Isomers Production of Sn Nucleus in Nuclear Reactions Induced by Photons and Fast Protons

C. Oprea, A. I. Oprea

Frank Laboratory for Neutron Physics, Joint Institute for Nuclear Research

Abstract. The isotopes of Sn can be obtained in the nuclear reactions of type (p,n) on Indium nucleus and in photoneutron processes on Sn nucleus. The cross sections of (p,n) and (γ, xn) processes were evaluated and compared with experimental data. For each reaction was evaluated the contribution of compound, direct and pre – equilibrium processes and extracted also the parameters of nuclear potentials and other nuclear data. It was obtained a quite good agreement between existing experimental data and present evaluations and therefore we have calculated the isomer ratios using different models of incident gamma and protons sources. We have also analyzed the possibility to effectuate experiments on cross sections and isomer ratios measurements at LNF JINR Dubna basic facilities.

OUTLINE

1. Introduction

2. Theoretical background

3. Results
- Fast Protons on Indium
- Photons on Sn

4. Discussion and Conclusions

Introduction. In Nucleus

Natural Indium. Isotopes

^{113}In – 4.29% ; ^{115}In – 95.71%

^{113}In – Fundamental state – $J^{\Pi} = \left(\frac{9}{2}\right)^{+}$

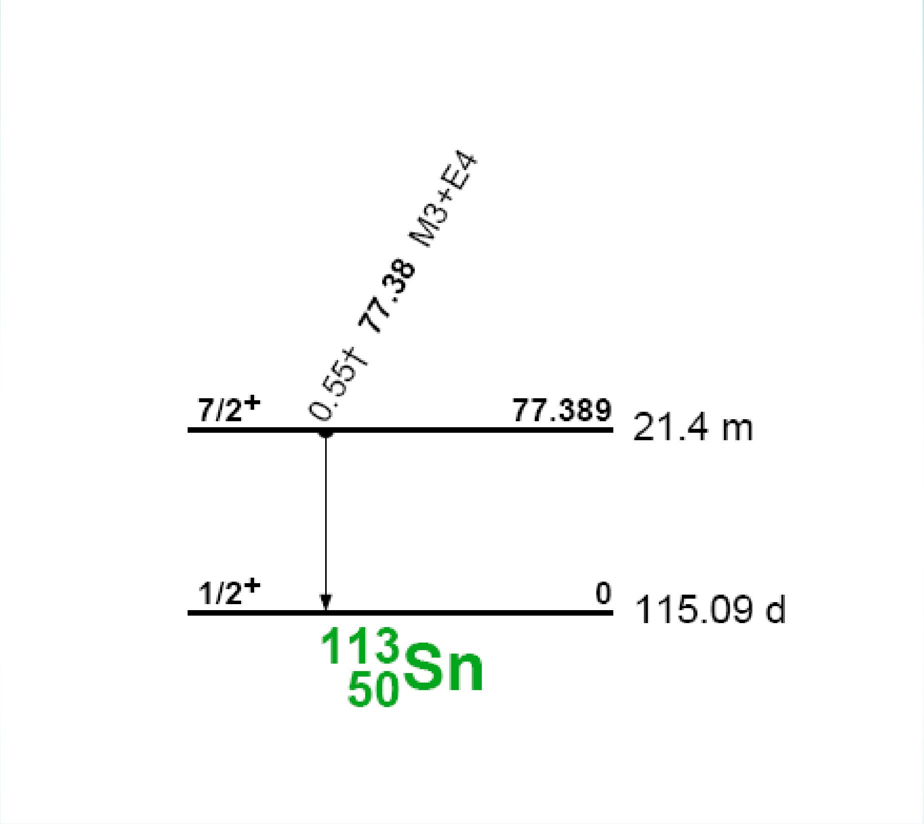
Nuclear Reactions With Fast Protons – Source of Isomer States

Analyzed Reactions

- ^{113}In(p,n)^{113m,g}Sn
- Q=-1.82 MeV

E_{th}=1.836 MeV

^{113m,g}Sn nucleus



Introduction. Sn Nucles

Natural Stanium. Isotopes

The atomic masses (*A*) and abundances (%) (*M-%*):

