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Cross sections of fast neutron reactions with emission of charged particles

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Structure of the presentation

1. Introduction
2. Theoretical background
3. Results and discussion

^{64}Zn(n,α)^{61}Ni

^{147}Sm(n,α)^{144}Nd

^{94}Mo(n,p)^{94}Nb

^{95}Mo(n,np)^{94}Nb

^{113}In(p,n)^{113}Sn

4. Conclusions

Cross Sections Evaluation in Nuclear Reactions with Fast Neutrons, A. Oprea, C. Oprea, Yu.M. Gledenov, P.V. Sedyshev, M.V. Sedysheva, Proceedings of the XXIII International Seminar on Interaction of Neutrons with Nuclei (ISINN22) FLNP - JINR, Dubna, RF, published 22 April 2015

1. Introduction

Precise nuclear data for:

- **Nuclear energy** – existing fission reactors ; future fusion reactors
- **Long lived radioactive waste**
- Reprocessing of U and Th (**Transmutation and Energy**)
- **ADS**
- **Fast Neutron Activation Analysis**

Fast Neutrons with Emission of Charged Particles

Neutron Data for Structural Material needed to estimate gas production by (n,p) and (n,α) reactions

Fast Proton Reactions

Cross Sections, Isotopes and **Isomer Production** and **Isomer Ratios** in (p,n) processes

2. Theoretical background

Cross Sections (XS) Evaluation

- XS calculated with Talys and also by the own computer programs (by Matematica 4.1)

Incident energy - from threshold up to 20 - 30 MeV with the contribution of:

- Direct Processes -> DWBA
- Compound Processes – >Hauser – Feshbach Formalism
- Pre - equilibrium – >Two Component Exciton Model

Nuclear Potential (implemented in Talys)

- Wood Saxon of type: Volume and Surface
- Spin Orbit Interactions
- Potential Parameters: Obtained from Nuclear Data Processing
    - Local with Real and Imaginary Part
    - Global with Parameters by Koning - Delaroche

Level Density – Constant Temperature Fermi Gas Model

2. Theoretical background

$$R = \frac{Y^m}{Y^g} =$$ Experimentally measured isomeric ratio

$$Y_m, Y_g =$$ Yields of isomeric and unstable ground states

General Expression

$$R = \frac{Y_m}{Y_g} = \frac{\int_{E_{th}}^{E_m} N_0 \phi(E) \sigma_m(E) dE}{\int_{E_{th}}^{E_m} N_0 \phi(E) \sigma_g(E) dE}$$

$E_{th} =$ Threshold energy of nuclear reaction

$E_m =$ Maximal energy of incident gamma quanta

$\phi =$ Flux of Incident Particles

$\sigma_{m,g} =$ Cross Sections of Isomer (*m*) and Ground (*g*) States Productions

2. Theoretical background

TALYS – Freeware soft working under LINUX – dedicated to nuclear reactions, fission and nuclear structure calculation

Possibility - to calculate inclusive and exclusive cross sections

Nuclear Reaction (binary) – X(x,y)Y

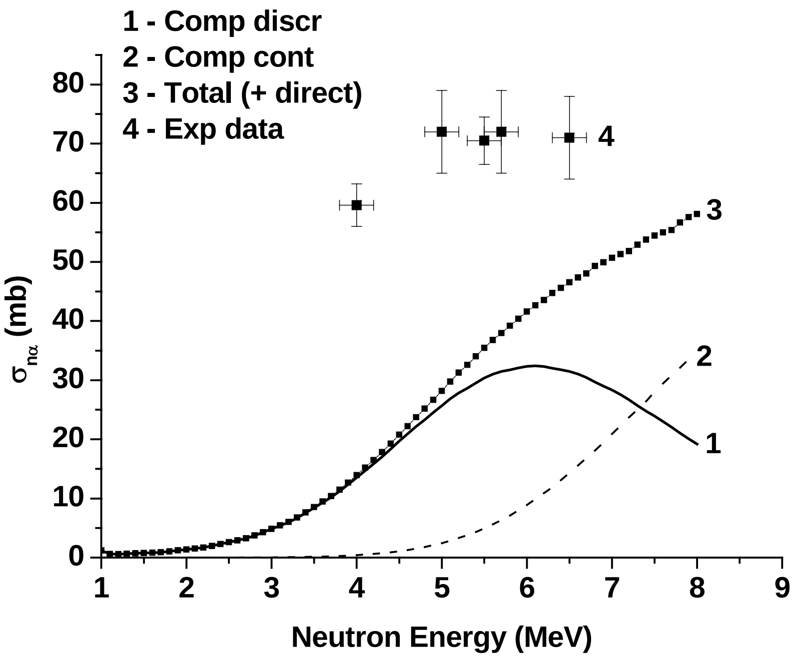
Inclusive cross section – including y particle from other open channels like

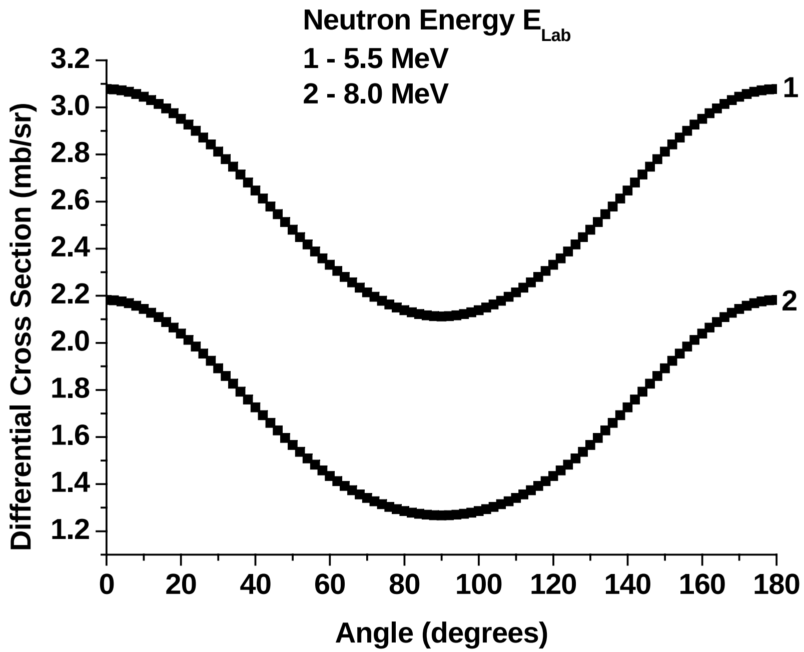
(x,ny), (x,2ny),…

Exclusive cross section – taking into account the y particle only from X(x,y)Y reaction

3. Results and Discussion

^{64}Zn(n,α)^{61}Ni – Fast Neutron Reaction





Cross section of $^{64}Zn(n,\alpha)^{51}Ni$ reaction

1- Contribution of the compound processes on discrete states of residual nucleus (10 levels);

