Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, Related Topics»

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State Key Laboratory of Intense Pulsed Radiation Simulation and Effect, NINT, CHINA

Fast proton induced processes on natural Indium

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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,γ)^{114}Sn, ^{113}In(p,2n)^{112}Sn, with fast protons from threshold up to 35 MeV

1. Introduction. 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

2. Theoretical background

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

- without fluctuation correction factor

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

- with fluctuation correction factor

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

$T =$ **transmission coefficient**

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

Differential cross section

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

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

A contains the dependence on

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

3. Computer codes and calculations – 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

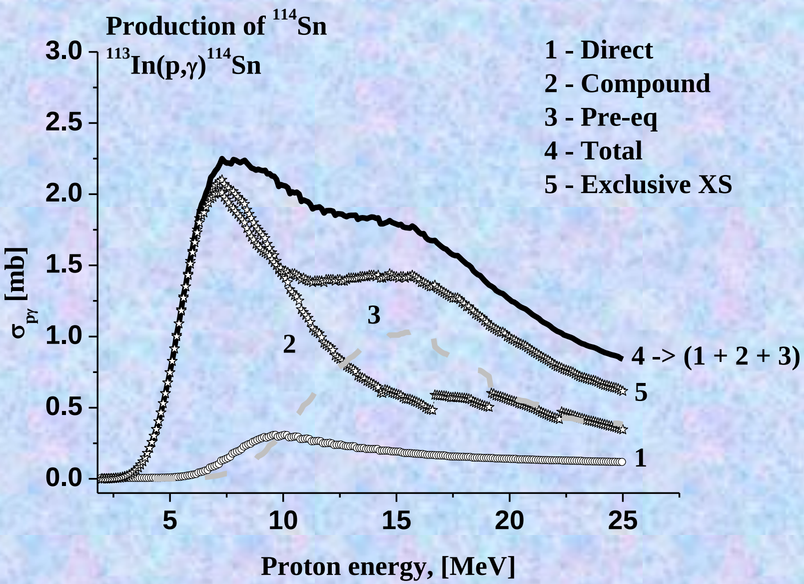
3. Computer codes and calculations – Nuclear Potential Parameters

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 – ^{113}In(p,γ)^{114}Sn Cross sections



Cross Sections are very low

Difficult to obtain experimental data

Compound processes are dominant (2)

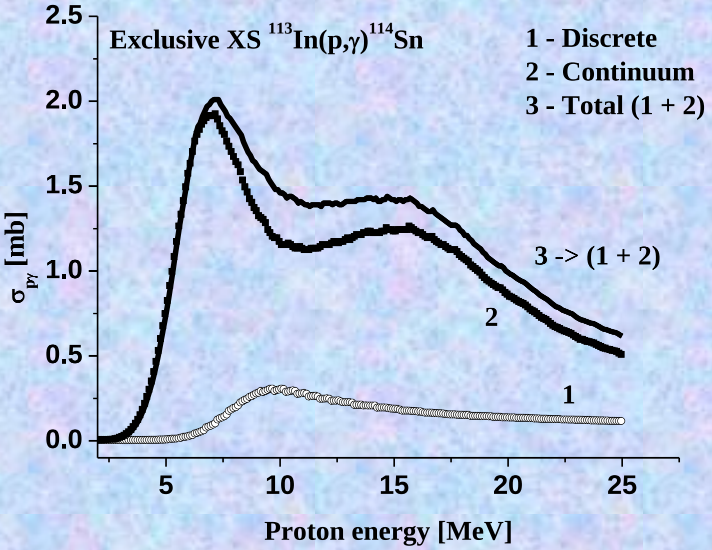
Small direct component – (1)

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,γ)^{114}Sn process (5) are compared with (4)

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

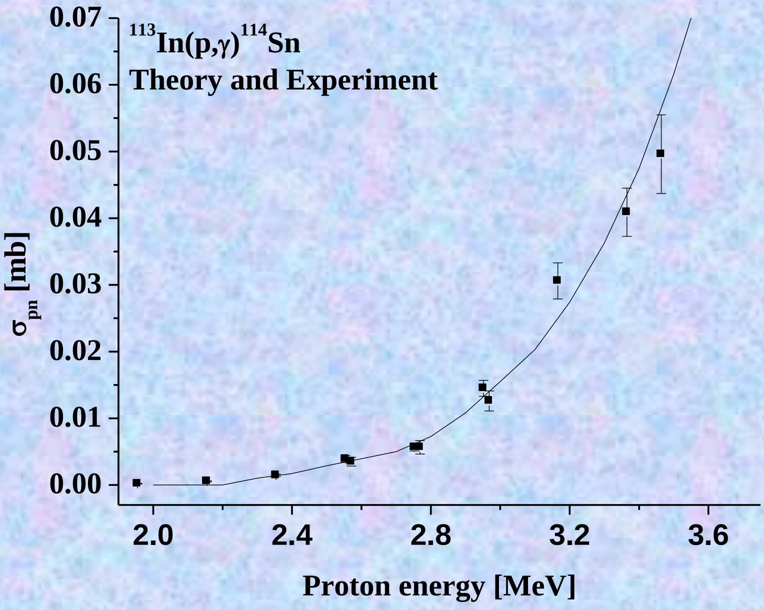


Discrete and Continuum States of Residual Nucleus - XS

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,γ)^{114}Sn XS. Theory and Experiment



