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Astrophysical production of p nuclides in the fast proton induced p - processes

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ABSTRACT

The fast proton induced p – processes reactions play a key role in the astrochemical elements yields of the big bang nucleosynthesis for standard cosmology. Astrophysical concurrence of several p - process mechanisms in the production of p – nuclei was analyzed for proton energy up to 25 MeV.

Cross sections of proton induced reactions and contribution of each nuclear reaction mechanism for each process are evaluated theoretically and measured experimentally at Electrostatic Generator EG-5 from FLNP for incident protons up to 5 - 10 MeV. For protons up to 4 - 8 MeV compound processes are dominant and they are described applying Hauser – Feshbach statistical approach. At higher energies direct and pre-equilibrium mechanisms cannot be neglected. Contribution to the cross section of direct mechanism was determined using DWBA approach and pre-equilibrium processes by exciton model. Parameters of optical potential and levels density for incident and emergent channels were also extracted. Cross sections, parameters of potentials and levels density are of a great importance for astrophysical reactions rates estimation and for estimation of the astrochemical elements abundance.

The statistical uncertainties reduction was done by Talys using a *Bayesian* Monte Carlo procedure based on the EXFOR database and they were in fair agreement with the standards. The uncertainties in the nuclear element abundances originating from the combined effect of experimental and theoretical errors leading to total uncertainties in the final abundances were determined.

Present results are obtained in the frame of the bilateral scientific JINR - Romania projects dedicated to nuclear reactions for astrophysics developed at JINR Dubna basic facilities.

Outline

1. Introduction

2. Theoretical background

3. Computer codes and calculations

4. Results and discussion

5. Conclusions

1. Introduction

Fast protons reactions - investigated at JINR Dubna facilities

Fundamental research – new data on nuclear reaction mechanisms and structure of nuclei

Applicative researches – Isotopes production for applications

Nuclear Astrophysics Investigations – Elements abundance models

Indium Nucleus – 2 stable isotopes, $^{113, 115}In$ (Z = 49); abundance 4.29%, 95.71%
Tin Nucleus – 10 stable isotopes, $^{112,114,115,116,117,118,119,120,122,124}Sn$ (Z = 50); abundance 0.96%, 0.66 %, 0.35 %, 14.30%, 7.61%, 24.03%, 8.58 %, 32.85%, 4.72 %, 5.94 %
- of interest in many applications

Investigated process – $^{115}In(p,n)^{115}Sn$, $^{115}In(p,2n)^{114}Sn$, $^{113}In(p,\gamma)^{114}Sn$, $^{113}In(p,2n)^{112}Sn$, with fast protons from threshold up to 35 MeV

2. Theoretical background

The cross section for (n,α) reaction (Hauser – Feshbach) (HF)

- without fluctuation correction factor

$$\sigma_{ab} = \pi\lambda_a^2 \frac{T_a T_b}{\sum_c T_c}$$

- with fluctuation correction factor

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

$T =$ **transmission coefficient**

$W_{ab} =$ **width fluctuation correction factor**

Differential cross section

$$\frac{d\sigma}{d\Omega} = \pi\lambda^2 (2l+1) T_l \sum_J \frac{A_J\left(l, j \mid l', j' \mid \theta\right)}{1 + \sum_{p,q} \frac{T_p\left(E_q'\right)}{T_{l'}\left(E'\right)}}$$

$$A_J\left(l, j \mid l', j' \mid \theta\right) = \sum_{m,m'} \left|\left(l, j; 0m \mid l, j; Jm\right)\right|^2 \left|\left(l', j'; m' m - m' \mid l', j'; Jm\right)\right|^2 \left|Y_{l'm'}(\theta, \varphi)\right|^2$$

A contains the dependence on

- quantum numbers in incident and emergent channels (l, j, l’, j’, J, m)
- solid angle Ω (θ,ϕ)

2. 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^μ, 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

3. Computer codes and calculations

TALYS Codes

- free software working under Linux operating system in continue development

- friendly interface

- a large number of models for nuclear structure and nuclear reactions (direct, compound, pre - equilibrium) implemented

- data base on nuclear structure for a large number of nuclei

- allows to evaluate: nuclear structure data, inclusive and exclusive cross sections (XS)

- **Inclusive XS – Ex,** in a binary reaction A(a,b), b will be considered emergent particles from other possible open channels

- **Exclusive XS** – in a binary reaction b will be considered emergent particles from a well defined “b+B” exit channel

- **Talys** will be used in the XS calculations of fast neutron induced reactions with emission of alpha particles

A.J. Koning, S. Hilaire and M.C. Duijvestijn, TALYS-1.0, Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22 - 27, 2007, Nice, France, editors O. Bersillon, F. Gunsing, E. Bauge, R. Jacqmin, S. Leray, EDP Sciences, p. 211 (2008)

4. Results and discussion – Investigated fast protons induced reactions

1. **$^{113}In(p,\gamma)^{114}Sn$** – Q = 8.4815 MeV

^{113}In nucleus $J^{\Pi} = (9/2)^{+}$ in fundamental state; stable nucleus

^{114}Sn nucleus $J^{\Pi} = 0^{+}$ in fundamental state; stable nucleus

2. **$^{113}In(p,2n)^{112}Sn$** – Q = -9.5657 MeV

^{112}Sn nucleus $J^{\Pi} = 0^{+}$ in fundamental state; stable nucleus

3. **$^{115}In(p,n)^{115}Sn$** – Q = -2.8486 MeV

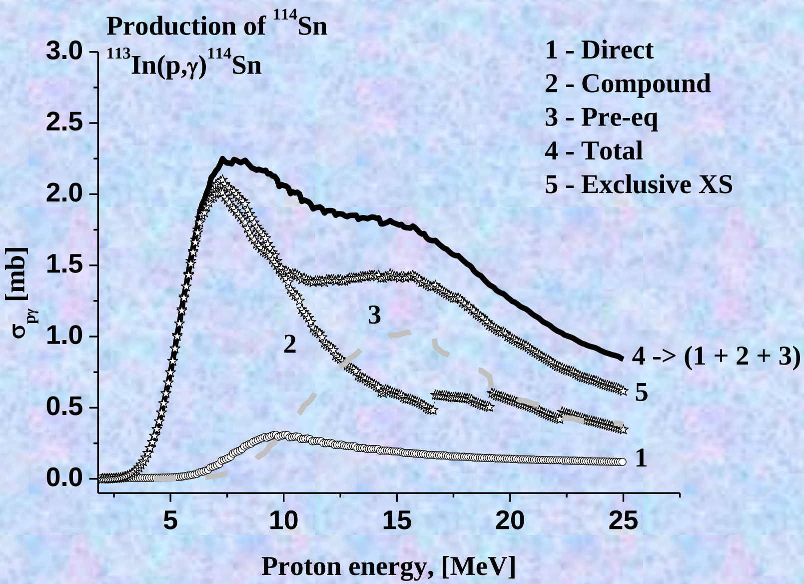
^{115}In nucleus $J^{\Pi} = (9/2)^{+}$ in fundamental state; stable nucleus

^{115}Sn nucleus $J^{\Pi} = (1/2)^{+}$ in fundamental state; stable nucleus

In the interaction of fast protons with natural Indium a large number of isomers and isotopes like ^{106}Pd, ^{109}Ag, $^{108, 109, 110, 111, 112}Cd$, $^{111, 112, 113, 114, 115, 116}In$, etc, are obtained

Important aspect in the analysis of experimental data radiation protection issues

4. Results and discussion – $^{113}In(p,\gamma)^{114}Sn$ Cross sections



Cross Sections are very low

Difficult to obtain experimental data

Compound processes are dominant (2)

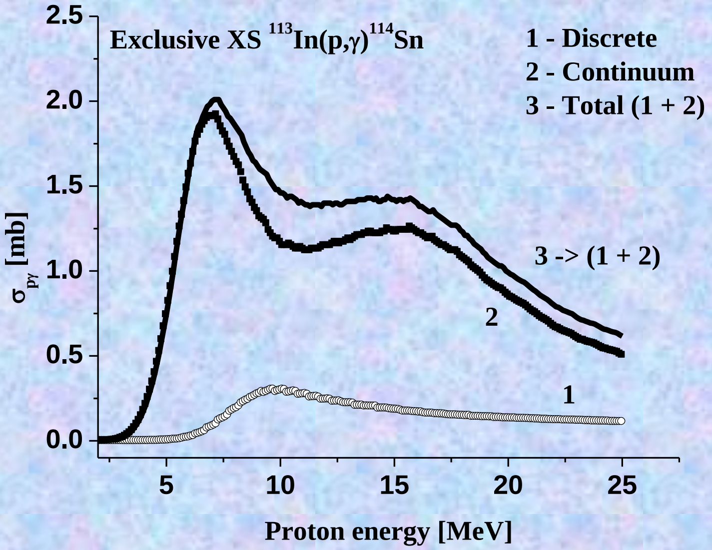
Small direct component – (1)

After 8 MeV pre-eq. processes are enabled (3) and mainly compound processes are coming from multistep compound mechanism

Sum of all components – (4)

Exclusive $^{113}In(p,\gamma)^{114}Sn$ process (5) are compared with (4)

Difference is coming from different decays leading to ^{114}Sn nucleus in ground state