112-0.96% 114-0,66 %, 115-0,35 %, 116-14,30 %, 117-7,61 %, 118-24,03 %, 119-8,58 %, 120-32,85 %, 122-4,72 %, 124-5,94 %

Cross section and isomeric ratio analyzed with Talys

	Reaction	Isotope	Isomeric Ratio R	Isomer (m)		Ground (g)	
				J^{π}	τ_m	J^{π}	τ_m
1	$^{114}Sn(\gamma,n)^{113m,g}Sn$	^{113}Sm	Y^{113mSn}/Y^{113gSn}	$(7/2)^+$	21.40 m	$(1/2)^+$	115.9d
2	$^{118}Sn(\gamma,n)^{117m,g}Sn$	^{117}Sm	Y^{117mSn}/Y^{117gSn}	$(11/2)^-$	13.60 d	$(1/2)^+$	stable
3	$^{120}Sn(\gamma,n)^{119m,g}Sn$	^{119}Sm	Y^{119mSn}/Y^{119gSn}	$(11/2)^-$	293.1 d	$(1/2)^+$	stable
4	$^{122}Sn(\gamma,n)^{121m,g}Sn$	^{121}Sm	Y^{121mSn}/Y^{121gSn}	$(11/2)^-$	55.00 y	$(3/2)^+$	27.06 h
5	$^{124}Sn(\gamma,n)^{123m,g}Sn$	^{123}Sm	Y^{123mSn}/Y^{123gSn}	$(3/2)^+$	40.60 m	$(11/2)^-$	129.2 d

Theoretical background. Cross Section

To evaluate the Isomer Ratio -> Cross Sections are necessary

-CS calculated with Talys

- CS – in the energy interval of incident protons up to 25 MeV were calculated the contribution of:

- Direct Processes -> DWBA

- Compound Processes – >Hauser – Feshbach Formalism

- Preequilibrium – >Two Component Exciton Model

Levels Density – Constant Temperature Fermi Gas Model

Theoretical background. Isomeric ratio

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

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

$\sigma^{m,g} =$ cross section production of isomer (m) and ground (s) states

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

Isomeric ratio

- in literature

$$R = \frac{\sigma^m}{\sigma^g}$$

$$R_{Talys} = \frac{\sigma^m}{\sigma^g + \sigma^m}$$

Incident particles = proton, gamma

$E_{inc} =$ Energy of incident particle

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

$E_m =$ Maximal energy of incident particles

Theoretical background. Talys

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

Theoretical background. Talys. Wood Saxon Potential (I)

Phenomenological Optical Model Potential – Nucleon + Nucleus

Local and Global Parameterisation – Koning and Delaroche

$$U(r,E) = -V_V(r,E) - iW_V(r,E) - iW_D(r,E) + V_{SO}(r,E)\vec{l}\cdot\vec{\sigma} +$$

$$+ iW_{SO}(r,E)\vec{l}\cdot\vec{\sigma} + V_C(r,E)$$

$$V_V(r,E) = V_V(E)f(r,R_V,a_V) =$$ Real Volume Central

$$W_V(r,E) = W_V(E)f(r,R_V,a_V) =$$ Imaginary Volume Central

$$W_D(r,E) = -4a_D W_D(E)\frac{d}{dr}f(r,R_D,a_D) =$$ Surface Central

$$V_C(r,E) = \begin{cases} \dfrac{zZe^2}{R_C}, r > R_C \\ \dfrac{zZe^2}{2R_C}\left(3 - \dfrac{r^2}{R_C^2}\right), r \le R_C \end{cases} =$$ Coulomb Potential

Theoretical background. Talys. Wood Saxon Potential (II)

