142}Nd(\alpha,\gamma)^{146}Nd$

$^{143}Nd(\alpha,n)^{146}Nd$

- No experimental data
- New measurements are of interest

**New measurements**

- necessary for nuclear model parameters
- CS for astrophysical rates calculations
- $^{146}Sm/^{144}Sm$ ratio discrepancy
- charged particles CS measurements – high background

# Thank you for your attention

# Cross sections of neutron reactions in S-Cl-Ar region in the s-process of nucleosynthesis

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# Abstract

One of the main questions in astrophysics is the origin and the relative abundance of $^{36}Cl$ and $^{36}S$ isotopes and their production during the s-process of nucleosynthesis. A series of problems connecting with the uncertainties in the (n,p), (n,$\alpha$) and (n,$\gamma$) reactions leading to the decreasing or increasing of the concentration of $^{36}Cl$ isotope were analyzed. The cross sections of mentioned reactions at the astrophysical relevant energies using Talys and Empire computer codes were evaluated. The theoretical calculations of cross sections for determination of isotopes astrophysical reaction rates were accomplished and the results are compared with experimental results from literature. These data are required for better understanding of the origin of the rare neutron rich isotopes in the S-Cl-Ar region and for evaluation of the $^{40}K/^{40}Ar$ chronometer.

# Cl – Properties

- VII group of halogens, very electronegative

- yellow-green color in standard conditions ($t = 25^0$ C, $p_{atm} = 1.01$ bar)

- $\rho = 2.898$ g/l, melting point $t = -101.5^0$ C, boiling point $t = 34.04^0$ C

- after $H_2$ and $O_2$ it is the most abundant in sea water – 19.4 g/l

- very common in Earth crust (145 mg/kg)

- electronegativity – 3.612724 eV - > high reactiveness – it is found only in chemical compounds – mostly salts NaCl, KCl etc

- Cl has two stable isotopes with the abundances – $^{35}$Cl (75.77%),
$^{37}$Cl (24.23%)

- 21 isotopes and 2 isomers are known

- $^{36}$Cl – produced in $^{35}$Cl neutron captures, Ar spallation, $^{40}$Ca muon capture

- $^{36}$Cl half life – $t_{1/2} = 3.01 \cdot 10^5$ y - > traces can be find in nature

# Burning phases of 20-25 $M_\odot$ star

| Burning phase | Main products | Secondary products | T $[10^9 K]$ | t [a] | Main reaction |
|---|---|---|---|---|---|
| H | He | $^{14}N$ | 0.02 | $10^7$ | pp-cycles, and CNO-cycles |
| He | C, O | $^{18}O$, $^{22}Ne$ | 0.2 | $10^6$ | triple $\alpha$ process , $^{12}C(\alpha,\gamma)^{16}O$ |
| C | Ne, Mg | Na | 0.8-1.2 | $10^3$ | $^{12}C(^{12}C,\alpha)^{20}Ne$, $^{12}C(^{12}C,n)^{23}Mg$, $^{12}C(^{12}C,p)^{23}Na$ |
| Ne | O, Mg | Al, P | 1.2-1.4 | 3 | $^{20}Ne(\gamma,\alpha)^{16}O$, $^{20}Ne(\alpha,\gamma)^{24}Mg$ |
| O | Si, S, P | Cl, Si, Ar, K, Ca, Ti, Ce | 2 | 0.8 | $^{16}O(^{16}O,\alpha)^{28}Si$, $^{16}O(^{16}O,2p)^{30}Si$, $^{16}O(^{16}O,n)^{31}S$, $^{16}O(^{16}O,d)^{30}P$, $^{16}C(^{16}O,p)^{31}P$ |
| Si | Fe | Co, Ni, Ti, V, Cr | 2.7-4 | 0.02 | $^{28}Si(\gamma,\alpha)^{24}Mg$, $^{28}Si(\gamma,p)^{27}Al$, $^{28}Si(\gamma,n)^{27}Si$, $^{24}Mg(\gamma,\alpha)^{20}Ne$, multiple $\alpha$, p, n captures; radioactive decay finally forms $^{56}Fe$ |

# Theoretical background

$a + X \rightarrow b + Y + \ldots$ X – target nucleus, Y – produced nuclei (of interest)

$N_Y = \sigma_{ab} N_X \Phi_a$ $N_Y$ - Number of produced nuclei, $\sigma_{ab}$ = cross section,

$\Phi_a$ = fluence (number of particles per area)

$\frac{dN}{dt} = \sigma_{ab} N_X \varphi$ Reaction rate, $\varphi =$ incident flux per area per time

$n$ = particles density [$m^{-3}$]

$r = n_a \sigma_{ab} v_a n_X = w n_X$

Cross Section – calculated in the frame of different nuclear reaction models

$\langle \sigma v \rangle = \int_0^\infty \Phi(v) \sigma v dv$ Averaged reaction rate: $\Phi(v)$ = distribution (normalized to 1; in our case MB distribution

# Theoretical background

***Cross Section Evaluation***

- Compound Processes – Hauser Feshbach Formalism
- Preequilibrium Processes – Two Component Exciton Model
- Direct Processes – DWBA