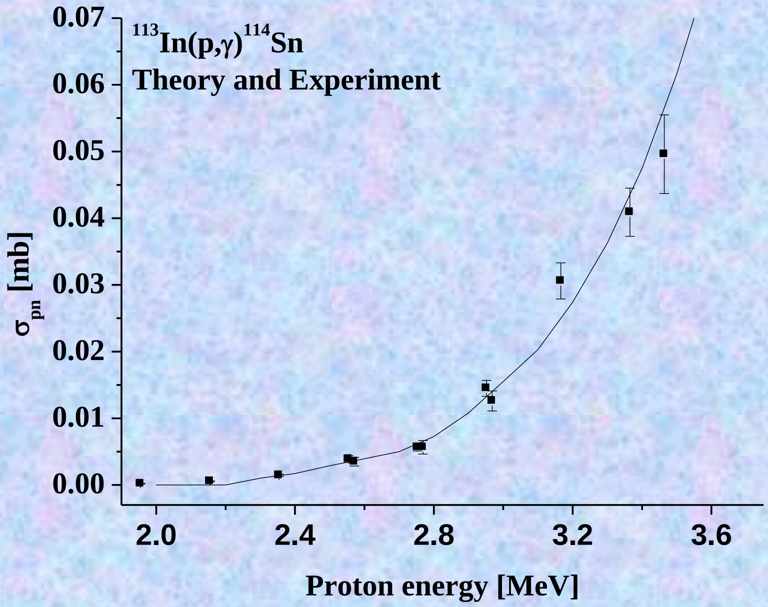


Discrete and Continuum States of Residual Nucleus - XS

Main contribution to the XS are given by continuum states of residual nucleus

Discrete state (10 levels) are important few MeV around threshold

4. Results and discussion – $^{113}In(p,\gamma)^{114}Sn$ XS. Theory and Experiment



Comparison with experimental data

Two sets of experimental data was taken from NDS database

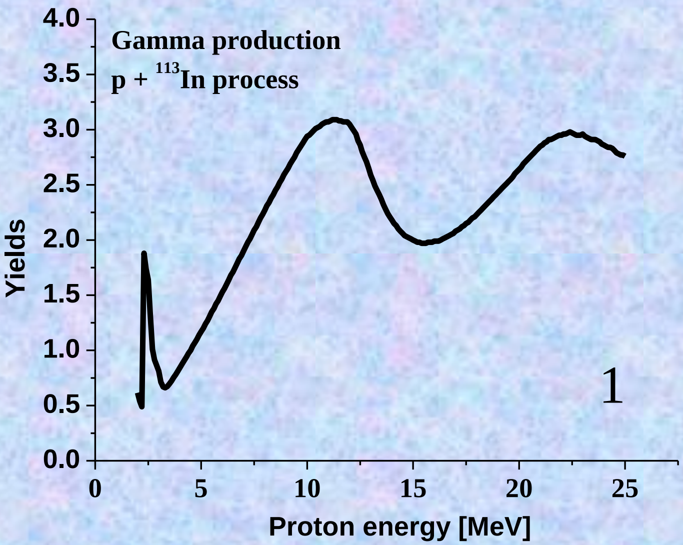
A good description of experimental data was obtained

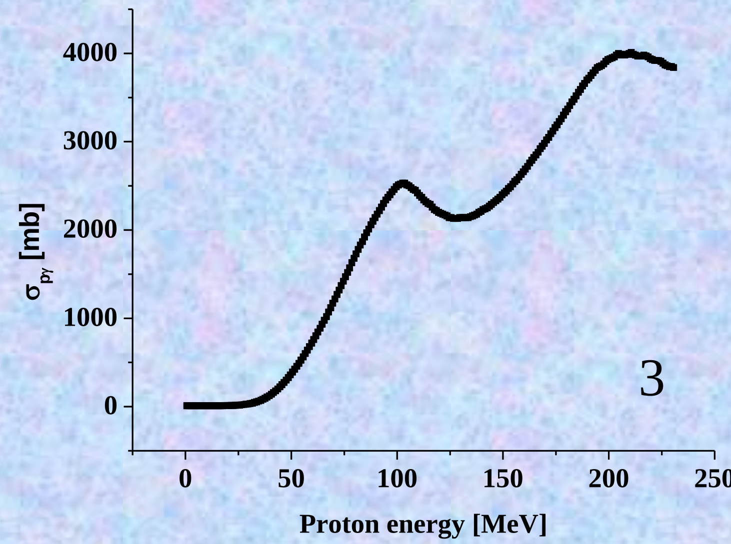
Cross section has very low values which make difficult the measurements

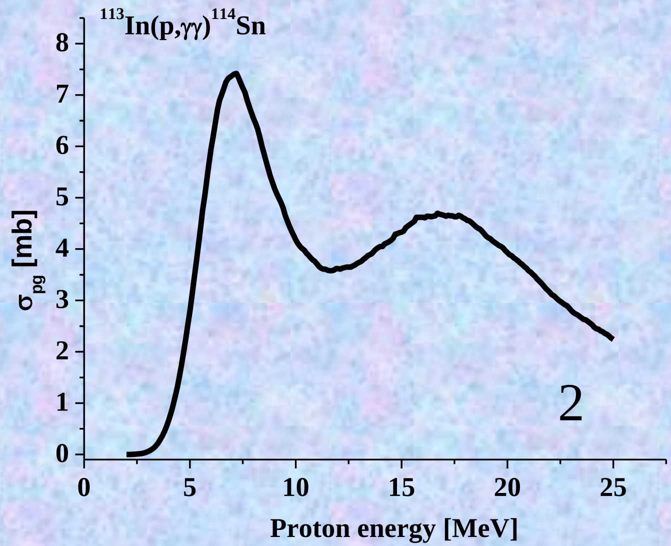
Measurements will be affected by a large background coming from exit channels with participation of neutrons, protons, gamma, alpha and other particles

Agreement between theoretical evaluations and experimental data was obtained by varying a large number of Talys input parameters like optical potentials and levels density

4. Results and discussion – Gamma production







1 – Gamma production in ^{113}In(p,γ)^{114}Sn process

2 – XS of ^{113}In(p, γγ)^{114}Sn reaction

3 – XS of total gamma production in ^{113}In(p, γ)^{114}Sn

-Gamma contribution from all open channels

- (1), (2), (3) -> necessary in the analysis of experimental data

4. Results and discussion – Production of ^{114}Sn in $^{113}In(p,\gamma)$

Natural Indium target with density 7.2 g/cm^3 with transversal area 1 cm^2 and thickness about 3 mm contains about 4.92425E20 ^{113}In nuclei and 1.0986E22 ^{115}In nuclei

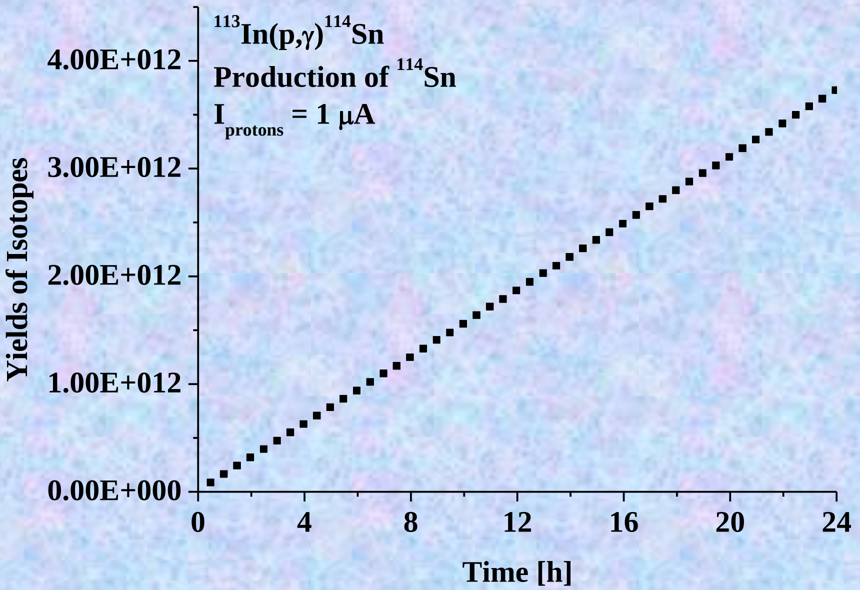
-3 mm – necessary thickness for protons to lose their energy in the target