2 – Contribution of the compound processes on continuum states of residual nucleus; 3 – Contribution of all processes; 4 – Experimental data (EG-5)

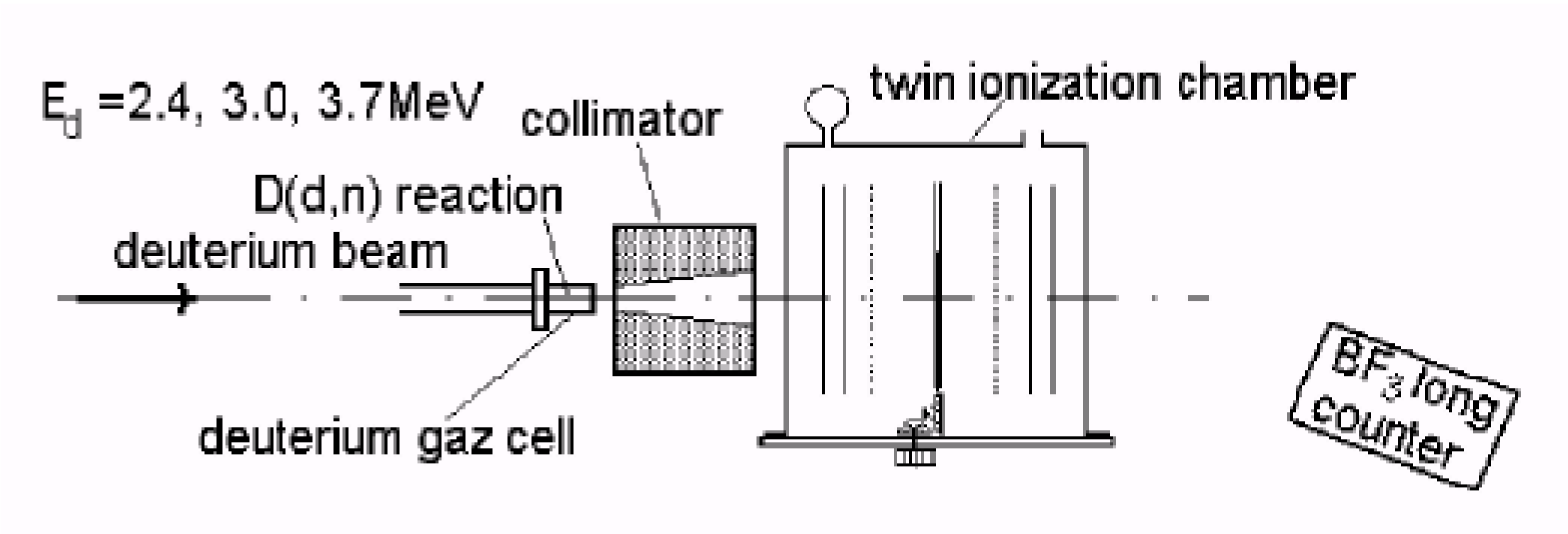
https://www-nds.iaea.org/exfor/servlet/X4sSearch5

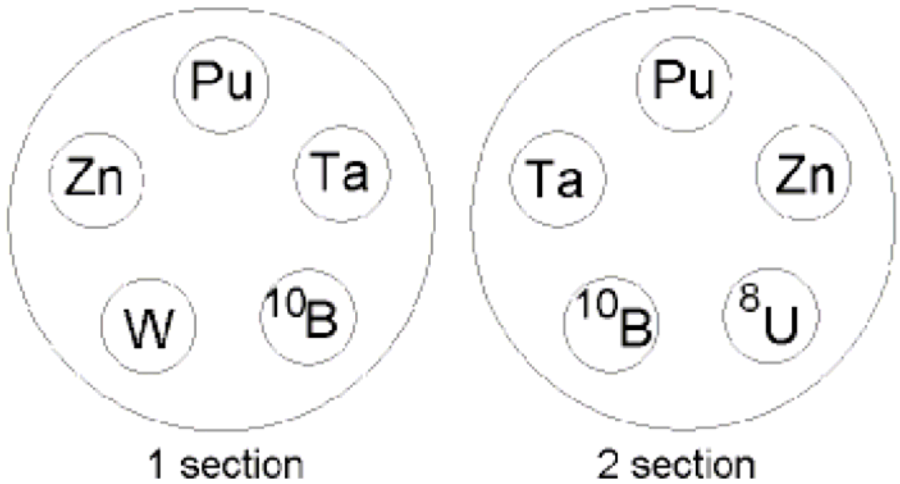
Differential cross section for $^{64}Zn(n,\alpha)^{51}Ni$ reaction: 1 – *5.5 MeV*,
2 – *8 MeV*

Compound processes are dominant

Cross section evaluation of the (n,α) reaction with fast neutrons on ^{64}Zn and ^{147}Sm nuclei using the Hauser - Feshbach approach, A. I. Oprea, C. Oprea, C. Pirvutoiu, D. Vladoiu, Romanian Reports in Physics, 63, 1, 107-114, 2011

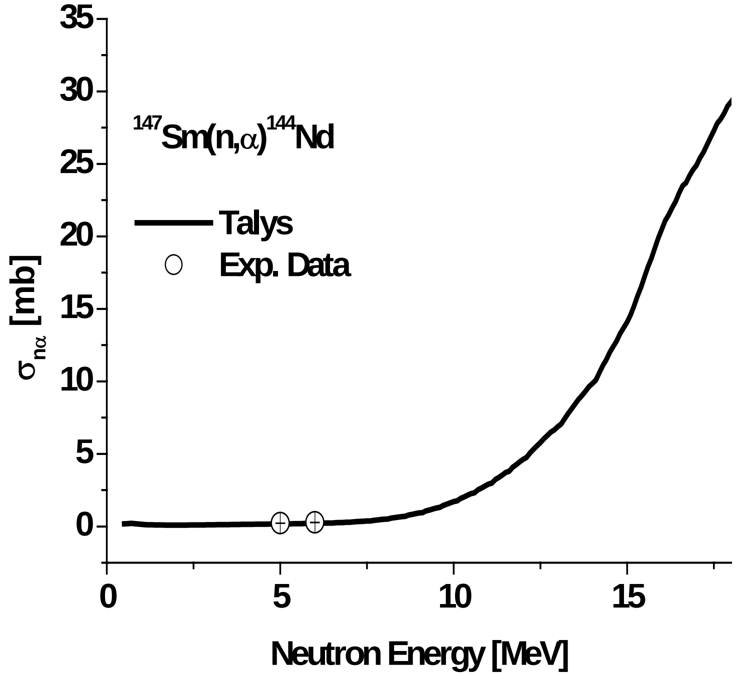
Experimental Setup – Double Grid Ionization Chamber – FLNP - JINR EG-5