Comparison with experimental data

Two sets of experimental data was taken from NDS database

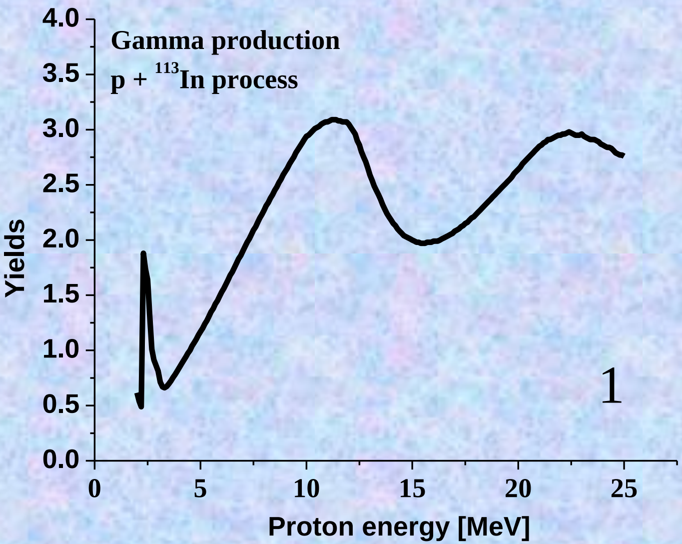
A good description of experimental data was obtained

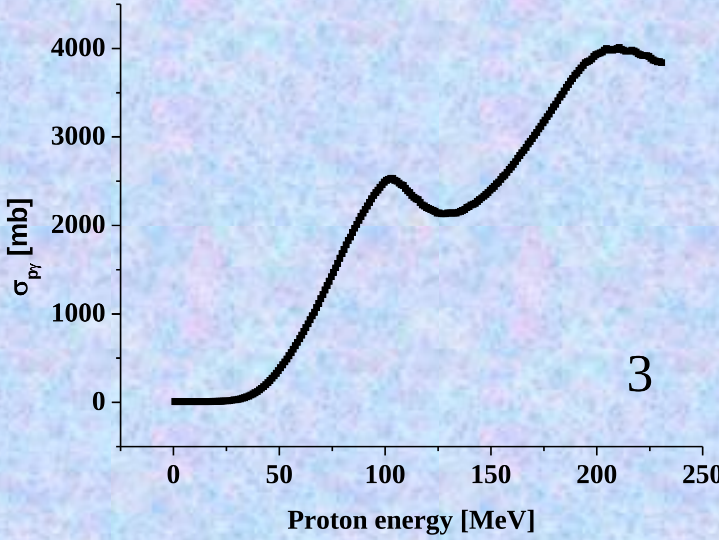
Cross section has very low values which make difficult the measurements

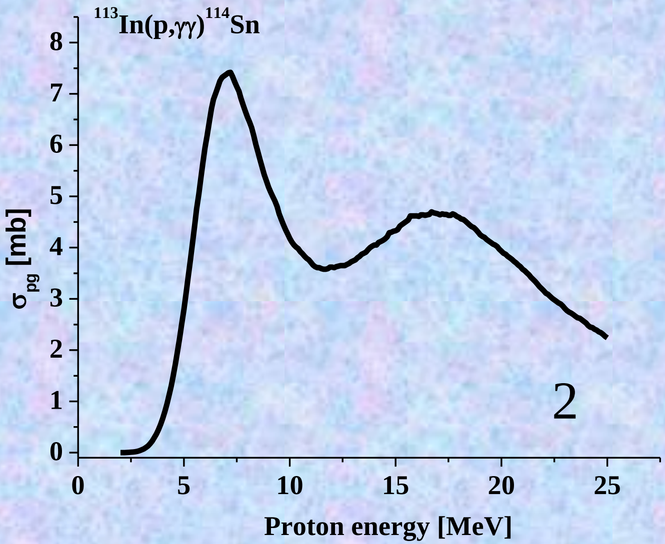
Measurements will be affected by a large background coming from exit channels with participation of neutrons, protons, gamma, alpha and other particles

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,γ)