Phenomenological Optical Model Potential – Nucleon + Nucleus

Local and Global Parameterisation – Koning and Delaroche

$$U(r,E) = -V_V(r,E) - iW_V(r,E) - iW_D(r,E) + V_{SO}(r,E)\vec{l}\cdot\vec{\sigma} +$$

$$+ iW_{SO}(r,E)\vec{l}\cdot\vec{\sigma} + V_C(r,E)$$

$$V_{SO}(r,E) = V_{SO}(E)\left(\frac{\hbar}{m_\pi c^2}\right)\frac{1}{r}\frac{d}{dr}f(r,R_{SO},a_{SO}) =$$ Real Spin Orbital

$$W_{SO}(r,E) = W_{SO}(E)\left(\frac{\hbar}{m_\pi c^2}\right)\frac{1}{r}\frac{d}{dr}f(r,R_{SO},a_{SO}) =$$ Imaginary Spin Orbital

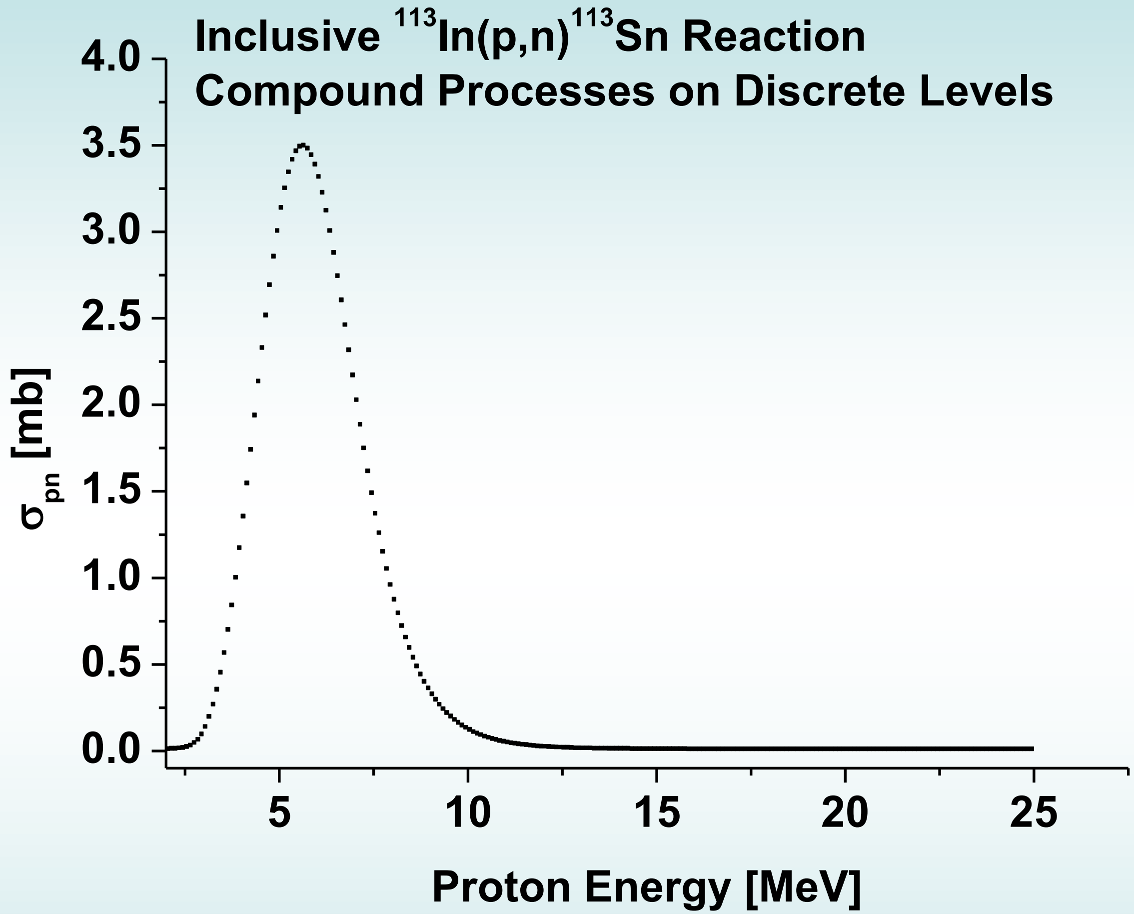
$$f(r,R_i,a_i) = \frac{1}{1+Exp\left(\frac{r-R_i}{a_i}\right)} =$$ WS Shape