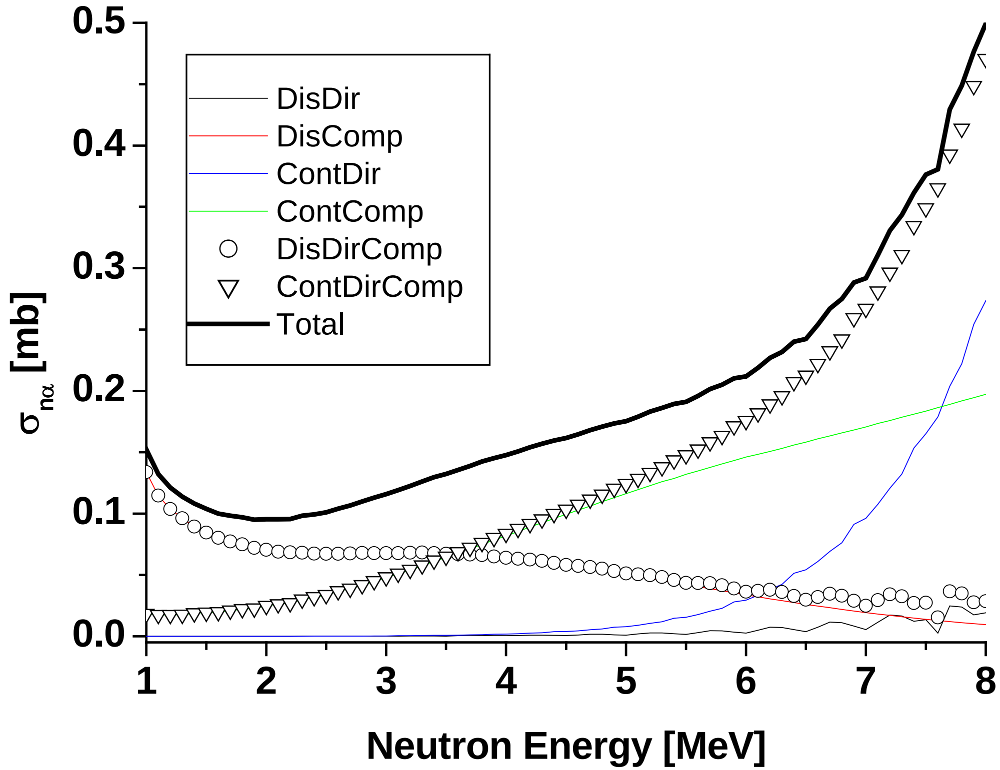




Rotating platform for
target near the cathode

$^{147}Sm(n,\alpha)^{144}Nd$ with fast neutrons. Cross Sections





Energy dependence of (n,alpha) cross section (Talys) and 2 experimental data (EG-5)

Direct processes on discrete states
Compound processes on discrete states
Direct on continuum
Compound on continuum

(contribution of different reaction mechanisms combined with continuum and discrete states of residual nuclei)

Neutron capture cross sections and strength functions of ^{147}Sm from slow - up to 14 MeV neutron, C. Oprea, A. I. Oprea, Report at the Annual Conference on Physics, Faculty of Physics, University of Bucharest, Bucharest Romania, 23-24 June 2017 (in press)

$^{147}Sm(n,\alpha)^{144}Nd$ with fast neutrons. Direct and Compound

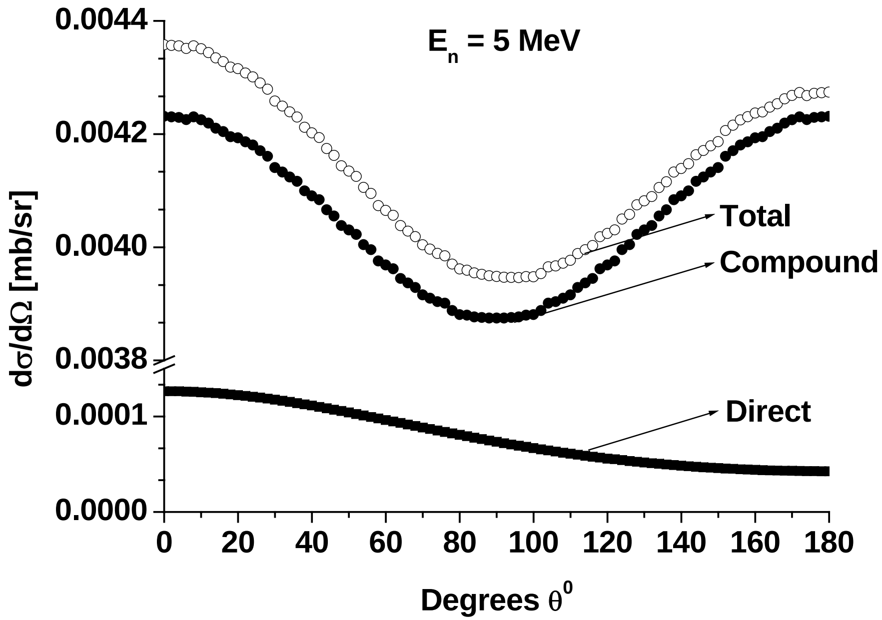
E_n [MeV]	$\sigma_{n\alpha}$ Direct [mb]		$\sigma_{n\alpha}$ Compound [mb]	
	Discr	Cont	Discr	Cont
5	0.00097	0.00787	0.05023	0.11627
6	0.00248	0.02951	0.03379	0.14606

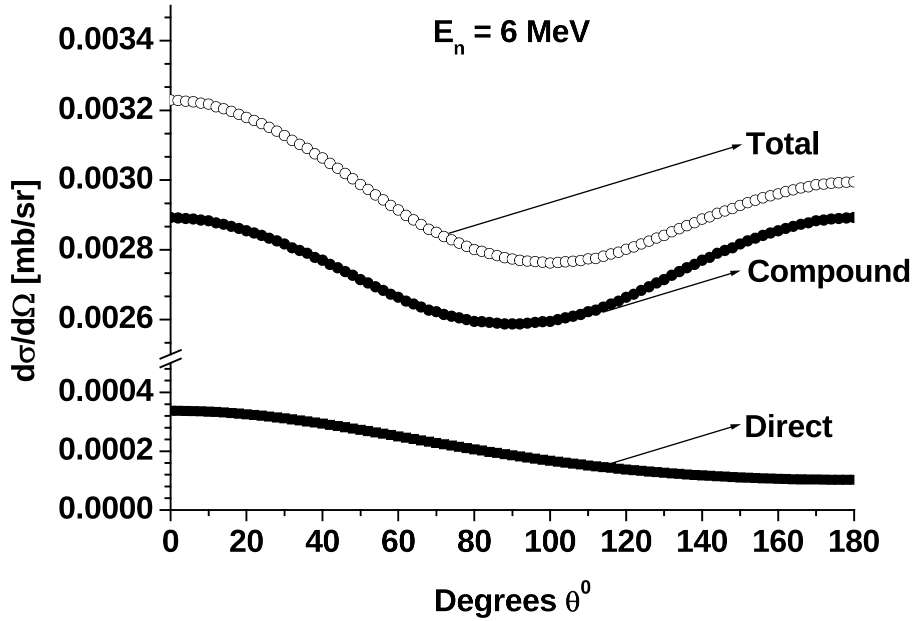
Talys evaluation
Wood –Saxon potential
- all components
Default Talys
V = 225 MeV
W = 0.15 MeV