**Levels Density –** Constant Temperature Fermi Gas Model
Neutron Energy – from 0.5 to 25 MeV

**Nuclear Potentials -** Wood – Saxon type with refinements

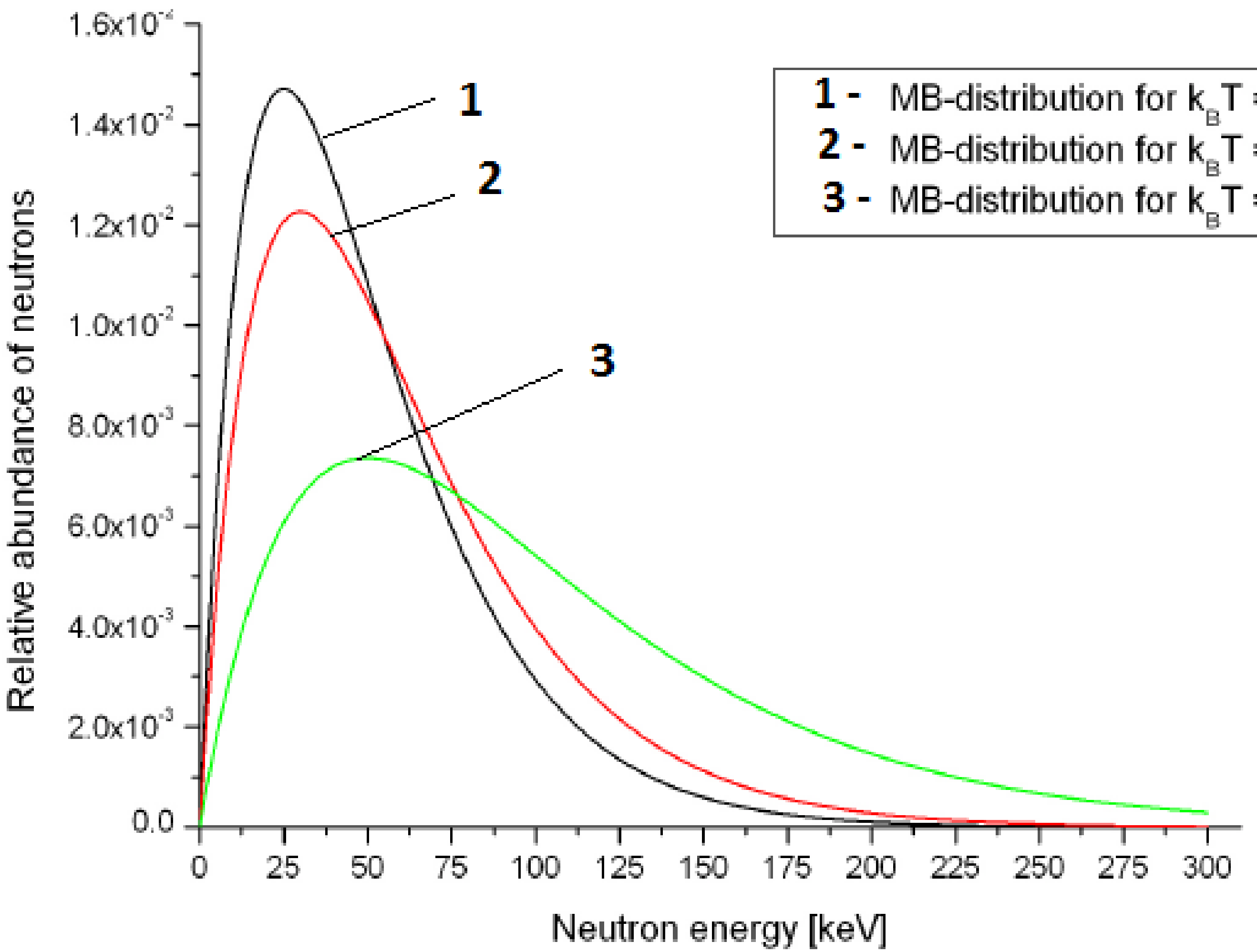
**Astrophysical Rate (effective stellar rate) a -> b**
- Calculated at temperature T taking into account various target excited states

$$N_A \langle \sigma v \rangle^*_{ab}(T) = \left(\frac{8}{\pi m}\right)^{\frac{1}{2}} \frac{N_A}{(k_B T)^{\frac{3}{2}} G(T)} \int_0^\infty \sum_\mu \frac{(2I^\mu + 1)}{(2I^0 + 1)} \sigma^\mu_{ab}(E) E \exp\left(-\frac{E + E^\mu_x}{k_B T}\right) dE$$

$$G(T) = \sum_\mu \frac{2I^\mu + 1}{2I^0 + 1} \exp\left(-\frac{E^\mu_x}{k_B T}\right)$$

# Maxwell – Boltzmann Distribution

**Relative neutrons abundance for different temperatures for 20-25 MΘ stars**



# Cl – Importance

## 1. Astrophysical

- In later burning phases of massive stars the production of heavy elements above iron strongly depends on neutron capture and radioactive decay
- $^{35}Cl$ consum neutrons -> decreases the production of heavy elements

## 2. Nuclear waste management

- by nuclear technology the production of any kind of stabile and radioactive isotopes (including $^{36}Cl$) is growing
- $^{35}Cl$ is very common in water and due to the neutrons $^{36}Cl$ is producing -> it is necessary to know the reaction rates

## 3. Geology

- $^{36}Cl/^{35}Cl$ ratio is used to date water and geological samples exposed to neutrons and cosmic rays

- cross sections are necessary to evaluate the production rate during the exposure