$R_i = r_i A^{\frac{1}{3}} =$ Radius

$A =$ Nucleus Mass

$a =$ Diffuseness Parameter

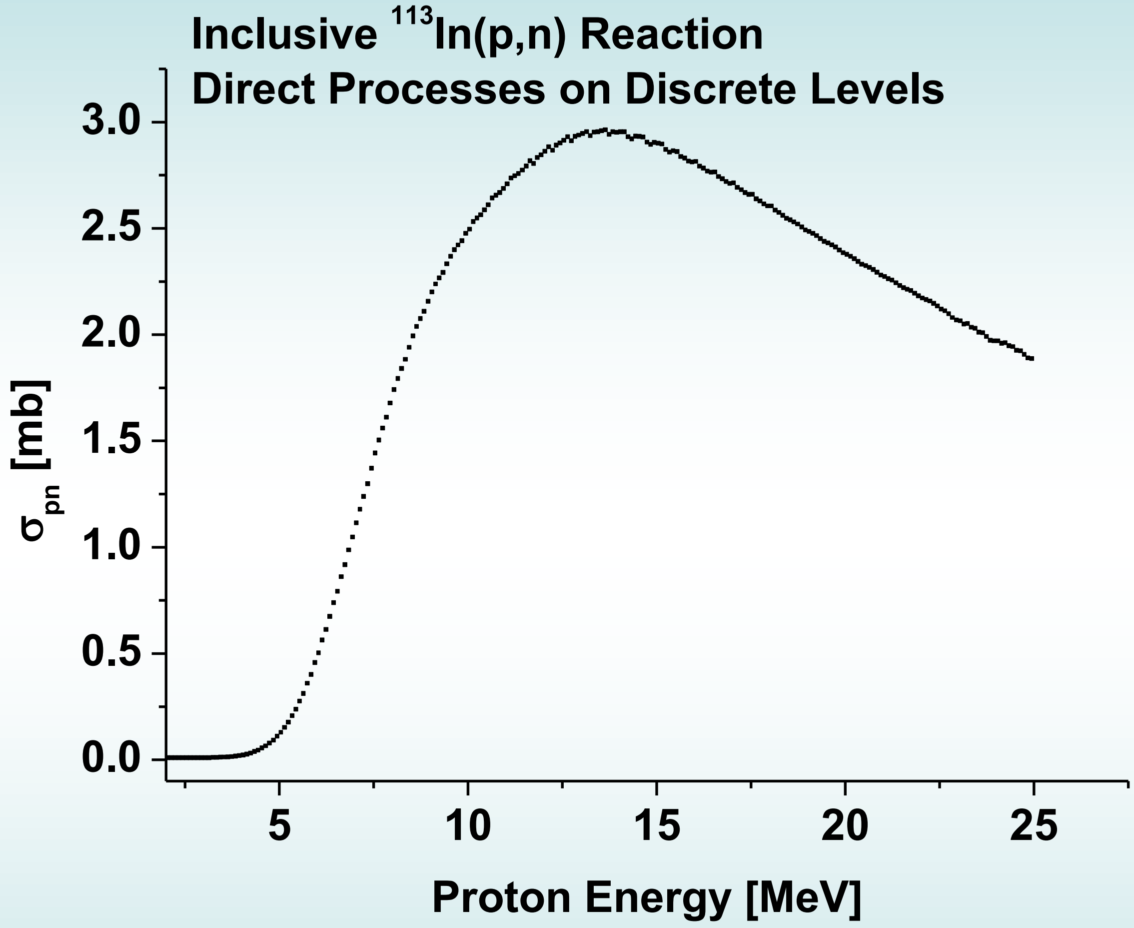
Results. Inclusive Cross section. ^{113}In(p,n)



Inclusive Cross Section

- In our case (p,n)
- Measured all neutrons not only from ^{113}In(p,n)^{113}Sn but also the neutrons from other reactions like (p,2n), (p,np), (p,2np), (p,n2p), (p,3n), …..
- These reactions are opening with the increasing of the incident protons energy
- Low contribution of Discrete States

Results. Inclusive Cross section. ^{113}In(p,n)