E_n [MeV]	$\sigma_{n\alpha}$ [mb]
5	0.1754
6	0.2118

- Good description of experimental data
- More experimental data are necessary

$^{147}Sm(n,\alpha)^{144}Nd$. Differential Cross Sections. Asymmetry Effects





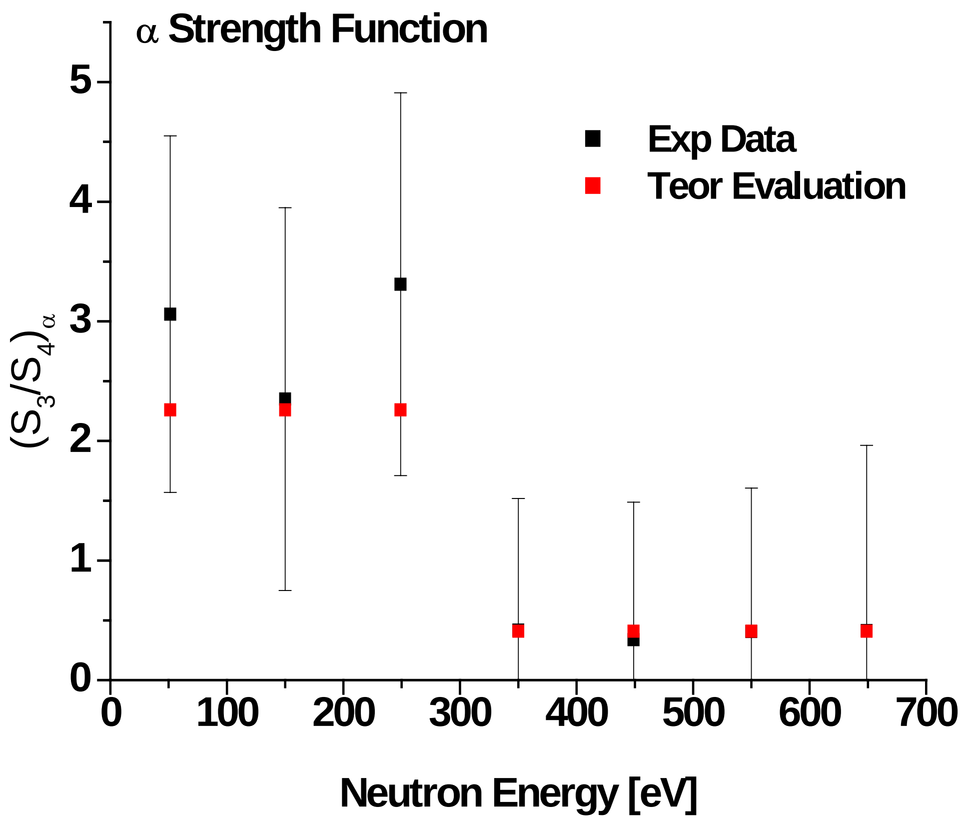
Compound processes are dominant
Measured FB ratio (exp) compared with Talys evaluation
Relevant discrepancy
Need further analyses
Possible:
Systematic errors from measurements
A higher direct component

Forward / backward ratio

E_n [MeV]	S_F/S_B (Talys)	$(S_F/S_B)_{exp}$
5	1.0122±0.0096	1.65±0.165
6	1.0436±0.0127	2.54±0.254

Search of parity violation effects in neutron reactions on natural Lead, A. Oprea, C. Oprea, Yu.M. Gledenov, P. V. Sedyshev, Romanian Reports in Physics, 66, 4, 952-962, 2014

$^{147}Sm(n,\alpha)^{144}Nd$. α Strength function / non - statistical effects



Strength functions

$$S = \frac{T}{2\pi} = \frac{\langle \Gamma \rangle}{D}$$

<Γ> - Averaged width

D - Averaged level spacing

T – Penetrability Coefficient   *S* = constant

Measured *S_3/S_4 – not constant*

α Strength funct.Corresponding to Comp. Nucl. Spin J = 3,4 ; S_3/S_4 has a serious change at 300 eV -> Non Statistical Effects ?