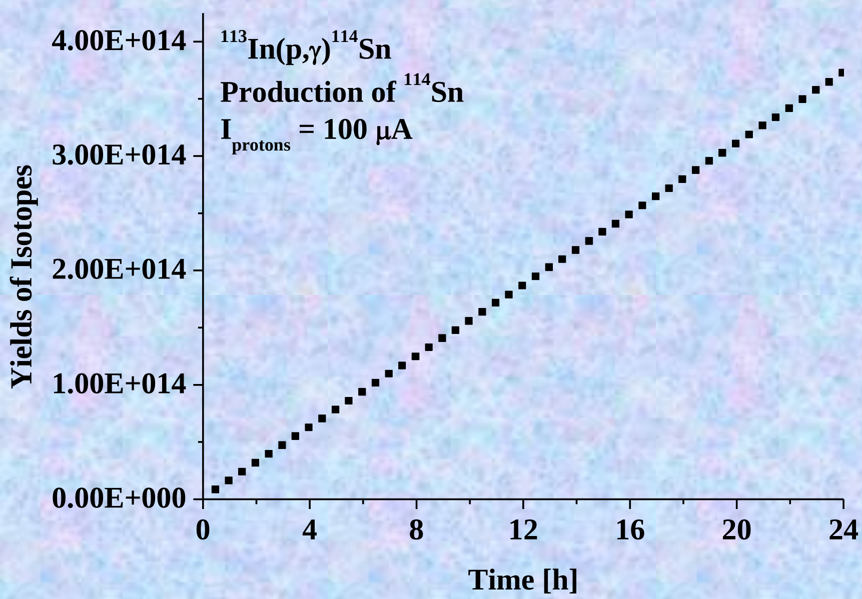
- Natural Indium target is irradiated with 35 MeV protons with beam intensity 1 μA and 100 μA, respectively

^{114}Sn can be produced in $^{113}In(p,\gamma)$ – irradiation time 24 h

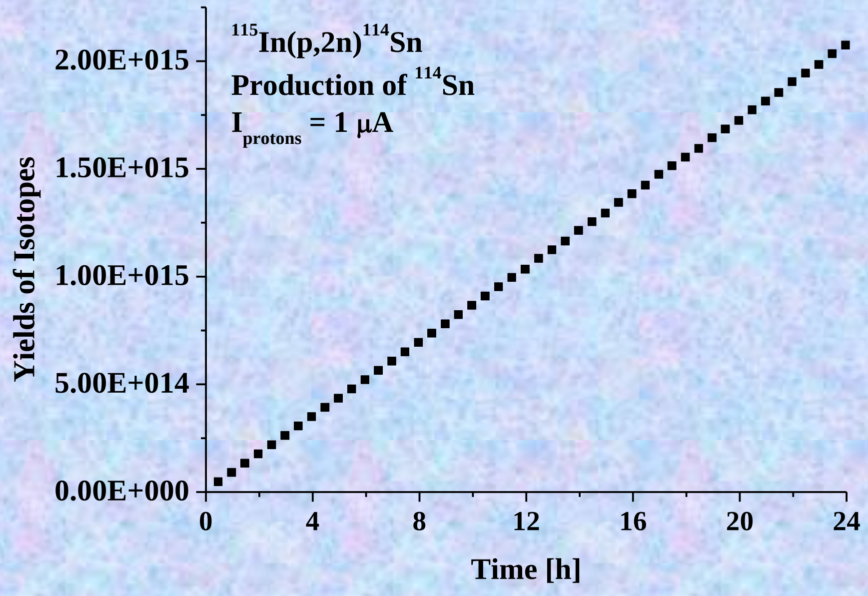
-In the Figures – Production of ^{114}Sn by $^{113}In(p,\gamma)$ reaction for different beam intensity

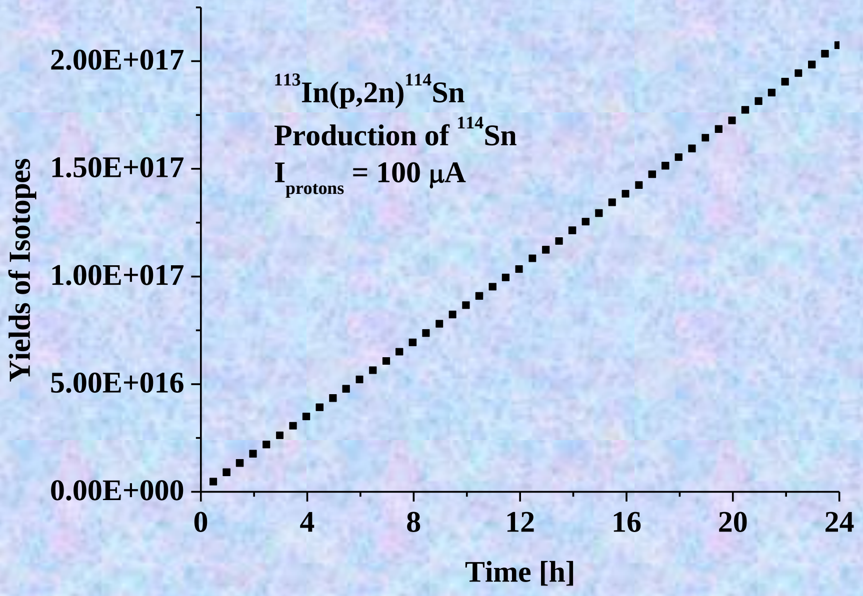
Number of Nuclei





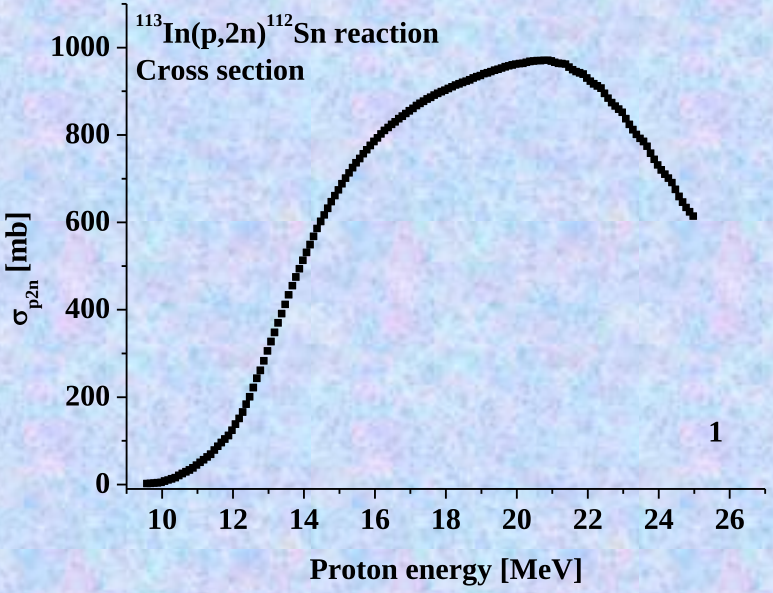
4. Results and discussion – Production of ^{114}Sn in ^{115}In(p,2n)

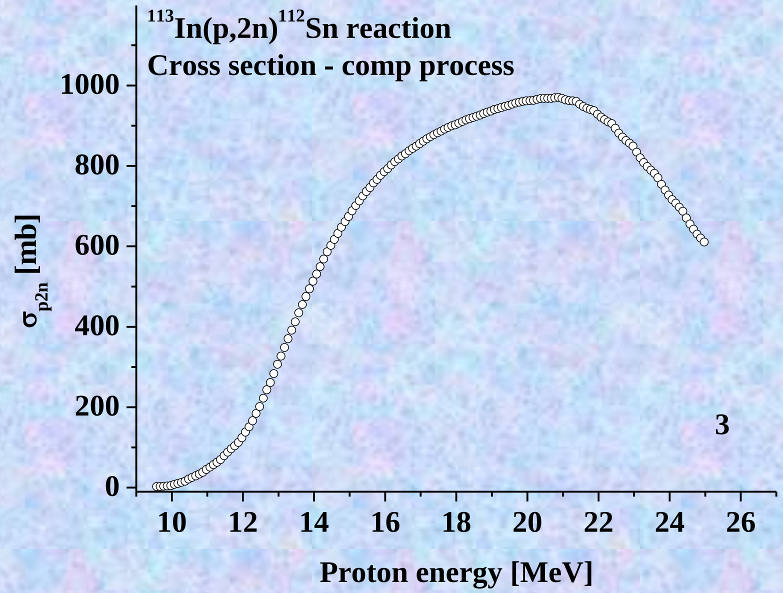


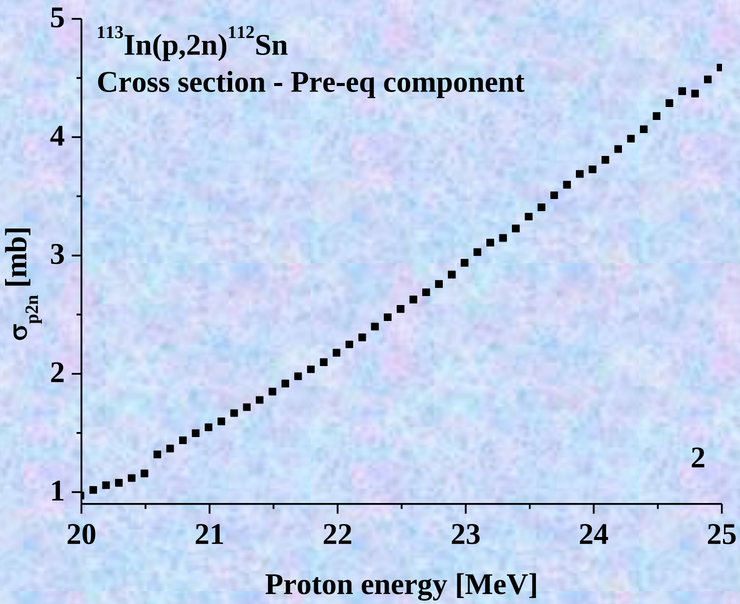


Number of nuclei of ^{114}Sn obtained in the same condition as the results from previous slide