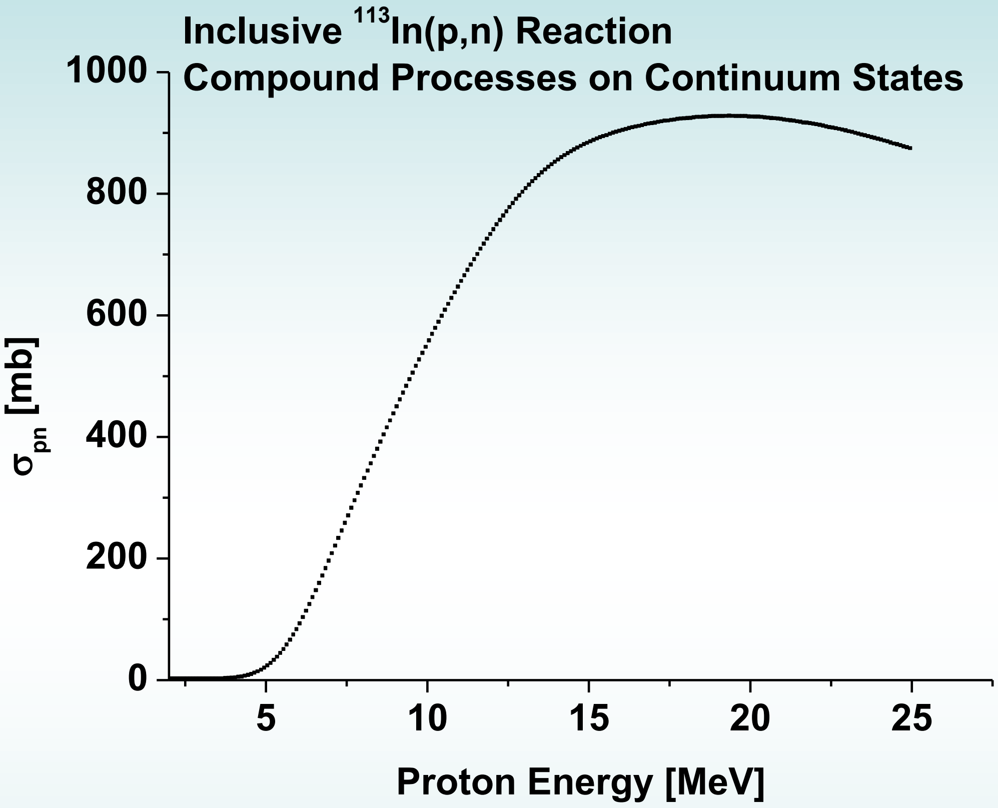


Inclusive Cross Section

- Also low contribution of Discrete States

- Taking into account the first 10 levels of residual nucleus

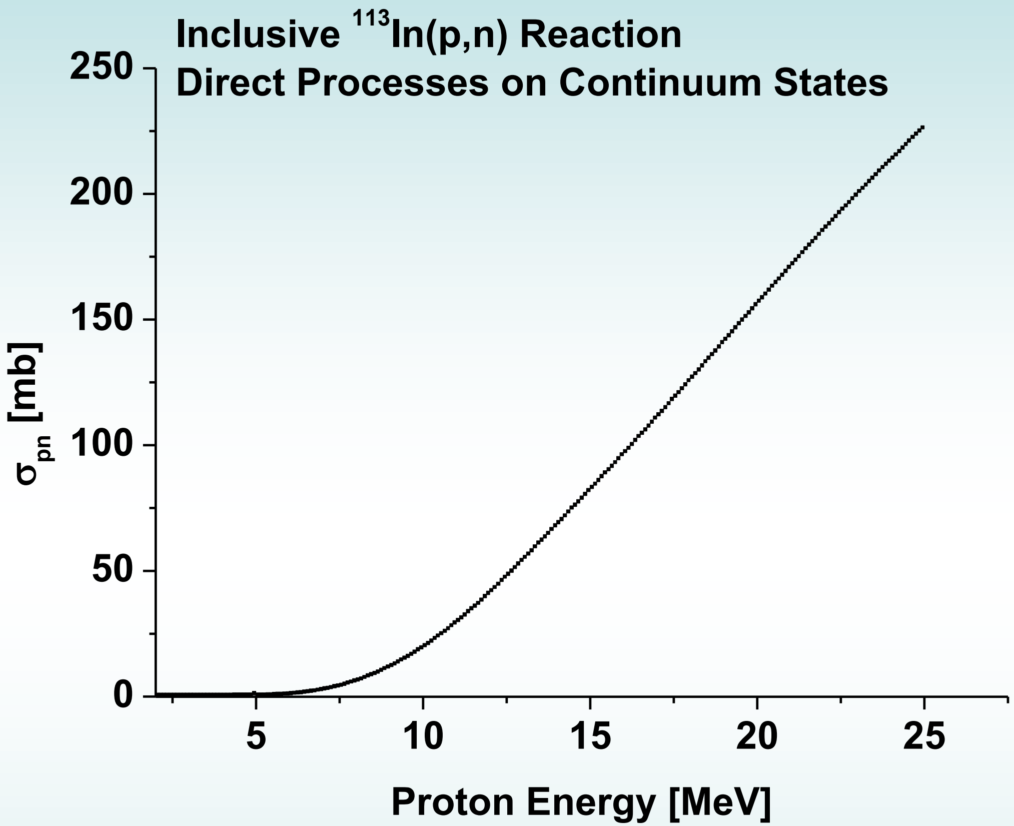
Results. Inclusive Cross section. $^{113}In(p,n)$



Inclusive Cross Section

- Compound Processes give the main contribution to the cross section