Conditions

described by our soft

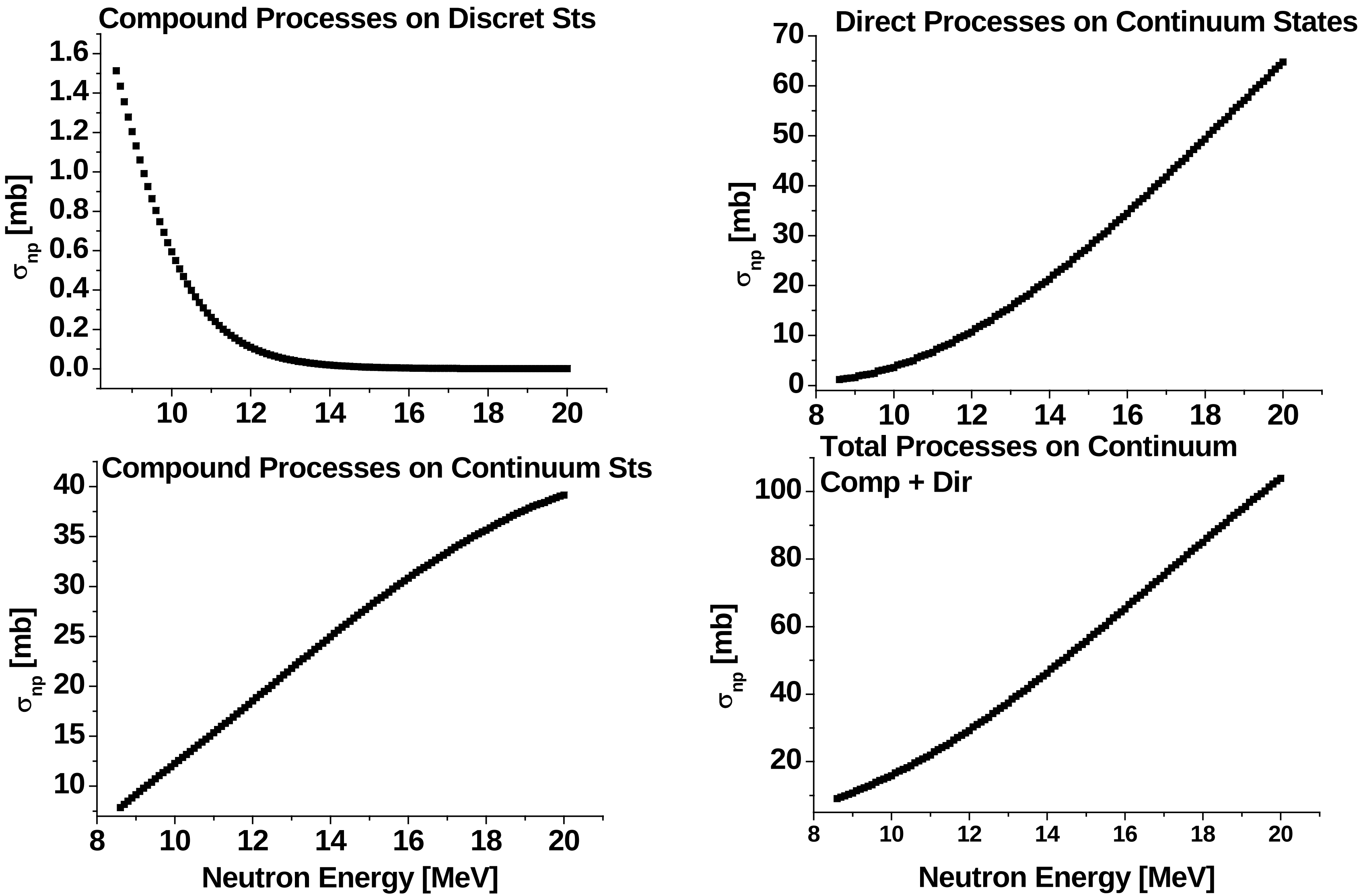
U = V + IW = (225 + I 0.45) MeV

$R = kR_0A^{(1/3)}$; k = factor

1) $E_n < 300$eV; k = 0.9

2) $E_n > 300$eV; k = 0.823

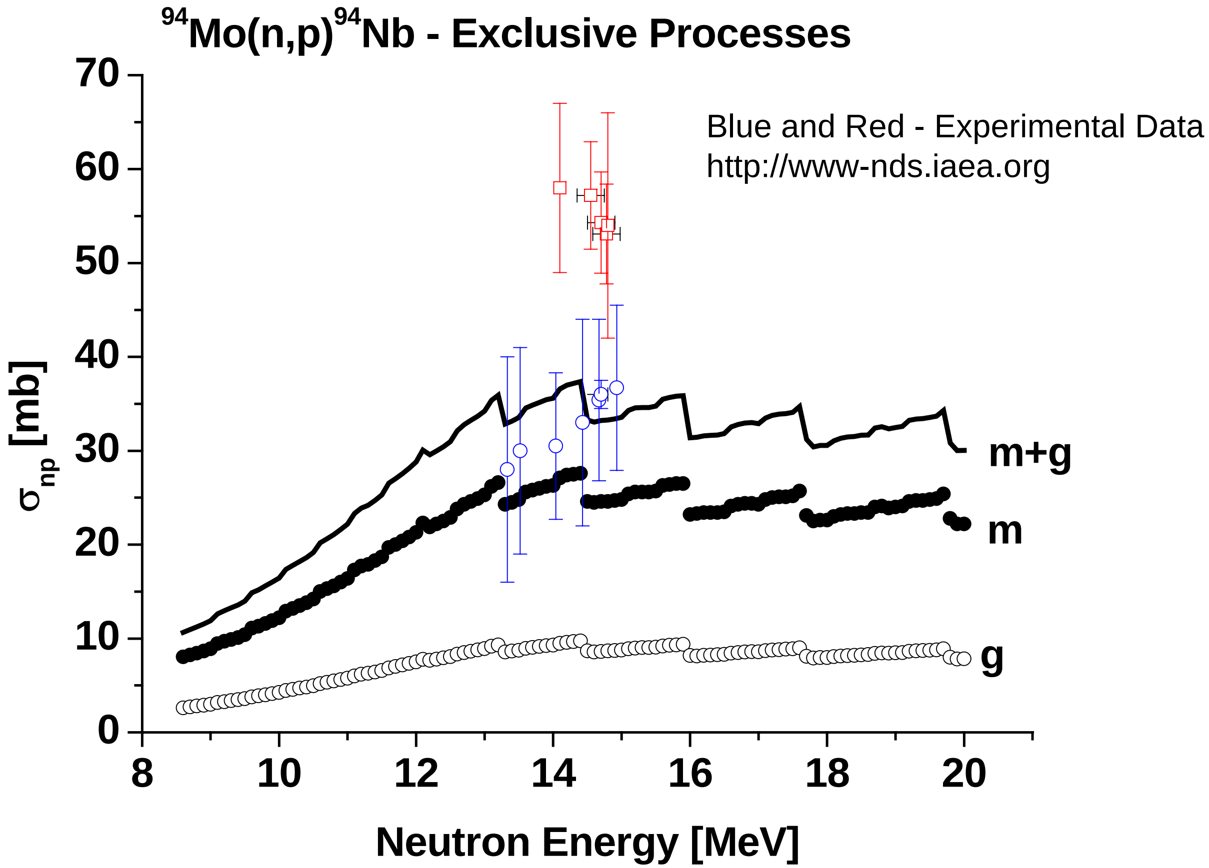
^{94}Mo(n,p) - Inclusive Processes



Nuclear reactions with 14 MeV neutrons on Molybdenum isotopes, Romanian Reports in Physics (accepted 07 July 2017)

Neutron induced cross sections of 14.1 MeV tagged neutron reactions leading to activation products, SAAGAS 26 VIENNA, 19 – 22 February 2017

EXCLUSIVE REACTIONS



PRODUCTION OF:

- ^{94}Nb nucleus in isomer and ground state (m, g)

Standard Talys Input:
- Potentials
- Density Levels

Experimental Data:
- Well described
- Further analysis of experimental data and adjustments of Talys Input Parameters

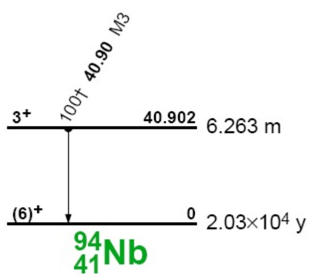
Cross Sections of isomer and ground states of ^{94}Nb

Isomer Ratio

R = 2.852 ± 0.013 – Incident Neutron Flux =1

R = 2.860 ± 0.010 – Incident Neutron Flux ~1/E$^{0.9}$(IREN, IBR-30)