4. Results and discussion – $^{113}In(p,2n)^{112}Sn$ reaction







1 – XS of $^{113}In(p,2n)^{112}Sn$ cross section

Contribution of nuclear reaction mechanisms

2 – Low pre-eq components

3 – XS mainly given by compound processes

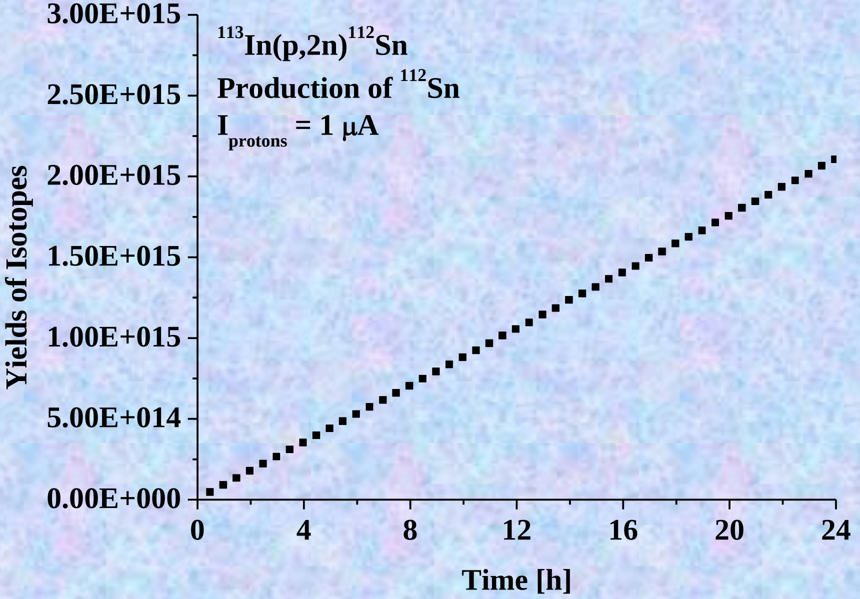
Direct mechanism practical can be neglected

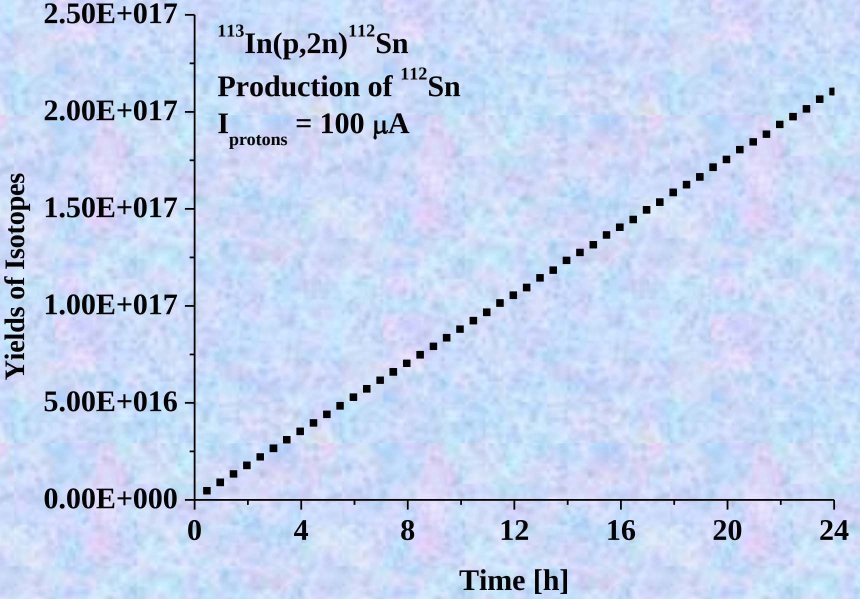
No experimental data

Discrete states – few MeV near the threshold

Continuum states – the main contribution to XS

4. Results and discussion – ^{113}In(p,2n)^{112}Sn. Production of ^{112}Sn

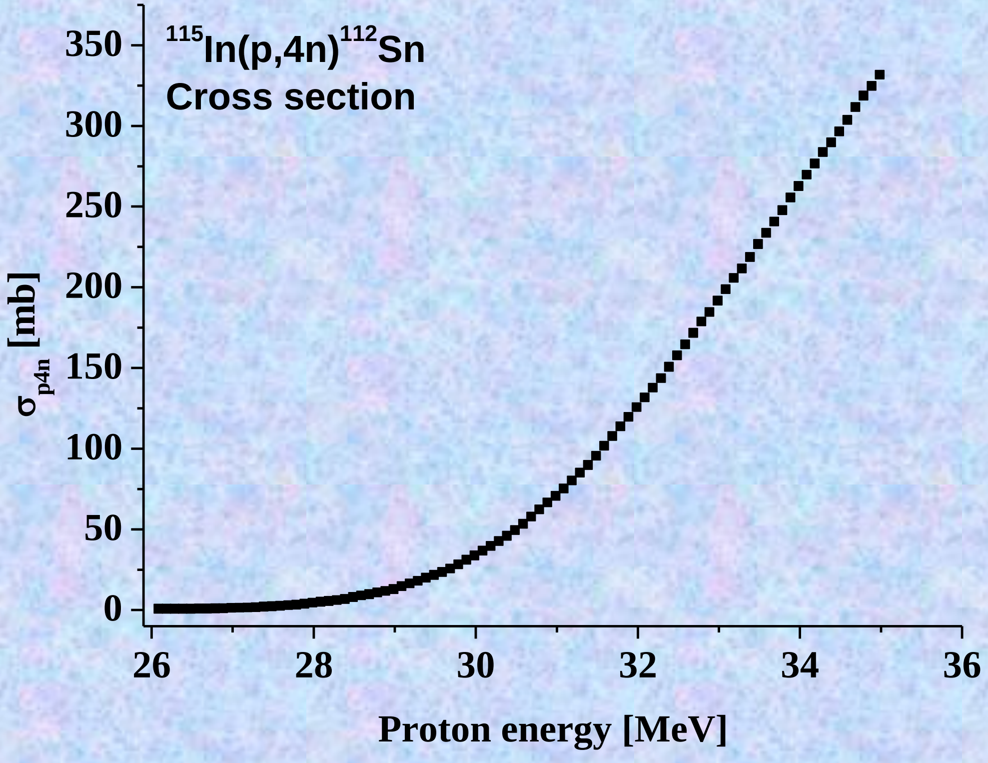




Production of ^{114}Sn for 1 μA and 100 μA protons beam intensity on a target of natural Indium

^{112}Sn nucleus can be produced in other reaction like ^{115}In(p,4n)^{112}Sn

4. Results and discussion – $^{115}In(p,4n)^{112}Sn$. Production of ^{112}Sn



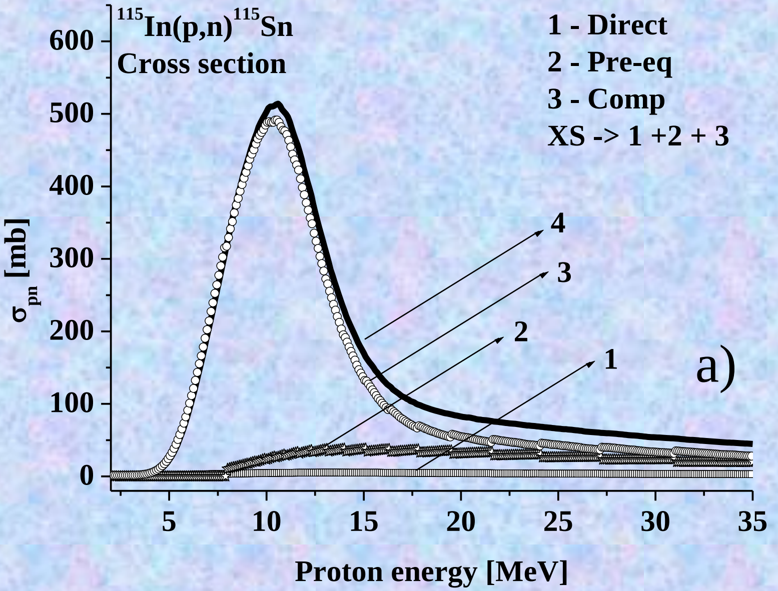
^{112}Sn nucleus can be produced in other reaction like $^{115}In(p,4n)^{112}Sn$, Q = -25.876 MeV

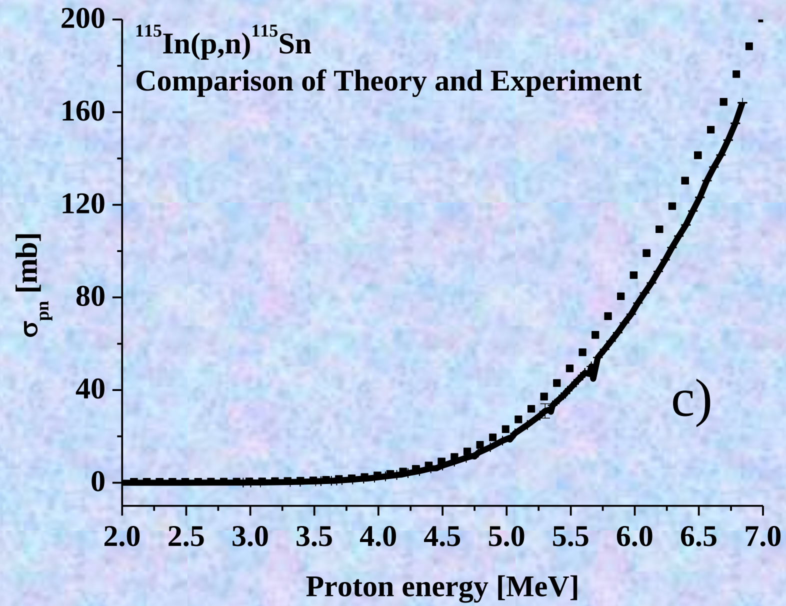
- in the given energy interval – only compound processes