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

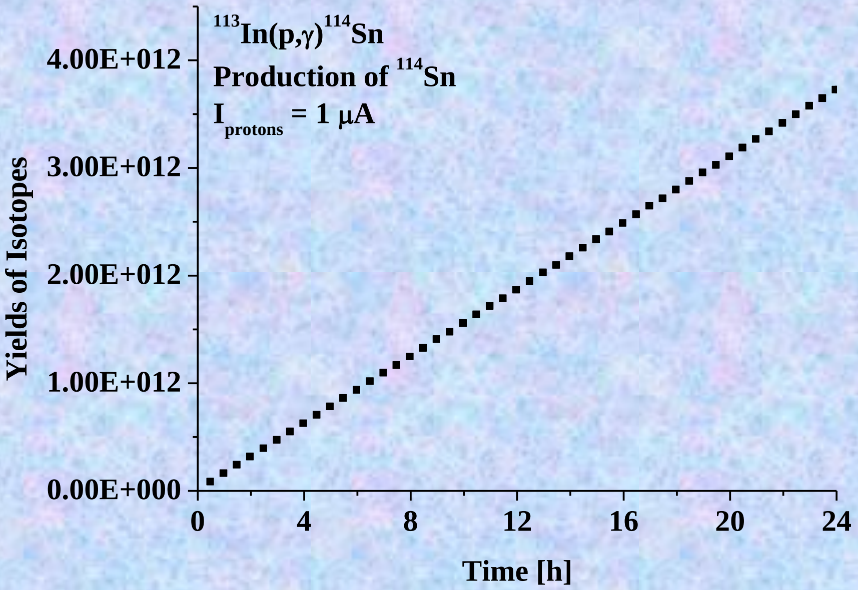
-3 mm – necessary thickness for protons to lose their energy in the target

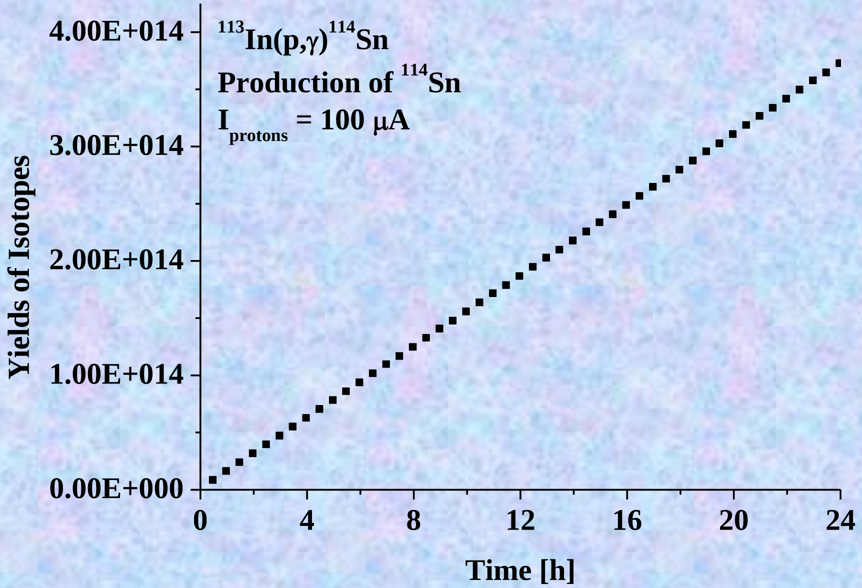
- Natural Indium target is irradiated with 35 MeV protons with beam intensity 1 μA and 100 μA, respectively

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

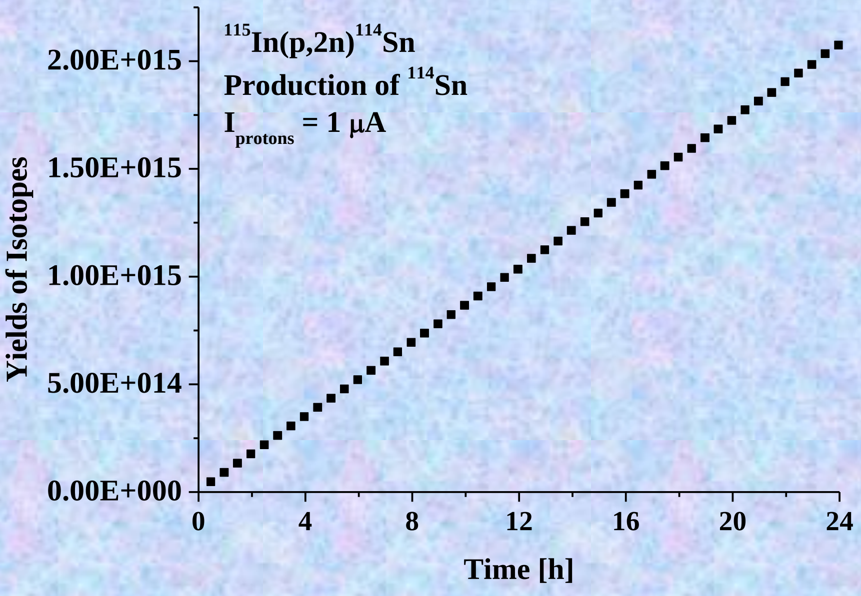
-In the Figures – Production of ^{114}Sn by ^{113}In(p,γ) reaction for different beam intensity