# Results

**In the interaction of fast neutrons (0.5 – 25 MeV) with $^{35}Cl$ the following isotopes are produced:**

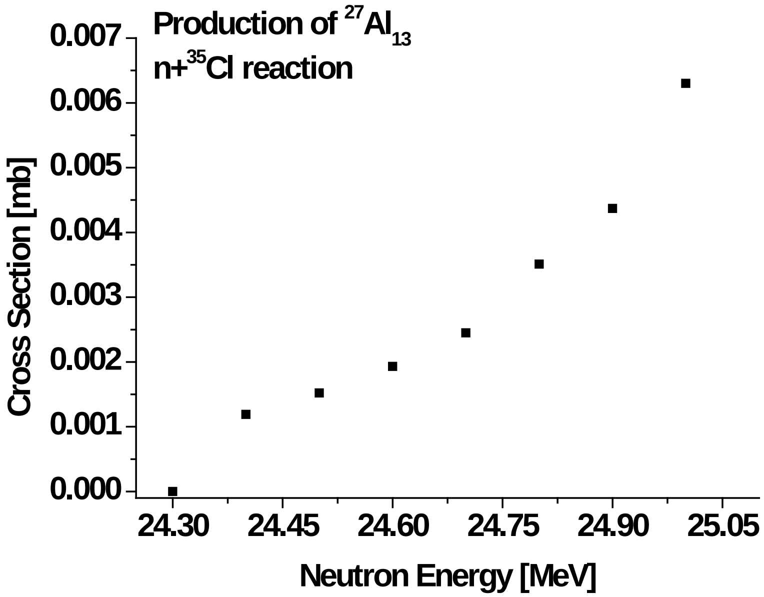
- $^{27}Al_{13}$, $^{28}Al_{13}$
- $^{29}Si_{14}$, $^{30}Si_{14}$, $^{31}Si_{14}$
- $^{30}P_{15}$, $^{31}P_{15}$, $^{32}P_{15}$, $^{33}P_{15}$, $^{34}P_{15}$
- $^{32}S_{16}$, $^{33}S_{16}$, $^{34}S_{16}$, $^{35}S_{16}$
- $^{34}Cl_{17}$, $^{35}Cl_{17}$, $^{36}Cl_{17}$

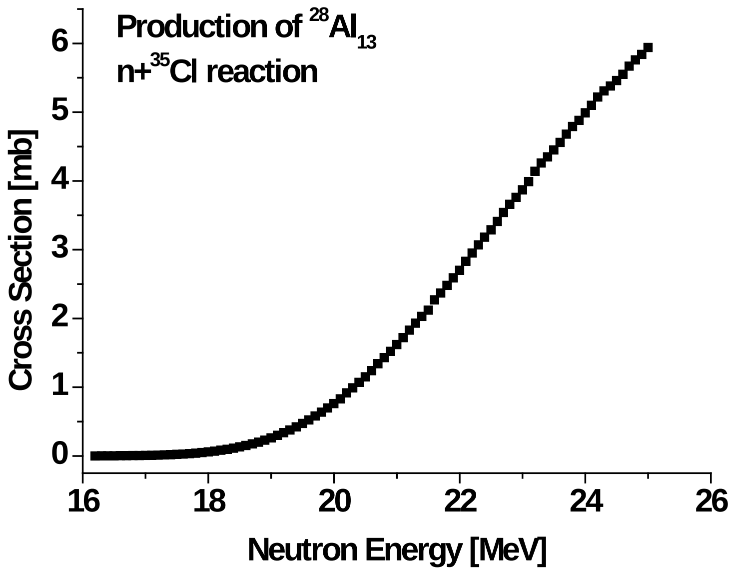
***Objectives***

1) The cross sections of productions of the above mentioned isotopes were calculated