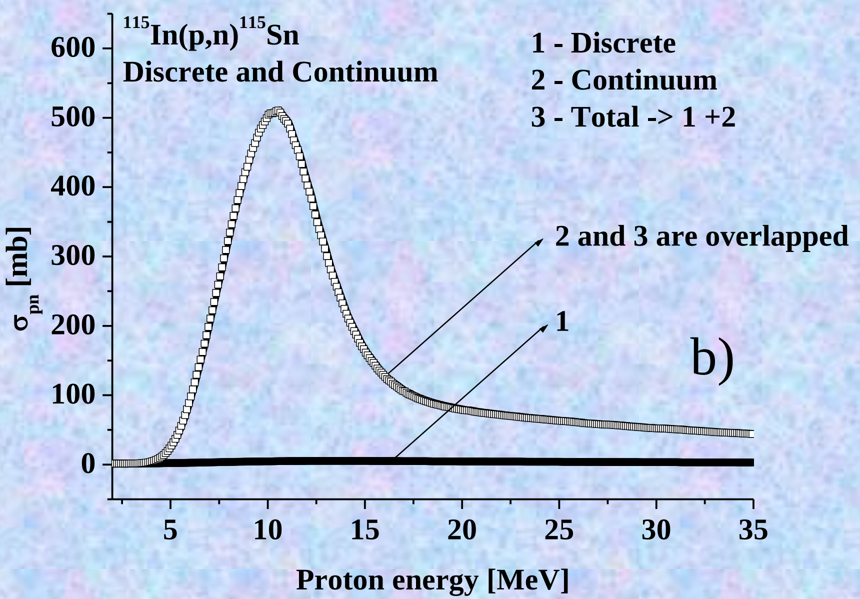
- Lack of experimental cross section data

Production of ^{112}Sn nucleus in this process has low values for 1 and 100 μA respectively

4. Results and discussion – $^{115}In(p,n)^{115}Sn$. Cross section







a) Decomposition of XS into Direct, Compound and Pre-eq mechanisms

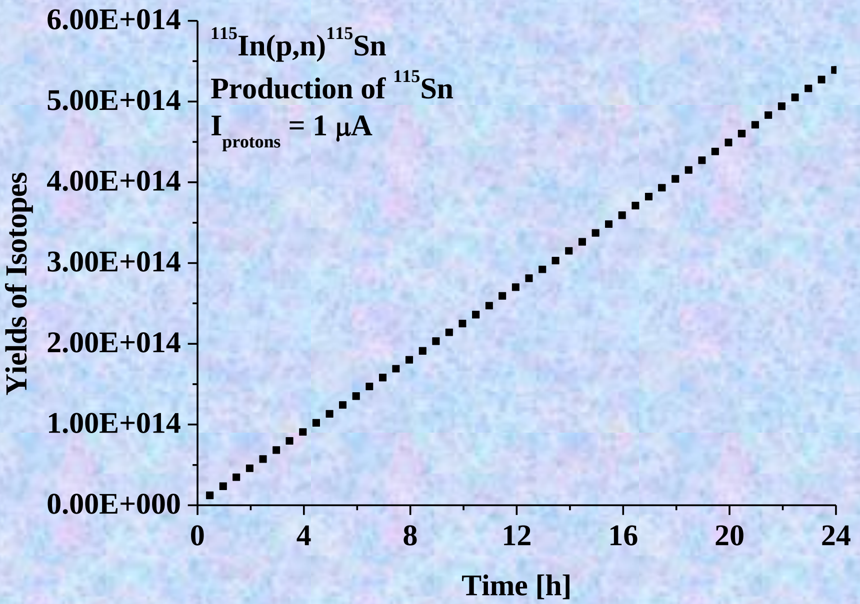
b) Contribution of Discrete and Continuum states of residual nuclei

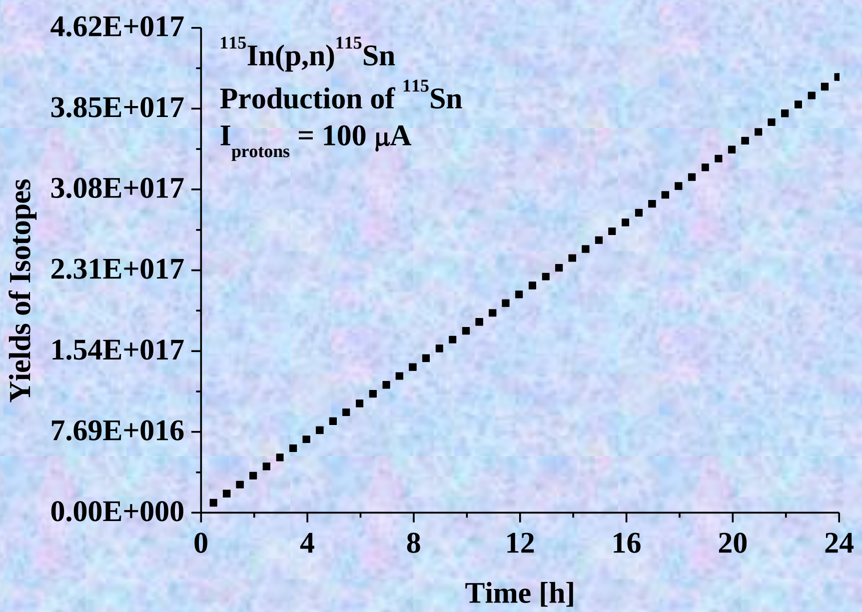
c) Comparison between Theory and Experiment

Compound processes given by Continuum states give main contribution to the XS

Good agreement between theory and experiment

4. Results and discussion – $^{115}In(p,n)^{115}Sn$. Production of ^{115}Sn

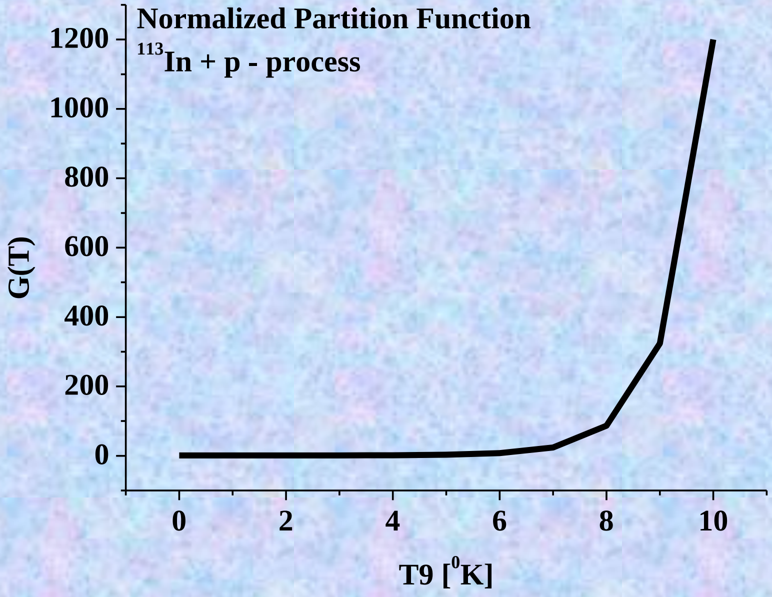


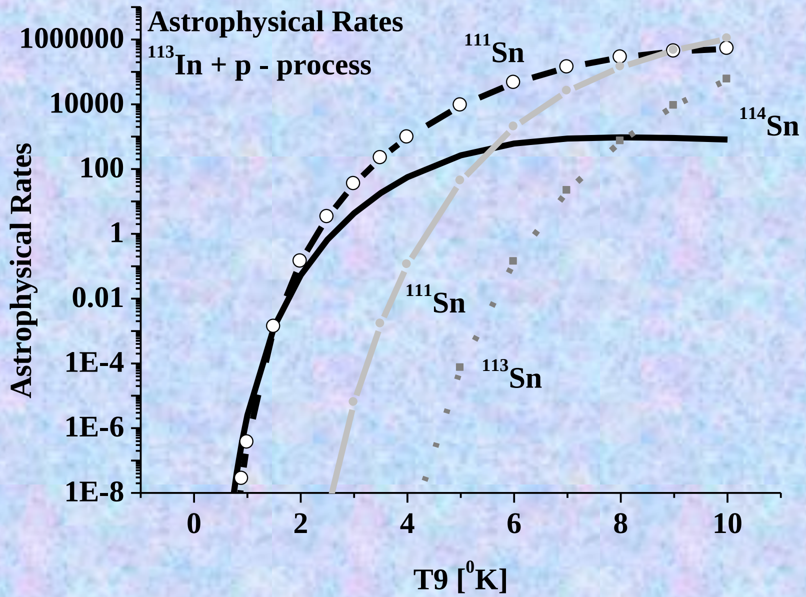


Production of ^{115}Sn in $^{115}In(p,n)$ process on a target of natural Indium irradiated with 1 and 100 μA protons beam intensity