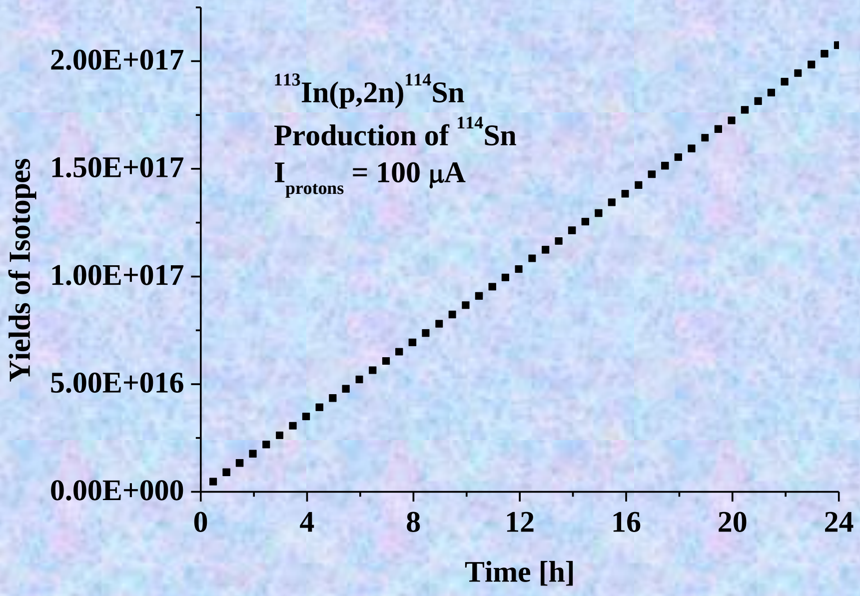
Number of Nuclei





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

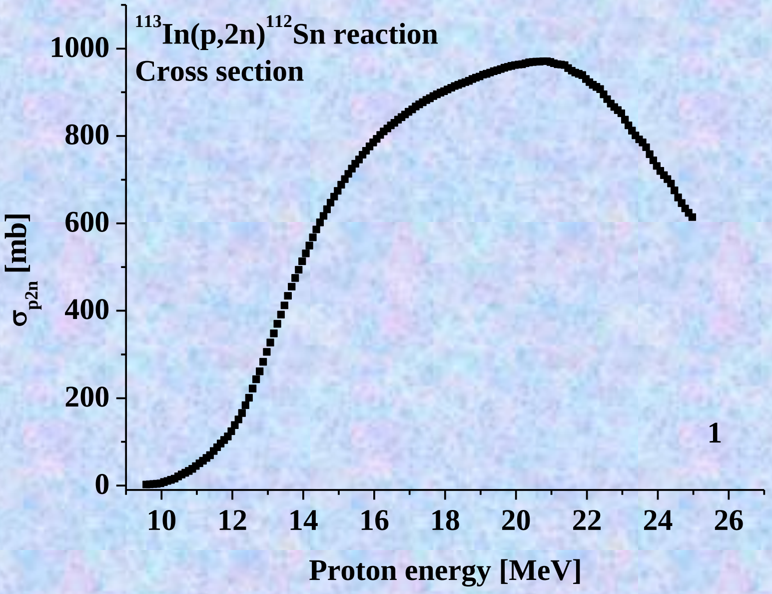


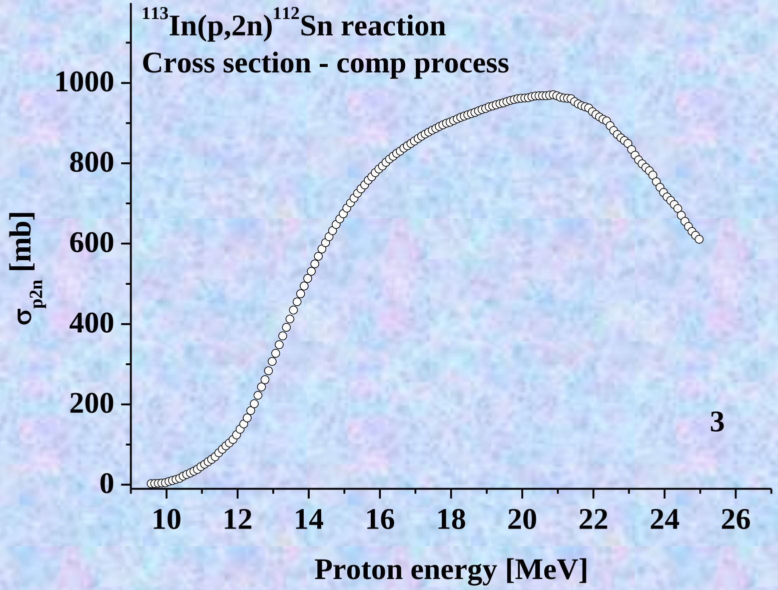


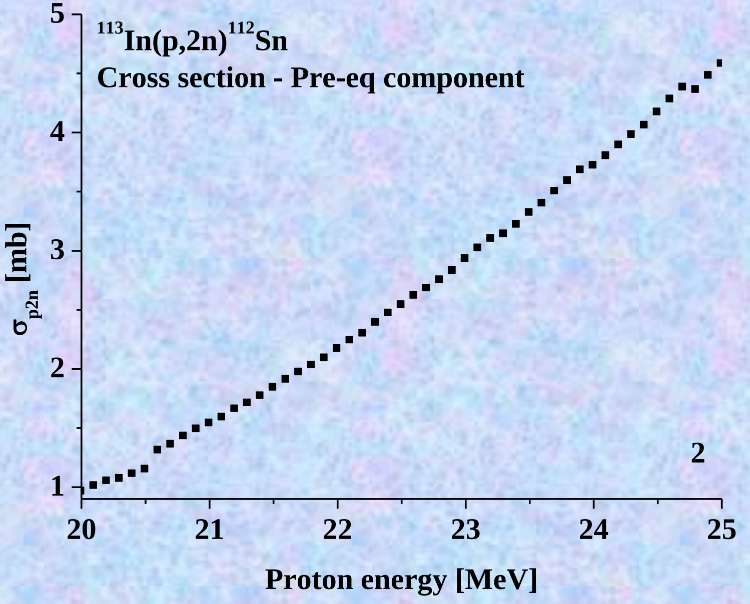
Number of nuclei of ^{114}Sn obtained in the same condition as the results from previous slide