2) Astrophysical rates of $^{35}Cl(n,\gamma)^{36}Cl$ reaction

# **Results -** Al isotopes production

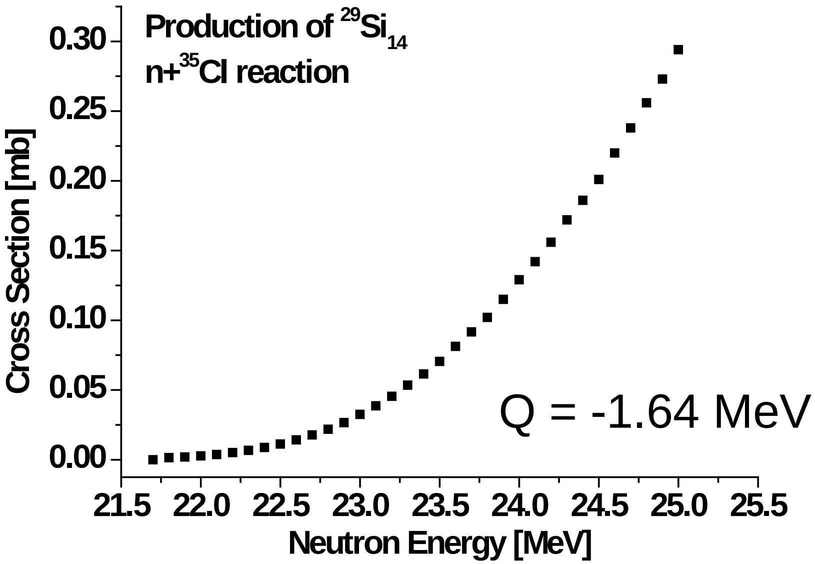


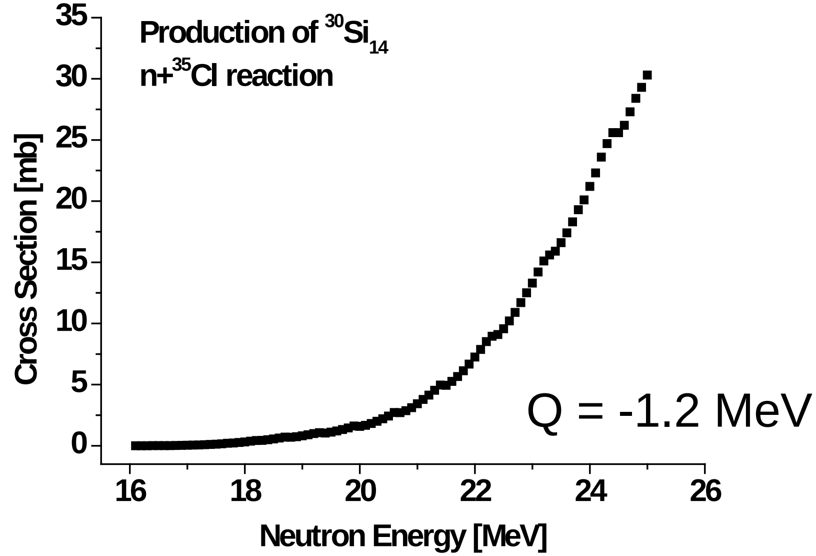



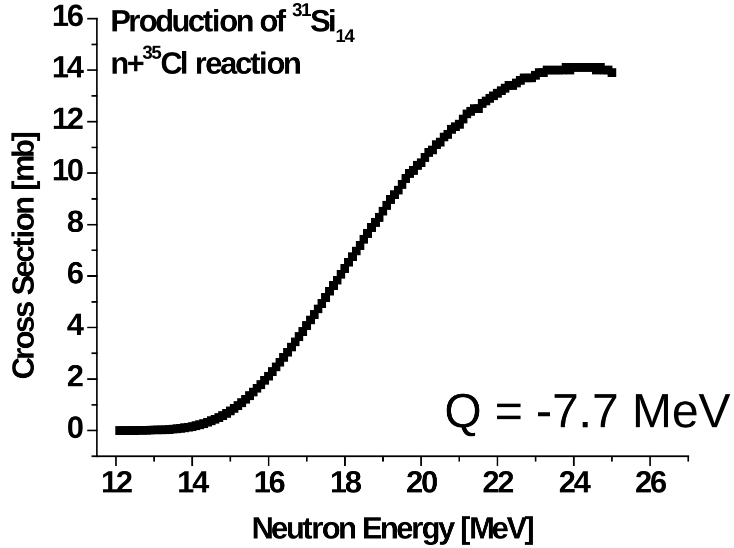

Q = -1.67 MeV

Q = -8.94 MeV

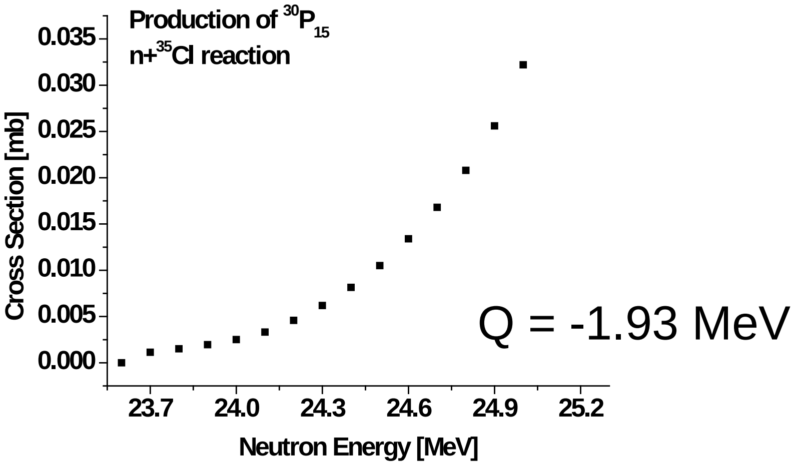