Gamma Transitions E_γ = 0.0409 MeV



Exclusive reactions. Talys potential parameters

Cross sections evaluation realized with standard input of Talys

Wood – Saxon potential parameters – $^{94}Mo(n,p)^{94}Nb$
n + ^{94}Mo channel

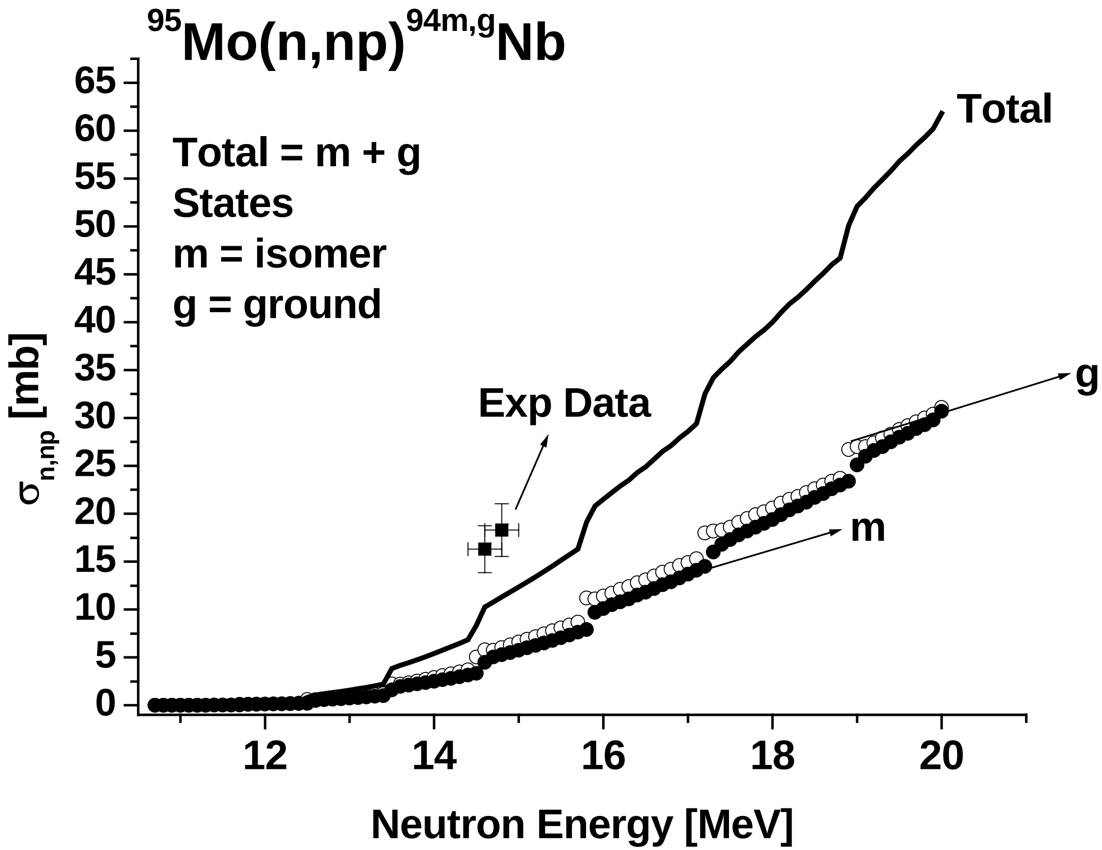
V [MeV]	r_v [fm]	a_v [fm^{-1}]	W [MeV]	r_w [fm]	a_w [fm^{-1}]	V_{so} [MeV]	r_{vso} [fm]	a_{vso} [fm^{-1}]
50.99	1.22	0.658	0.16	1.22	0.658	5.99	1.05	0.58

p + ^{94}Nb channel

V [MeV]	r_v [fm]	a_v [fm^{-1}]	W [MeV	r_w [fm]	a_w [fm^{-1}]	V_{so} [MeV	r_{vso} [fm]	a_{vso} [fm^{-1}]
61.94	1.215	0.664	0.13	1.215	0.664	6.03	1.043	0.59

Another way of ^{94}Nb production

^{94}Nb isotopes – obtained by ^{95}Mo(n,np)^{94}Nb reaction
An analysis of Inclusive and Exclusive Reactions was realized
Only the main results on Exclusive Reactions were presented



Experimental Data – EXFOR http://www-nds.iaea.org

Concurrence between Direct and Compound Processes of pre – Equilibrium origin mainly

XS close to ^{94}Mo(n,p)

High Energy part dominated by Direct Processes ->

Isomer Ratio

- Neutron Flux =1

R = 0.927 ±0.019

- Neutron Flux ~ 1/E$^{0.9}$

R = 0.923 ±0.018

Exclusive reactions. Talys potential parameters

Cross sections evaluation realized with standard input of Talys
Wood – Saxon potential parameters – $^{95}Mo(n,np)^{94}Nb$
n + ^{95}Mo channel

V [MeV]	r_v [fm]	a_v [fm^{-1}]	W [MeV	r_w [fm]	a_w [fm^{-1}]	V_{so} [MeV]	r_{vso} [fm]	a_{vso} [fm^{-1}]
51.27	1.215	0.664	0.16	1.215	0.664	5.99	1.044	0.59

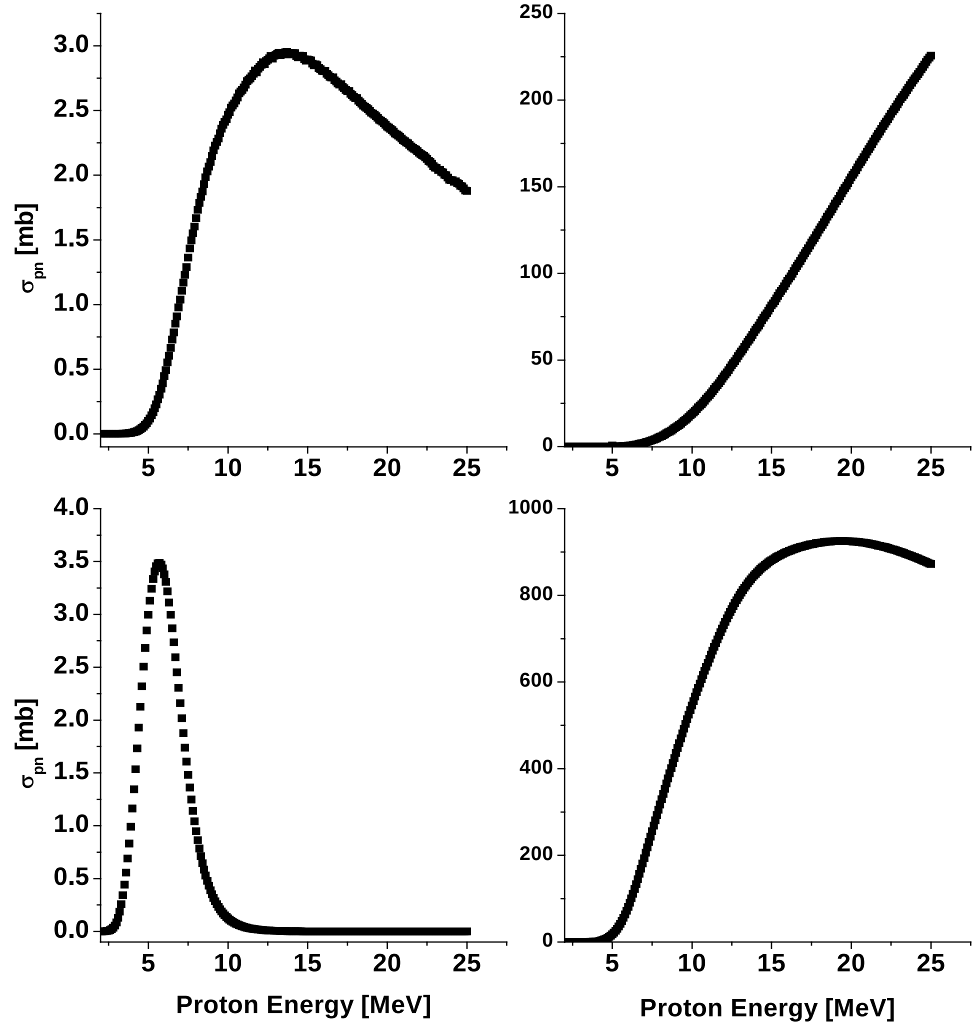
p + ^{94}Nb channel

V [MeV]	r_v [fm]	a_v [fm^{-1}]	W [MeV]	r_w [fm]	a_w [fm^{-1}]	V_{so} [MeV]	r_{vso} [fm]	a_{vso} [fm^{-1}]
62.10	1.215	0.664	0.13	1.215	0.664	6.03	1.044	0.59