The concentration is enough to be measured in experiment because is higher then 1 ppm

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-equilibrium components

3 – XS mainly given by compound processes

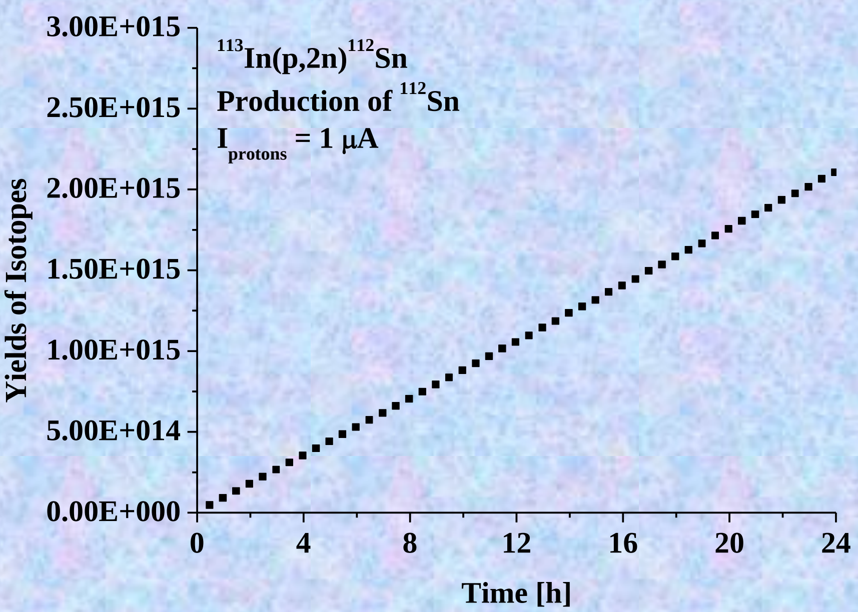
Direct mechanism practical can be neglected