# **Results -** Si isotopes production

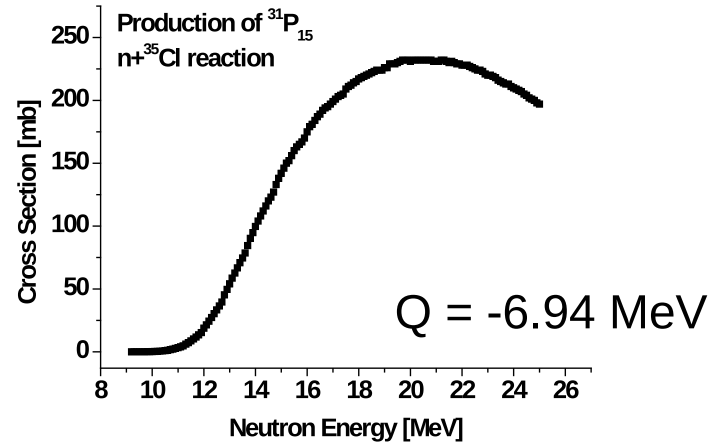


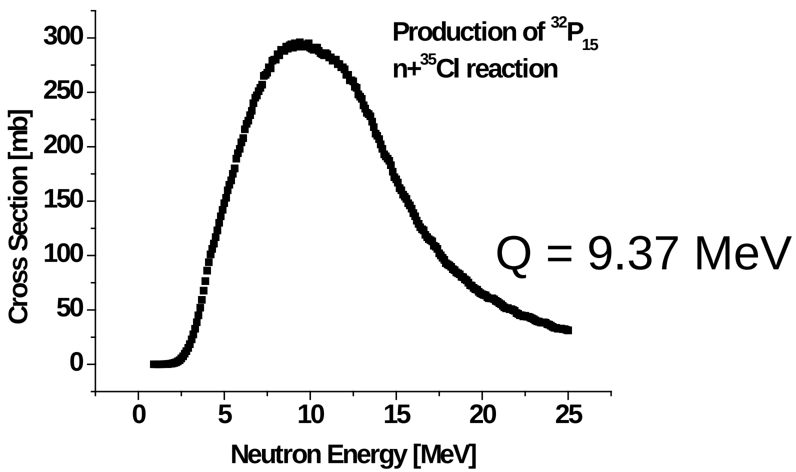



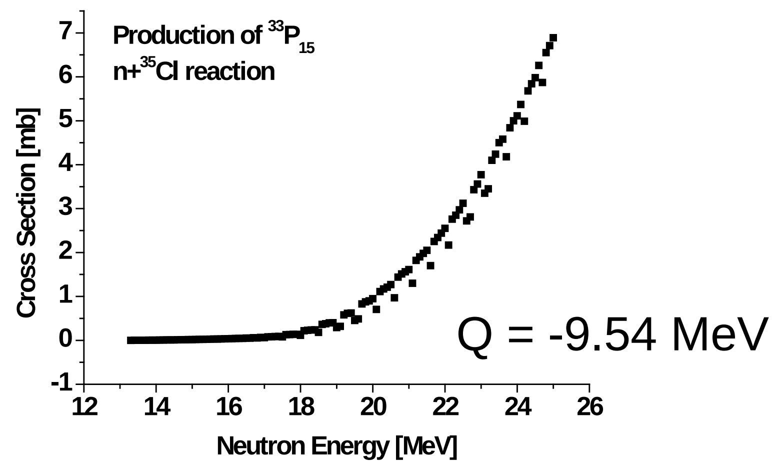



# **Results -** P isotopes production (I)

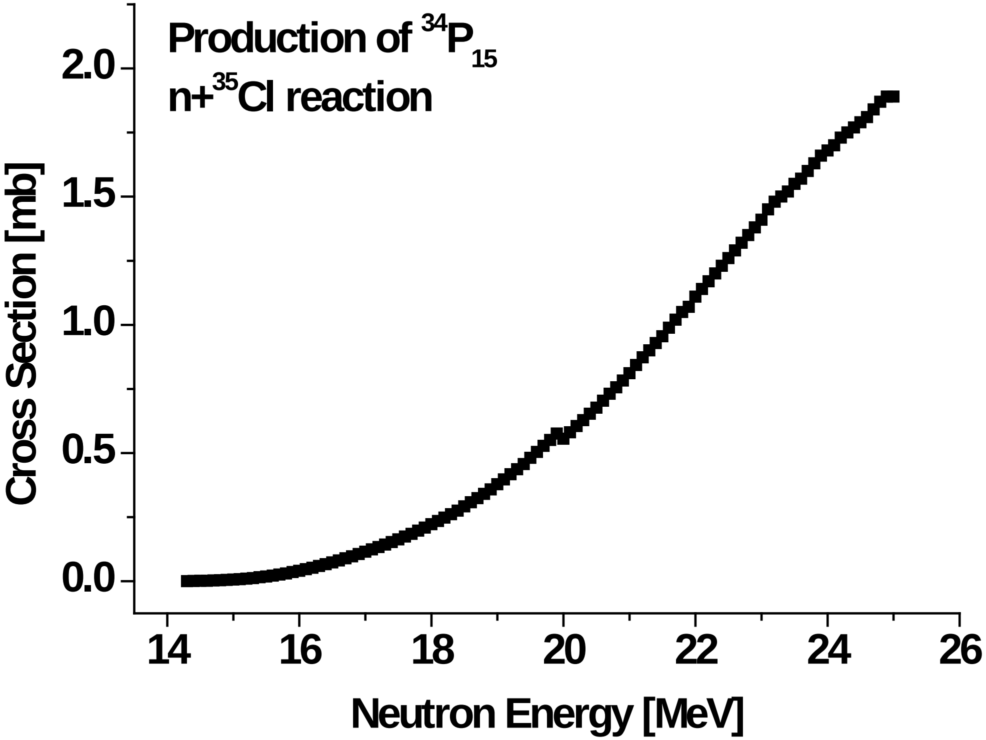


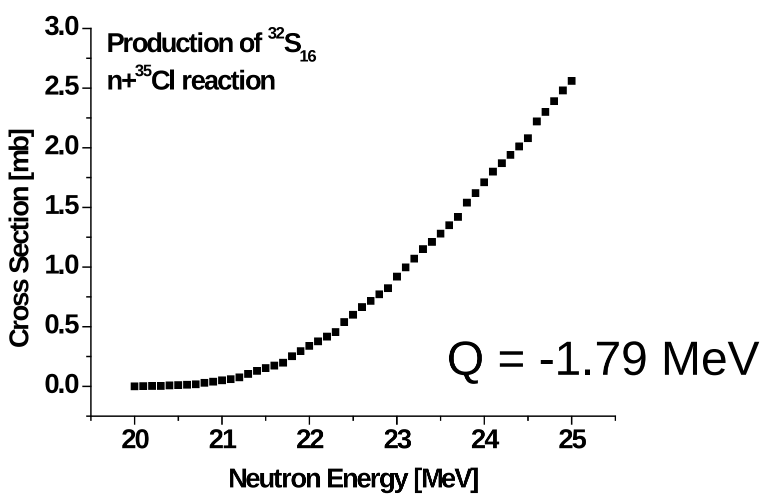



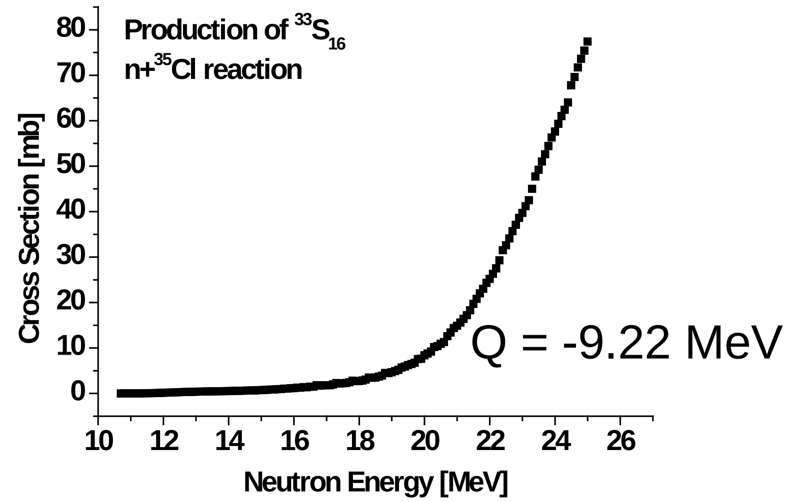
# **Results -** P isotopes production (II)