- Target are 1 cm^2 – time of irradiation 24 h

4. Results and discussion – ^{113}In + p. Astrophysical rates



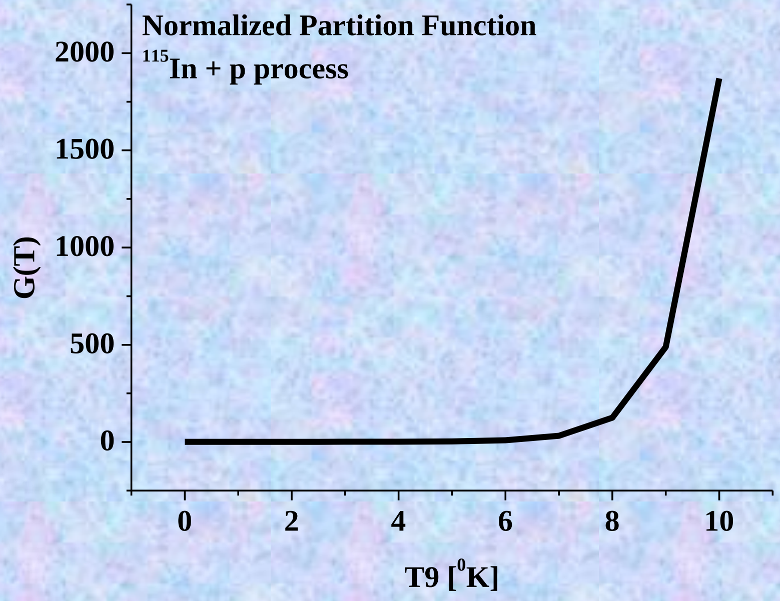


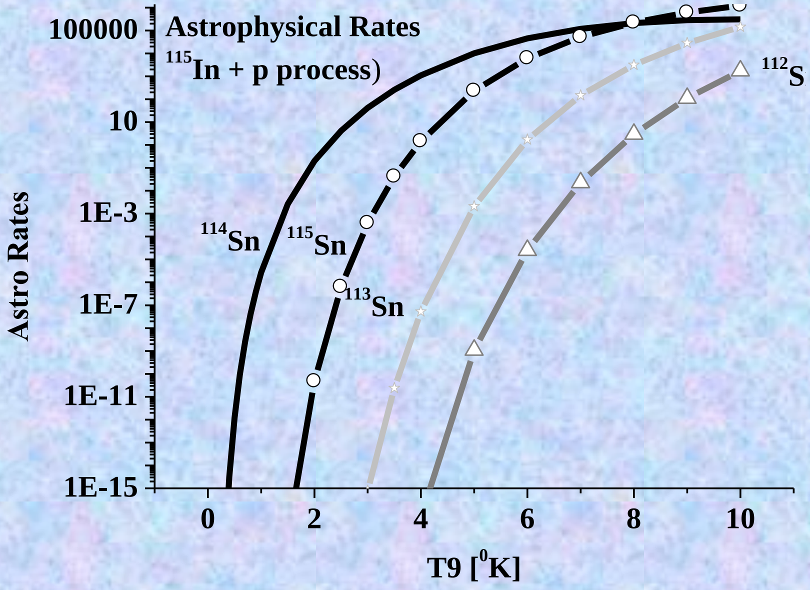
Used relations

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

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

4. Results and discussion – ^{115}In + p. Astrophysical rates





Normalized Partition Function and Astrophysical Rates calculated using cross sections and nuclear data from Talys for different isotopes of Tin

Astrophysical rates will be calculated for other isotopes of interest as well

4. Results and discussion – Talys Input Parameters

Evaluations - Talys - Conditions

Considered Compound, Direct and Pre-equilibrium processes together with Discrete and Continuum States of Residual Nuclei

- 10 residual states for reaction channels
- 30 for elastic and inelastic channels

Wood Saxon Optical Potential with components – volume, surface and spin – orbit, each with real and imaginary part

Level Density – Fermi gas model

General remarks – Compound processes are dominant for all investigated reactions

- Near the threshold discrete states give the main contribution to the cross sections but at higher energies continuum states are dominant.
- In many cases compound processes have pre-equilibrium origin of type multistep compound

4. Results and discussion – Nuclear Potential Parameters

Wood - Saxon Potential

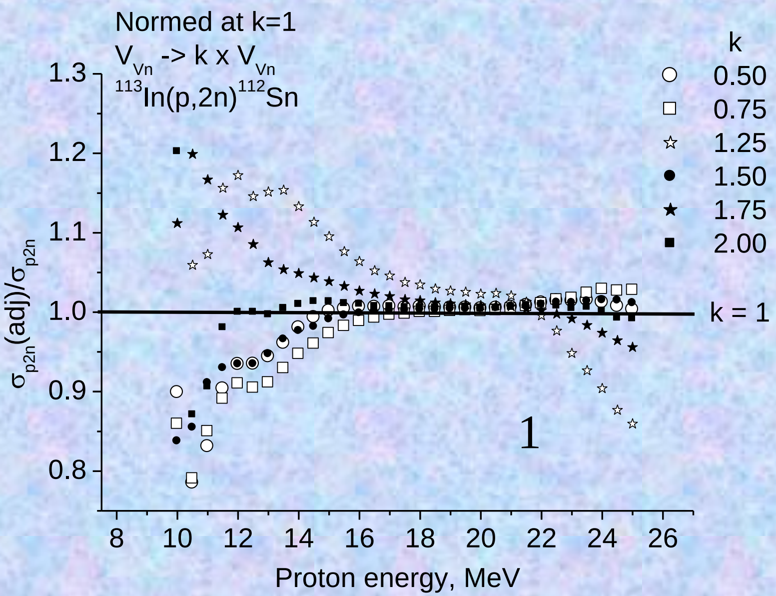
Volume WS – Real Part | Volume WS – Imaginary | Surface WS – Imaginary

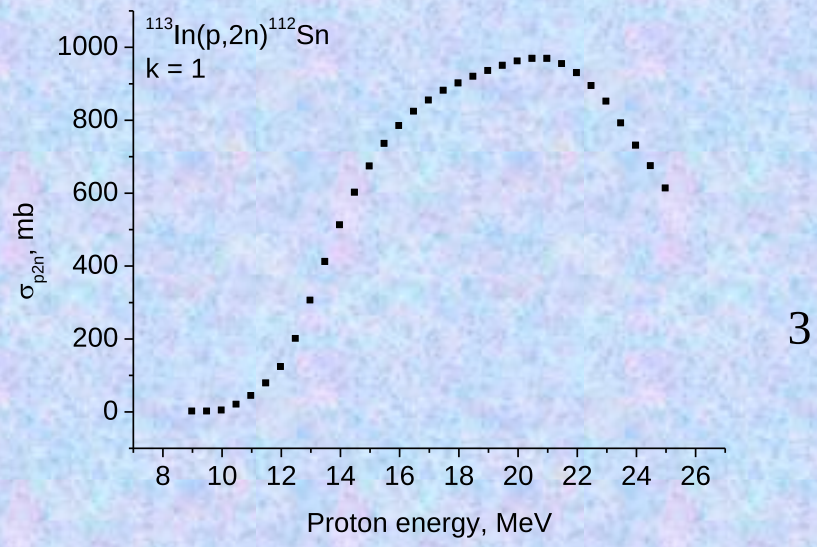
	V [MeV]	r_v [fm]	a_v [fm^{-1}]	W [MeV]	r_w [fm]	a_w [fm^{-1}]	W_d [MeV]	r_{dw} [fm]	a_{wd} [fm^{-1}]
p + ^{113}In	62.42	1.220	0.661	0.11	1.220	0.661	4.25	1.266	0.578
p + ^{115}In	62.69	1.221	0.661	0.11	1,221	0.661	4.28	1.265	0.579
n + ^{115}Sn	50.74	1.221	0.661	0.14	1.221	0.661	3.94	1.265	0.526

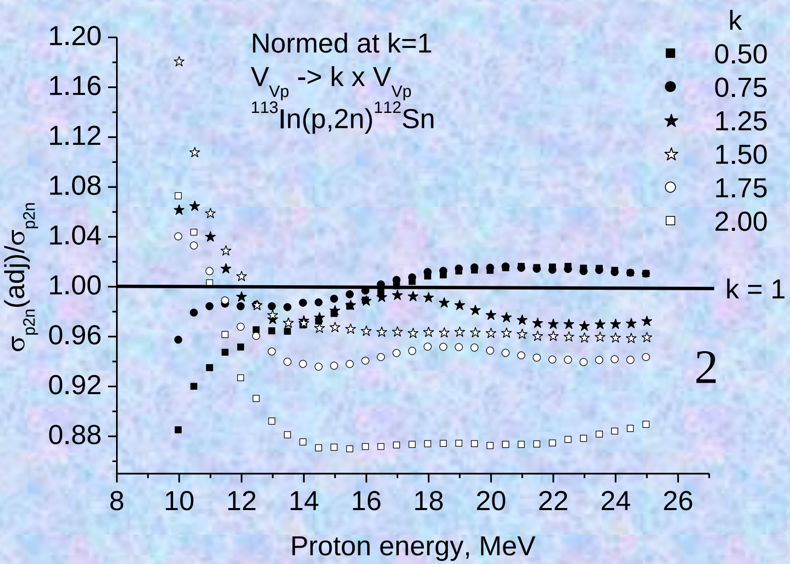
Spin orbit – Real Part | Spin orbit – Imaginary