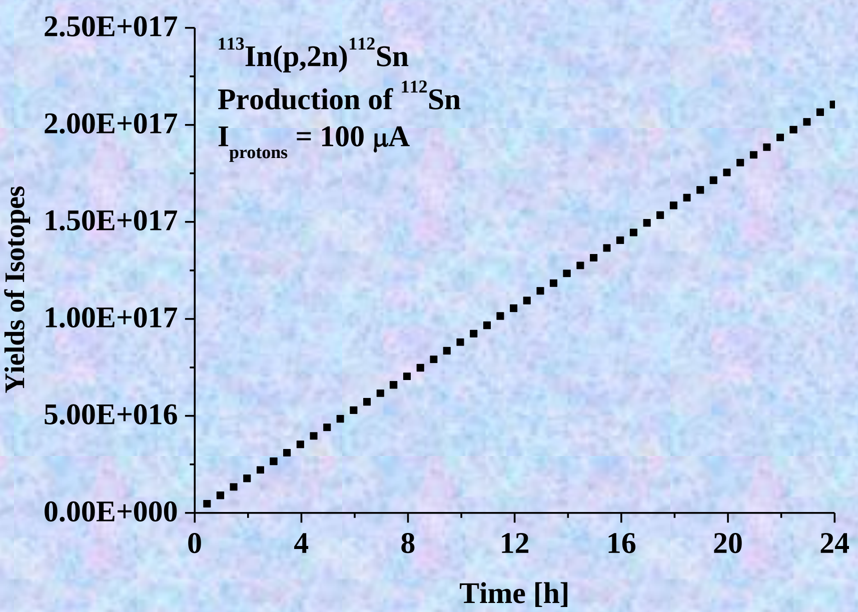
No experimental data

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



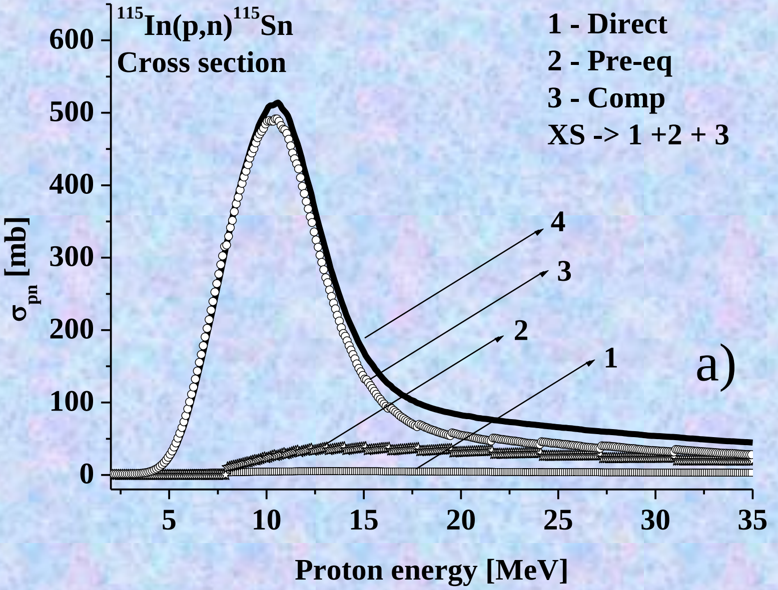


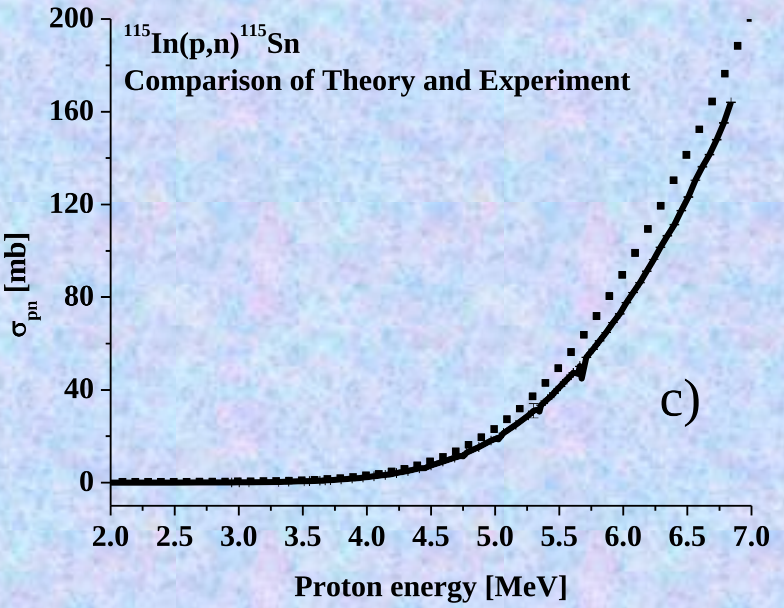
Production of ^{114}Sn for 1 μA and 100 μA protons beam intensity on a target of natural Indium

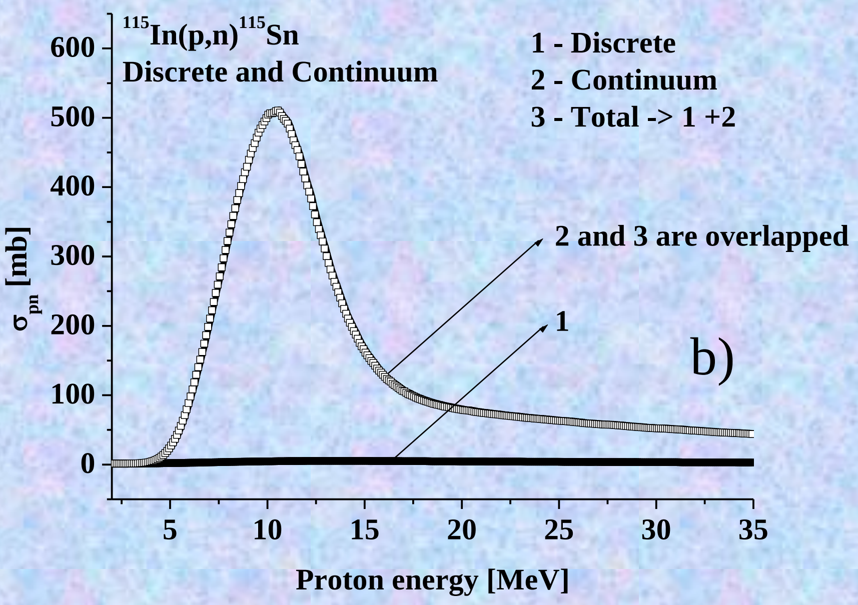
The concentration is enough to be measured because is higher then 1 ppm