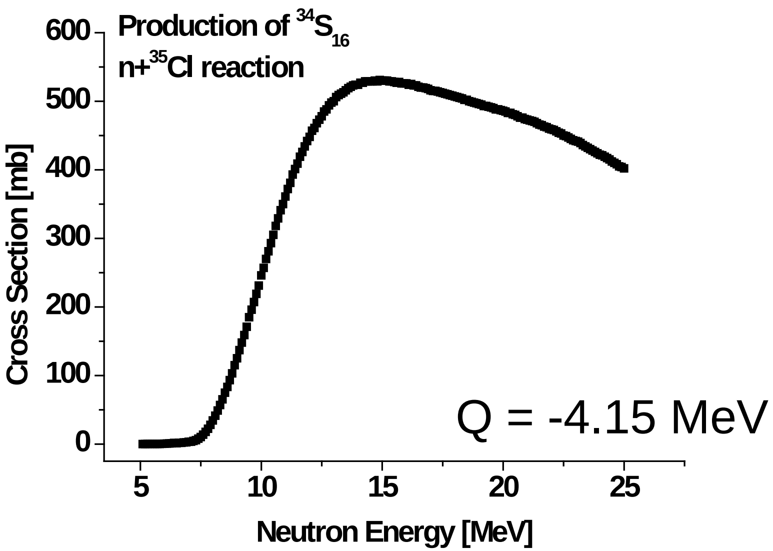


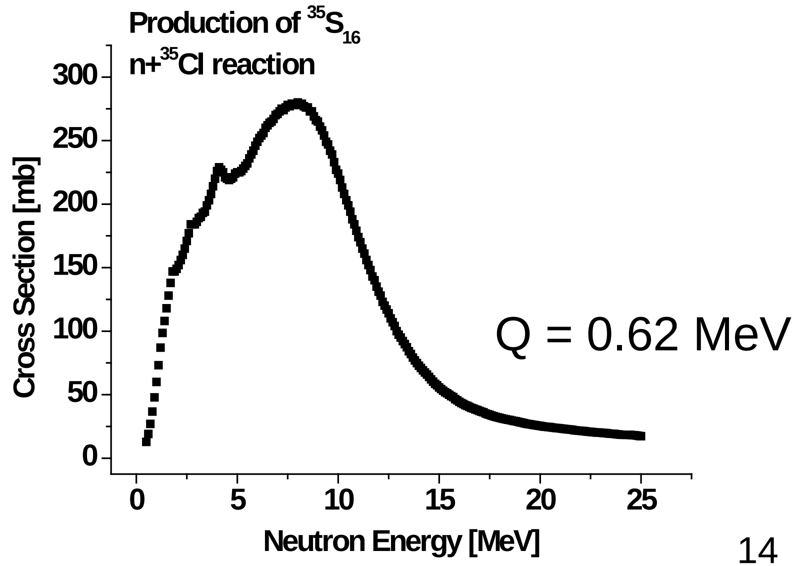

Q = -1.1 MeV

# **Results -** S isotopes production

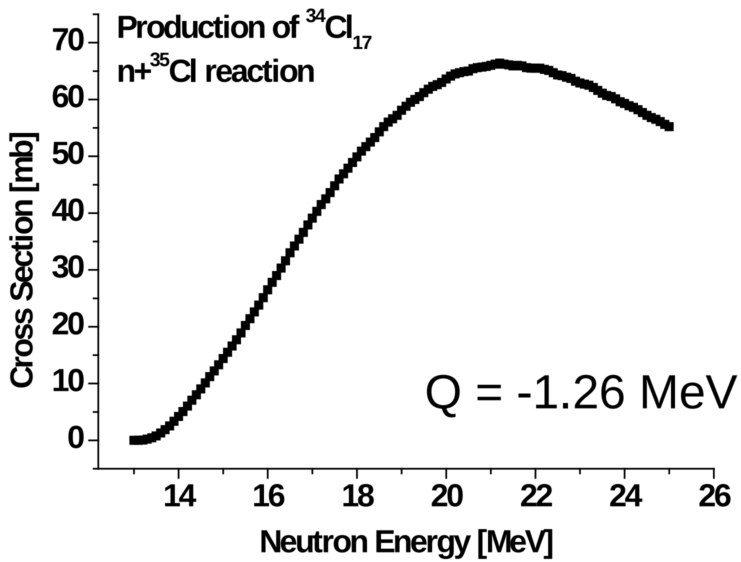


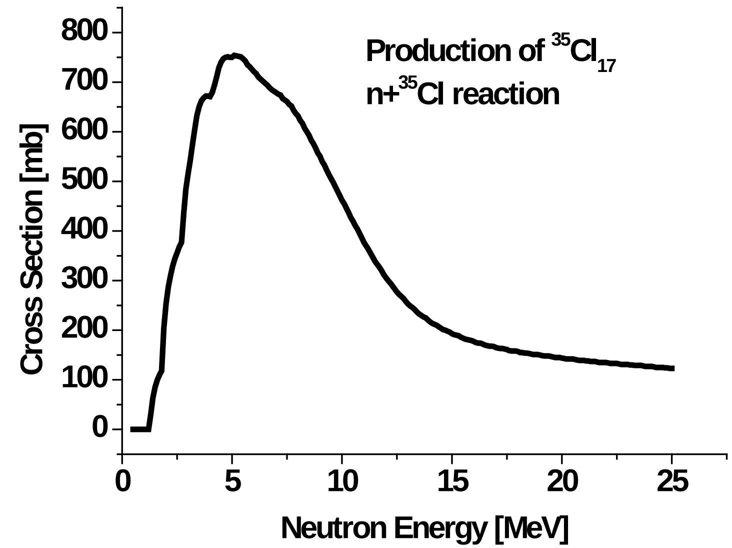



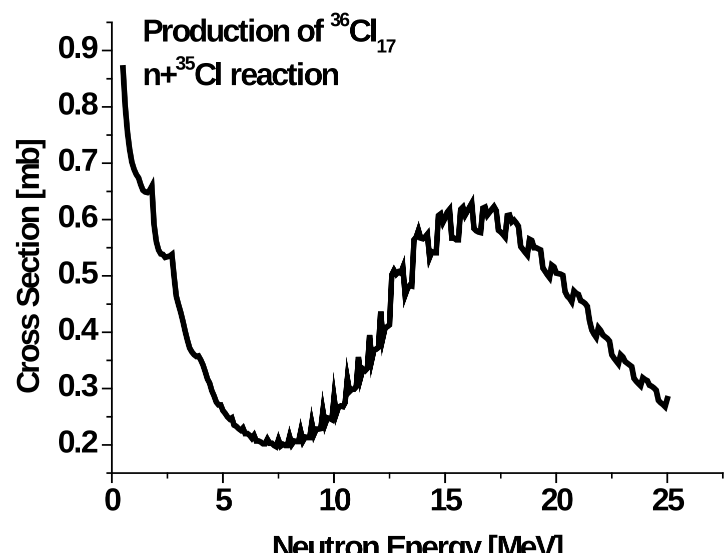



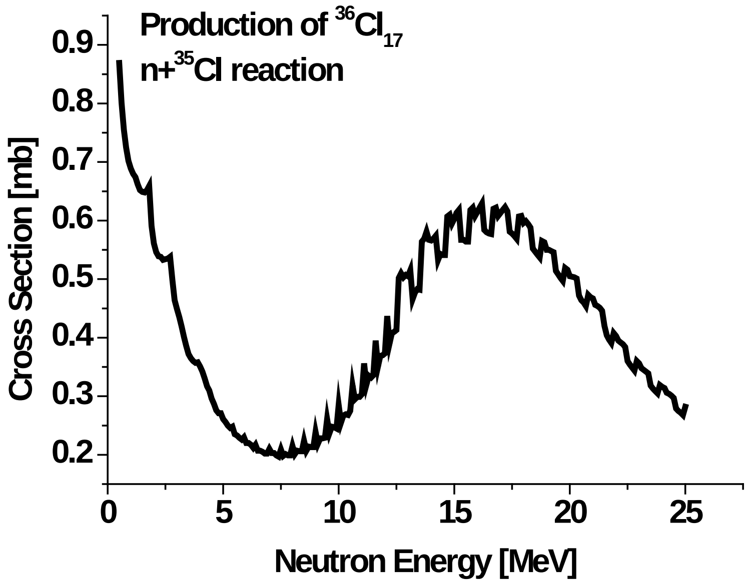
# **Results -** Cl isotopes production

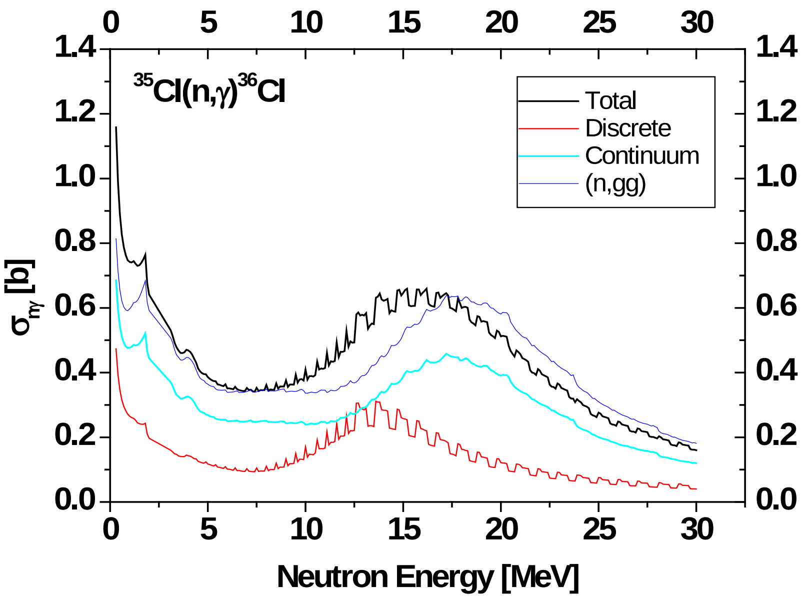


# Results - $^{36}$Cl Isotope Cross Section




Energy of emitted gamma= 8.79 MeV

Contribution to the cross section

- discrete and continuum states

- Total = discrete + continuum

different $\gamma-\gamma$ cascades were evaluated

# **Results** – Cross Section Calculation Conditions

CS – evaluated with Talys (standard input)