	V_{so} [MeV]	r_{vso} [fm]	a_{vso} [fm^{-1}]	W_{so} [MeV]	r_{wso} [fm]	a_{wso} [fm^{-1}]
p + ^{113}In	6.09	1.052	0.590	-0.01	1.052	0.590
p + ^{115}In	6.09	1.652	0.590	-0.01	1.052	0.690
n + ^{115}Sn	6.06	1.052	0.590	-0.01	1.052	0.590

4. Results and discussion – Analysis of Uncertainty







Real part of WS potential was varied in the neutrons and protons channels, respectively

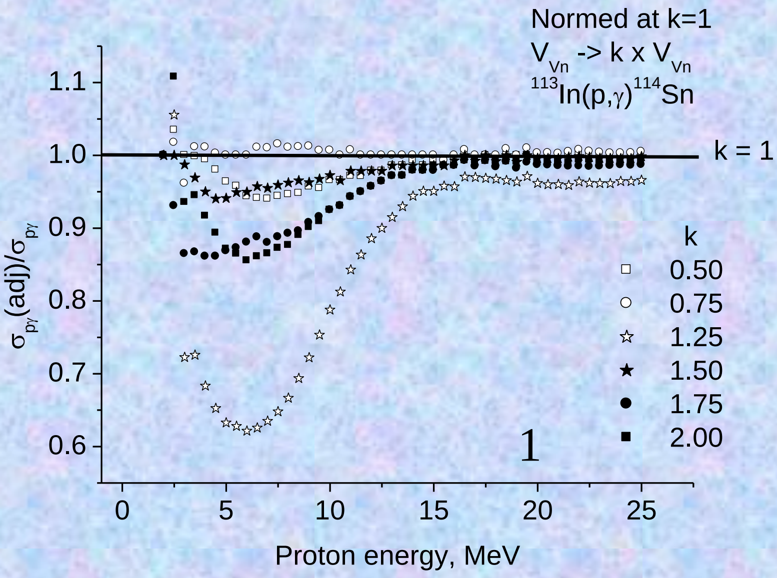
V_{vn}[MeV] ϵ [25,100] (Fig.1),V_{vp}[MeV] ϵ [30,125] (Fig.2)

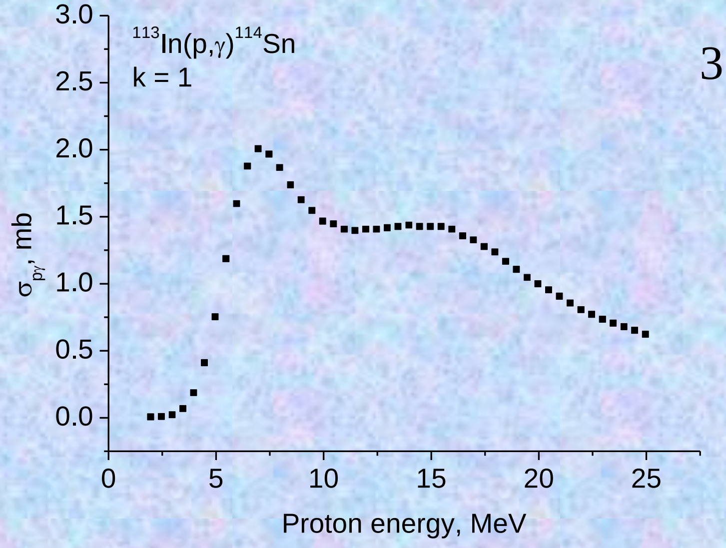
Normalized XS to values from Fig. 3

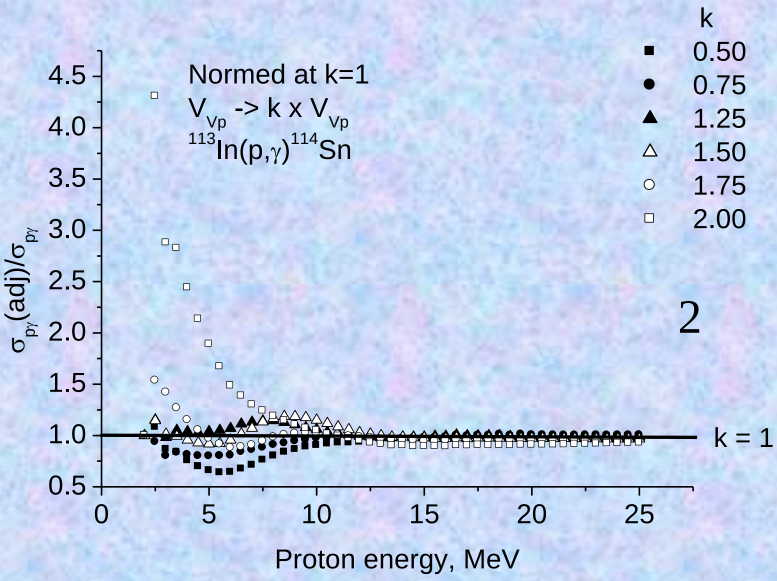
XS is sensible to the modification of real part of volume WS potential with about 20-30 % in the region of interest for astrophysics

Fig. 3 XS data – for k = 1 (not normalized)

4. Results and discussion – Analysis of Uncertainty







Reaction $^{113}In(p,\gamma)^{114}Sn$

Real part of WS potential was varied in the neutrons and protons channels, respectively

V_{vn}[MeV] ϵ [25,100] (Fig.1),V_{vp}[MeV] ϵ [30,125] (Fig.2)

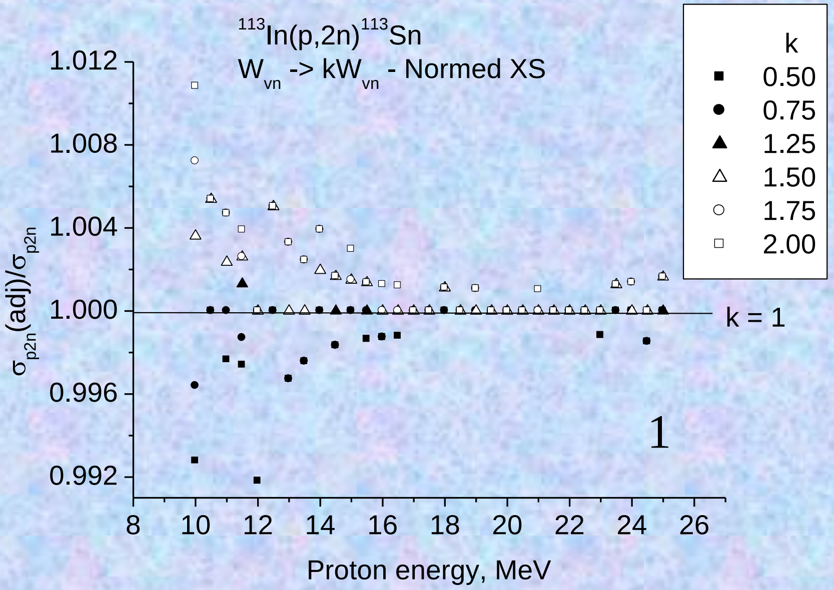
Normalized XS to values from Fig. 3
XS si sensible to the modification of real part of volume WS

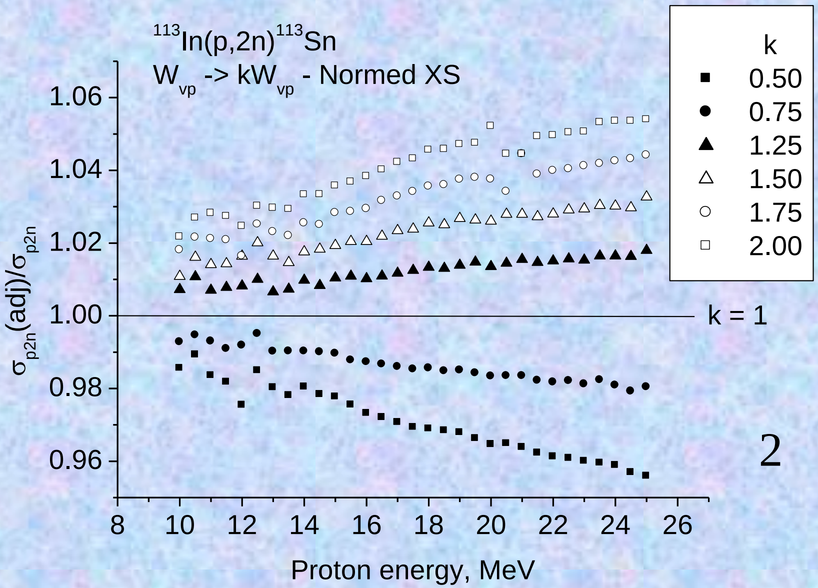
Open channels with neutrons participation are also influence the (p,γ) cross section