Inclusive XS. ^{113}In(p,n) ^{113}Sn

Inclusive ^{113}In(p,n) Reaction
Direct Processes on Discrete

Inclusive ^{113}In(p,n) Reaction
Direct Processes on Continuum



Inclusive ^{113}In(p,n)^{113}Sn Reaction
Compound Processes on Discrete

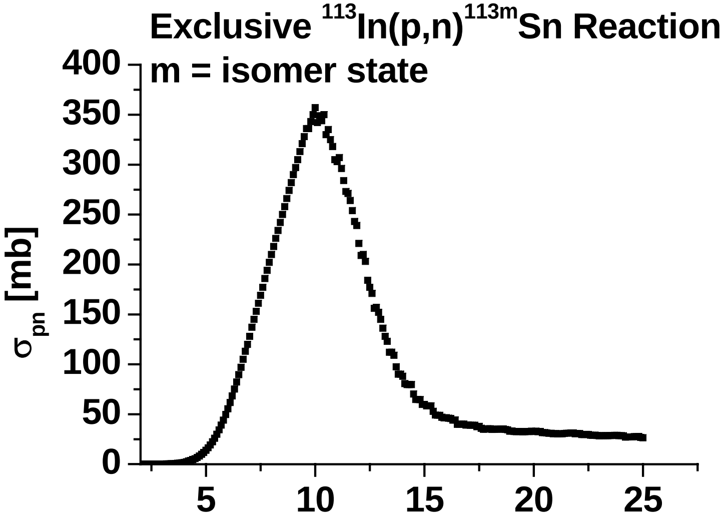
Inclusive ^{113}In(p,n) Reaction
Compound Processes on Continuum

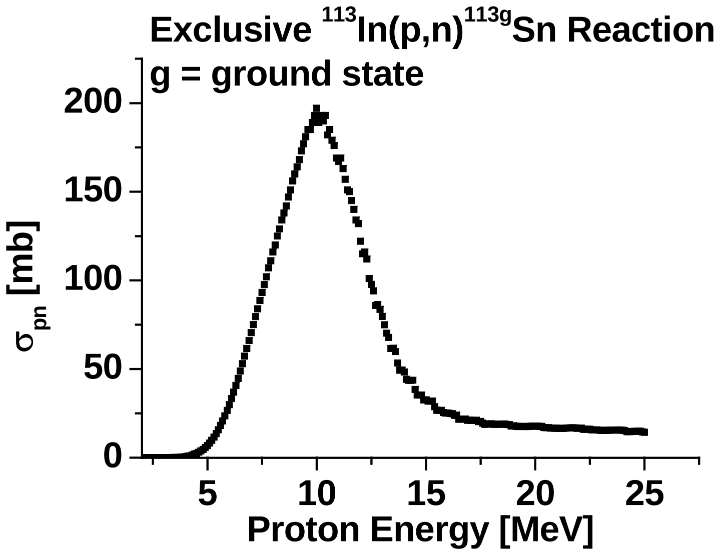
Inclusive XS
- All Figures

Compound processes on continuum states are majoritary followed by direct processes on continuum states
-Contributions of discrete states can be neglected

Importance
Fundamental research
Production of ^{113}Sn with magic number of neutrons

Exclusive Cross section. $^{113}In(p,n)^{113m,g}Sn$

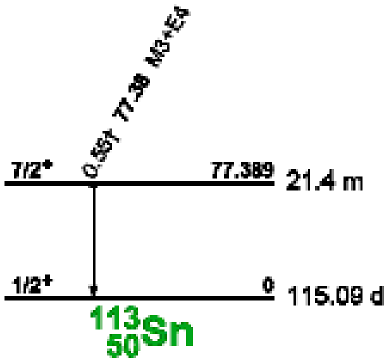




Exclusive Cross Section

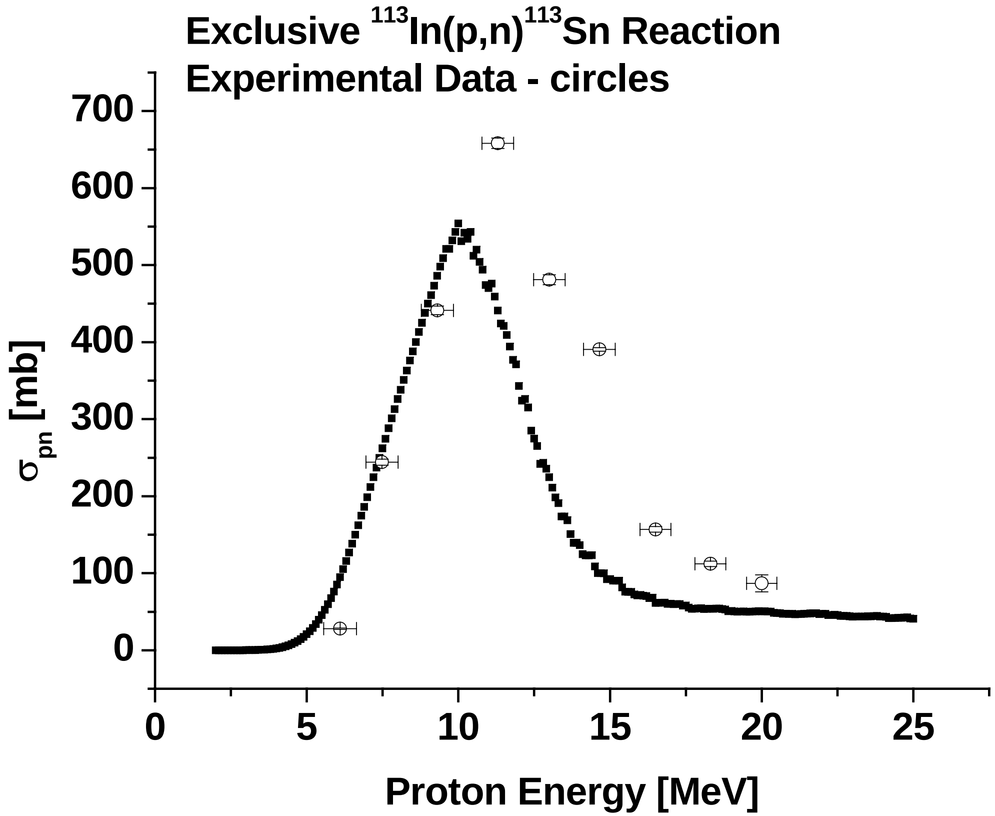
- In our case (p,n)
- All neutrons were measured only from $^{113}In(p,n)^{113}Sn$
- These cross sections are used for isomer ratio calculation according with the relation

$$R = \frac{Y_m}{Y_g} = \frac{\int_{E_{th}}^{E_m} N_0 \phi(E) \sigma_m(E) dE}{\int_{E_{th}}^{E_m} N_0 \phi(E) \sigma_g(E) dE}$$