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

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







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

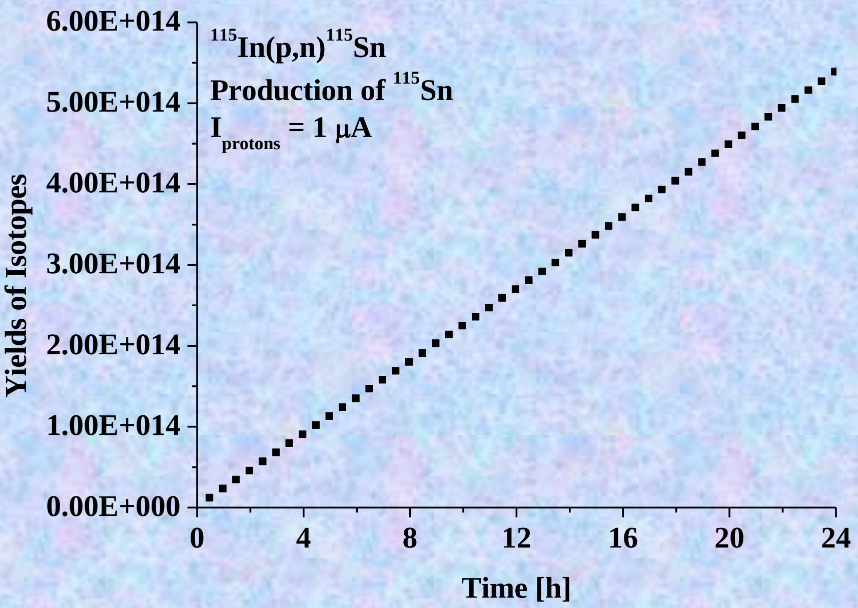
b) Contribution of Discrete and Continuum states of residual nuclei

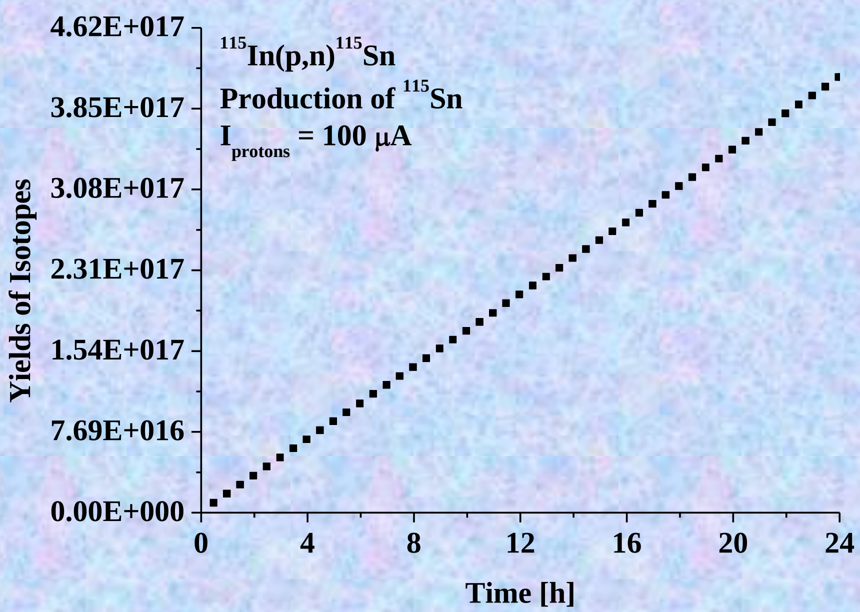
c) Comparison between Theory and Experiment