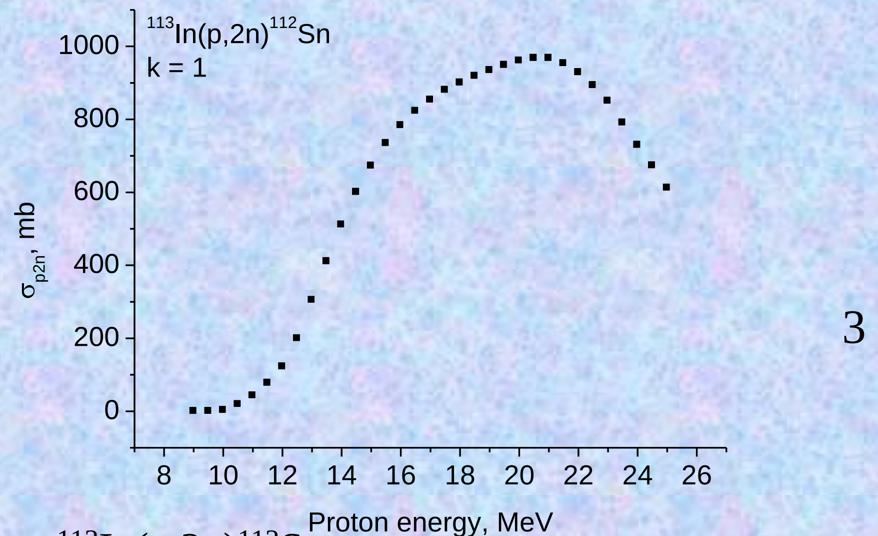
XS is low but V_{vn}, V_{vp} – influence XS at up to 10 MeV – the region of astrophysical interest

Fig. 3 XS data – for k = 1 (not normalized)

4. Results and discussion – Analysis of Uncertainty







Reaction: ^{113}In(p,2n)^{112}Sn

Real part of WS potential was varied in the neutrons and protons channels, respectively

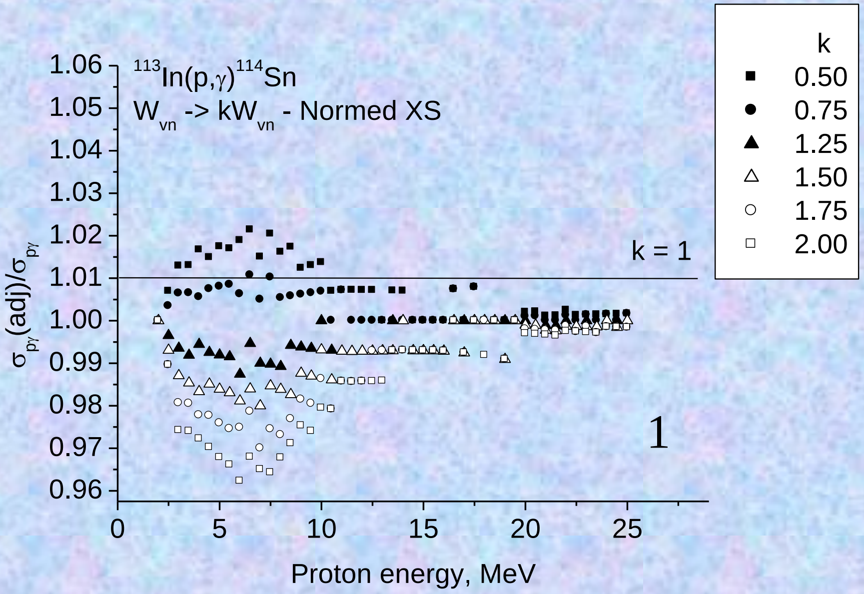
V_{vn}[MeV] ϵ [25,100] (Fig.1), V_{vp}[MeV] ϵ [30,125] (Fig.2)

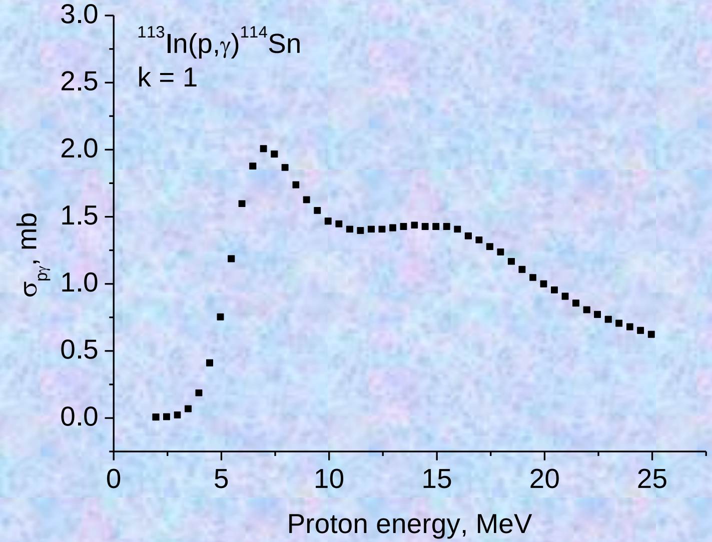
Normalized XS to values from Fig. 3

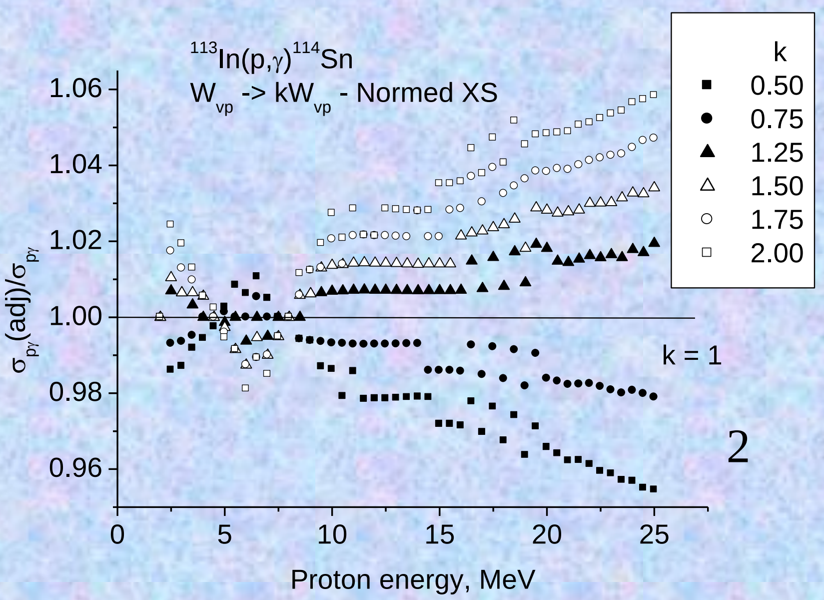
XS it is not so sensible to the modification of imaginary part of volume WS potential - about few percent

Fig. 3 XS data – for k = 1 (not normalized)

4. Results and discussion – Analysis of Uncertainty







Reaction: $^{113}In(p,\gamma)^{114}Sn$

Real part of WS potential was varied in the neutrons and protons channels, respectively

V_{vn}[MeV] ϵ [25,100] (Fig.1), V_{vp}[MeV] ϵ [30,125] (Fig.2)

Normalized XS to values from Fig. 3

For this process also XS it is not so sensible to the modification of imaginary part of volume WS potential - about few percent

Fig. 3 XS data – for k = 1 (not normalized)

5. Conclusions

Cross sections – Cross sections of $^{113}In(p,\gamma)^{113}Sn$, $^{113}In(p,2n)^{112}Sn$ and $^{115}In(p,n)^{115}Sn$ reactions were investigated. Evaluations were realized in Talys. Contribution to the XS of nuclear reaction mechanisms related to discrete and continuum states of residual nuclei were obtained. A good agreement with experimental data was obtained. Parameters of optical potential were extracted

Production of $^{112, 114, 115}Sn$ nuclei – using Talys cross sections yields of Sn isotopes were modeled considering a target with finite dimensions at a given time of irradiation

Astrophysical rates – For mentioned processes and isotopes Normalized Partition Function and Astrophysical rates were also calculated using initial conditions suggested by Talys

Uncertainties – Analysis of the influence of WS potential parameters
Results given by variation of real and imaginary part of volume WS potential demonstrated that at low energies, near the threshold up to 8-10 MeV the influence to the XS is relative large, about 20 - 30%. Imaginary part influences the XS with some percent
The present results demonstrate the necessity of reliable experimental data in a large energy range necessary to extract new optical potential parameters for protons induced processes on In nucleus

The present investigations will be continued for other parameters, processes and computer simulations

5. Conclusions

Future tasks

- New theoretical evaluations based on the new XS and diff. XS measurements in wide energy interval
- To determine for each energy the contribution of nuclear reaction mechanisms based on future experimental data
- Improvements of Monte Carlo simulation for isotopes production
- To use the present evaluations for the realization of nuclear networks for astrophysics issues and determination of nuclei abundance
- New investigations of uncertainties

Present work - proposal for new experiments at FLNP JINR Dubna Facilities

THANK YOU VERY MUCH FOR YOUR ATTENTION! ☺

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