Isomer ratio of ^{113}Sn in fast protons induced reactions, C. Oprea, A. I. Oprea, I. Gruia, Romanian Reports in Physics (in press, accepted August 2015)

Total ^{113}Sn nucleus production. Experimental data



Exclusive XS

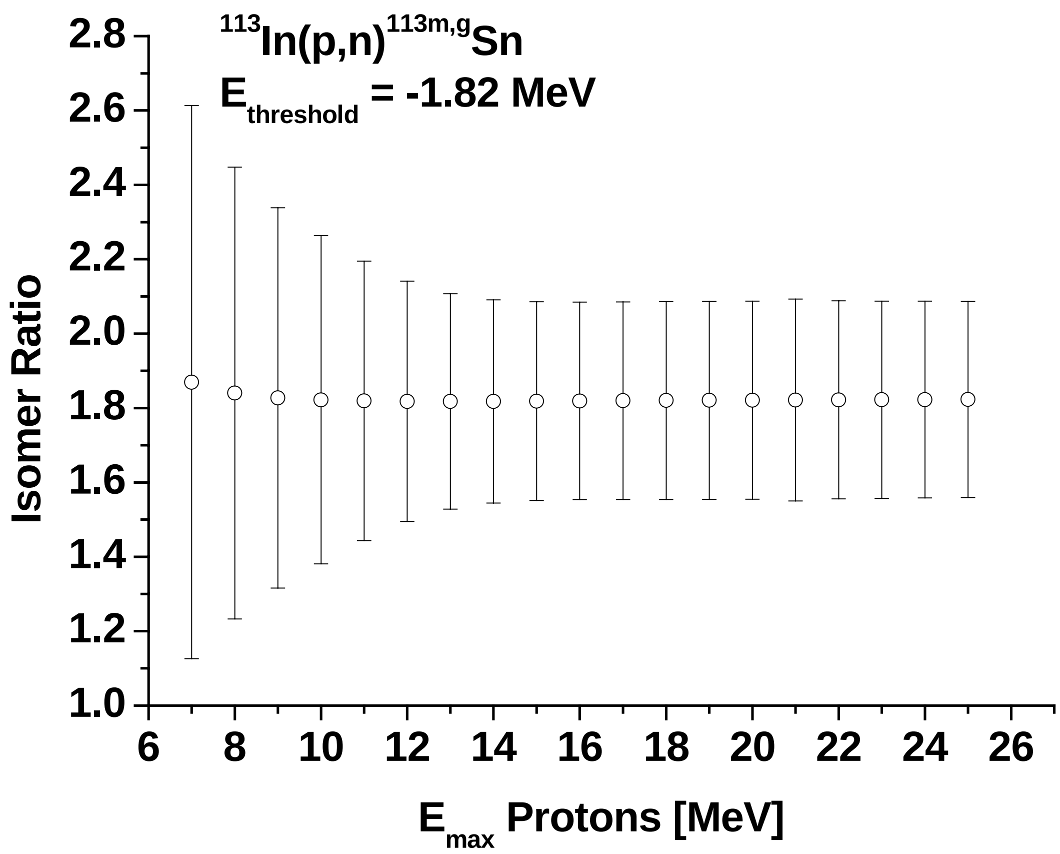
- The low energy part is well described using standard Talys input with neutrons and protons potential
- Main contribution is given by Compound Processes in the low energy part

From the previous figures one can see that the direct processes on continuum states are also important with the increasing of incident energy of protons

- The shape of the cross section is the same in the theory and experiment
- As the ground and isomer XS are satisfactorily described it is possible to evaluate the isomeric ratio

Experimental Data – EXFOR http://www-nds.iaea.org

Evaluated Isomeric Ratio



Incident proton flux

$$\phi(E_p) = 1$$

Ep[MeV]	R	ΔR
8	1.84025	0.6074
9	1.82725	0.51136
10	1.82214	0.44122
11	1.81905	0.37567
12	1.81792	0.32299
13	1.81775	0.28953
14	1.81791	0.2733
15	1.81841	0.26719
16	1.81898	0.26551
17	1.81956	0.26552
18	1.8201	0.26594
19	1.82062	0.26603
20	1.82109	0.26628
21	1.82155	0.27157
22	1.82193	0.26657
23	1.82231	0.26517
24	1.82266	0.26453
25	1.82299	0.26388

4. Conclusions

This study demonstrates the possibility to obtain a wide range of data (as cross sections, nuclear structure data, isomer ratio, asymmetry effects) for theoretical and applied researches which can be included in databases.

Results of analyzed nuclear reactions are in a good agreement with existing experimental data.

Provide new nuclear data, not evaluated yet, necessary for the preparation of new experiments

In a similar way, we analyzed other nuclear processes like:
- (γ,n) on Sm and Sn isotopes
- (γ,p), (γ,α) on Sm isotopes
- neutron and gamma induced fission on $^{235,238}U$

Talys – a powerful instrument in the analysis of nuclear reactions for:
- fundamental researches -> nuclear reaction mechanism and atomic nuclei structure, nuclear data
- applicative researches -> material sciences for nuclear reactor construction, nuclear data, astrophysics, fast neutron activation analysis, tagged neutron methods, etc

4. Conclusions

Present Results

- Nuclear Data Program at FLNP JINR Facilities
- FLNP Facilities: Electrostatic Generator EG-5, Pulsed Neutron Source IREN, Reactor IBR-2
- FLNP Staff: large and traditional experience in nuclear physics with neutrons

Nuclear Data Program at IREN

Fundamental Researches

- Parity violation research in nuclear reactions induced by neutrons
- Electromagnetic structure of the neutron
- Quantum aspects of neutrons induced fission
- Phase transitions in excited nuclei

Applied Researches

- Nuclear data for astrophysics and technology
- Isotope analysis with neutrons
- Neutron Activation Analysis
-Tagged neutrons method

Educational Activities

- Traditionally Bachelor, Master and PhD Programs in collaboration with Institutes and Universities from Russia, member states and abroad.


THANK YOU VERY MUCH
FOR YOUR ATTENTION! ☺