**Wood Saxon potential parameters**

1) Incident channels

**(n + $^{35}$Cl)**

| Real part | Imaginary part |
|---|---|
| U = 54 MeV | W = 0.32 MeV |
| r = 1.2 fm; a = 0.67 | r = 1.2 fm; a = 0.67 |

**2.2 (d + $^{34}$S)**

| | |
|---|---|
| U = 112 MeV | W = 0.4 MeV |
| r = 1.2 fm; a = 0.67 | r =1.2 fm; a = 0.67 |

2) Emergent channels

**2.3 (t + $^{33}$S)**

| | |
|---|---|
| U = 166 MeV | W = 0.64 MeV |
| r = 1.2 fm; a = 0.67 | r = 1.2 fm; a = 0.67 |

**2.1 (p + $^{35}$S)**

| | |
|---|---|
| U = 59.6 MeV | W = 0.16 MeV |
| r = 1.2 fm; a = 0.67 | r = 1.2 fm; a = 0.67 |

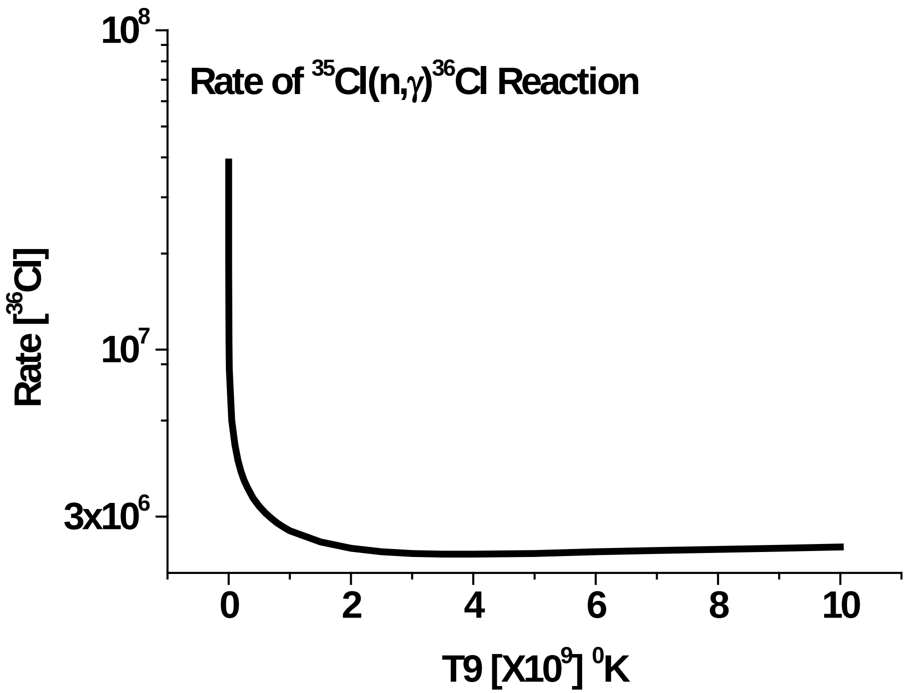
**2.4 ($^{3}$He + $^{33}$P)**

| | |
|---|---|
| U = 172 MeV; | W = 0.57 MeV |
| r = 1.2 fm; a = 0.67 | r = 1.2 fm; a = 0.67 |

**2.5 ($\alpha$ + $^{32}$P)**

| | |
|---|---|
| U = 224 MeV | W = 0.8 MeV |
| r = 1.2 fm; a = 0.67 | r = 1.2 fm; a = 0.67 |

# Results - $^{36}$Cl Astrophysical Rate




$$N_A \langle \sigma v \rangle^*_{ab}(T) = \left(\frac{8}{\pi m}\right)^{\frac{1}{2}} \frac{N_A}{(k_B T)^{\frac{3}{2}} G(T)} \int_0^\infty \sum_\mu \frac{(2I^\mu + 1)}{(2I^0 + 1)} \sigma^\mu_{ab}(E) E \exp\left(-\frac{E + E^\mu_x}{k_B T}\right) dE$$

# Discussion and Conclusions

**CS evaluation**

- Talys standard input

- Necessary for astrophysical rate evaluations

– Improving the nuclear astrophysical data of $^{36}Cl$ abundance, its origin and production during the s – process

- Improving a series of problems connecting with the uncertainties in the (n,p), (n,$\alpha$) and (n,$\gamma$) reactions leading to the decreasing or increasing of the concentration of $^{36}Cl$

- These data are required for better understanding of the origin of the rare neutron rich isotopes in the S-Cl-Ar region and for a discussion of the $^{40}K/^{40}Ar$ chronometer.

**CS Experimental Data**

- Poor data for incident fast neutrons in comparison with thermal and resonance region for all possible emergent channels

- Necessary new experimental data evaluation

- One possibility – IREN the LNF new **I**ntense **R**esonance **N**eutron **S**ource

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