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



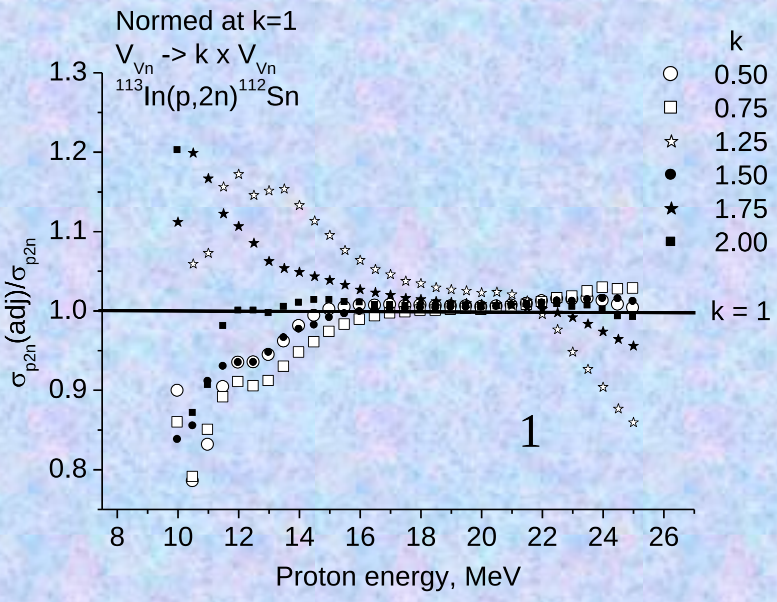


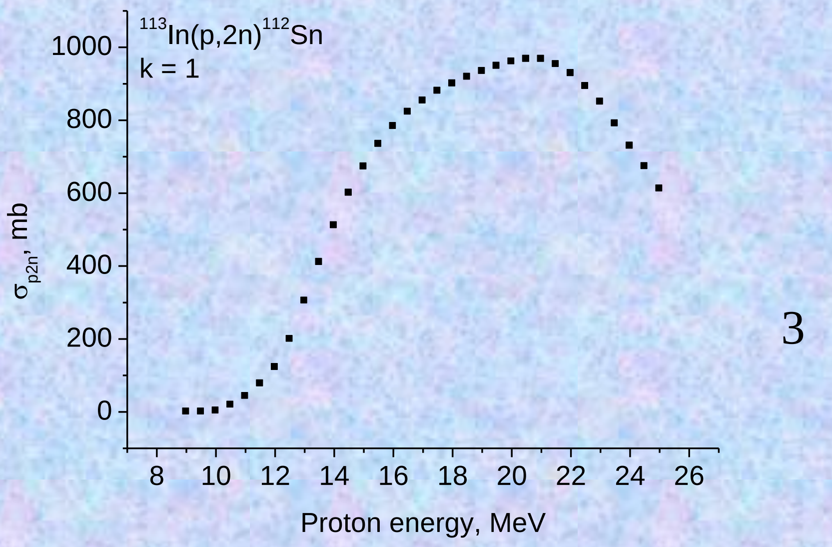
Production of ^{115}Sn in ^{115}In(p,n) process on a target of natural Indium irradiated with 1μA and 100 μA protons beam intensity, respectively

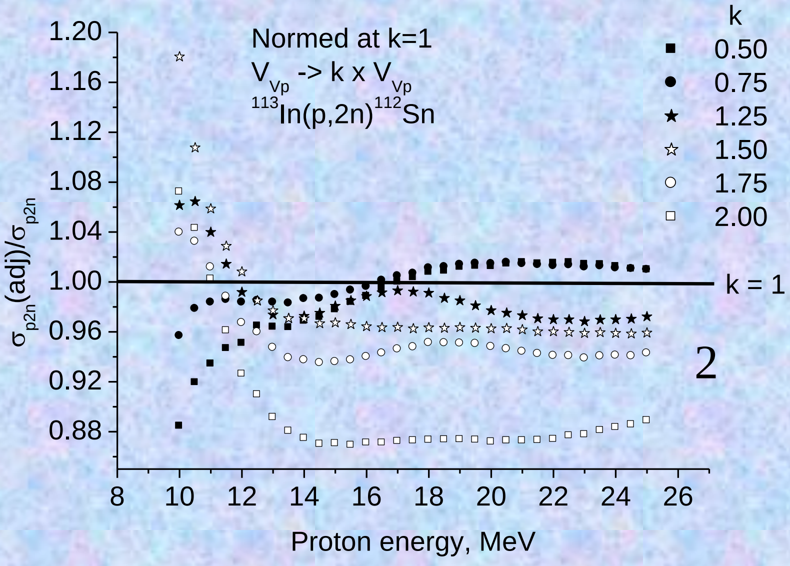
Target are of 1 cm^2, time of irradiation 24 h

As obtained, enough concentration of ^{115}Sn is produced for 100 μA.

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

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

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

5. Conclusions

Cross sections – Cross sections of ^{113}In(p,γ)^{113}Sn, ^{113}In(p,2n)^{112}Sn and ^{115}In(p,n)^{115}Sn reactions were investigated. Evaluations were realized in Talys and own computer programs. 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

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

Future tasks

To determine for each energy the contribution of nuclear reaction mechanisms based on experimental data

Improvements of Monte Carlo simulation for isotopes production

To use the present evaluations for the realization of nuclear networks for nuclear databases, astrophysics issues, etc.

New investigations of uncertainties

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

THANK YOU VERY MUCH FOR YOUR ATTENTION! ☺