Results. Inclusive Cross section. ^{113}In(p,n)



Inclusive Cross Section

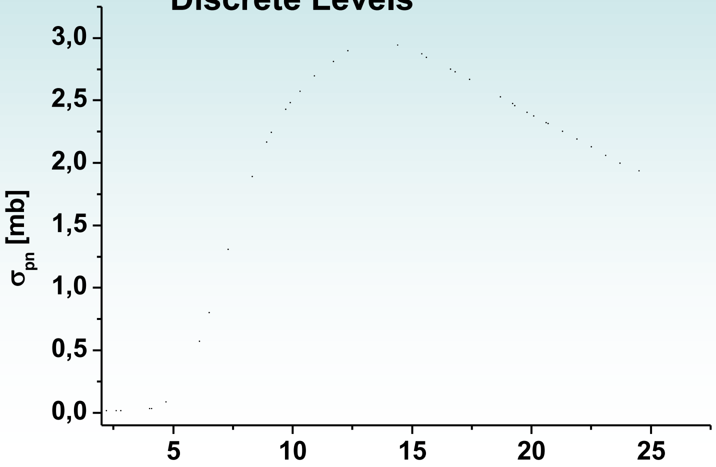
- Direct Processes are also important

- Direct Processes on Continuum -> increase with energy

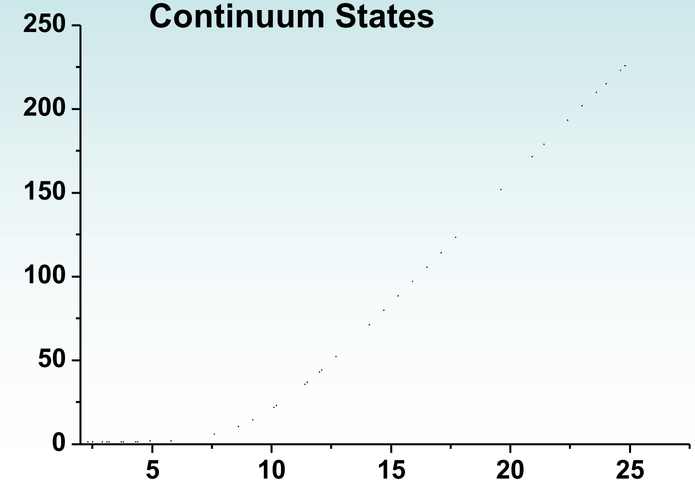
Results. Inclusive Cross section. $^{113}In(p,n)$

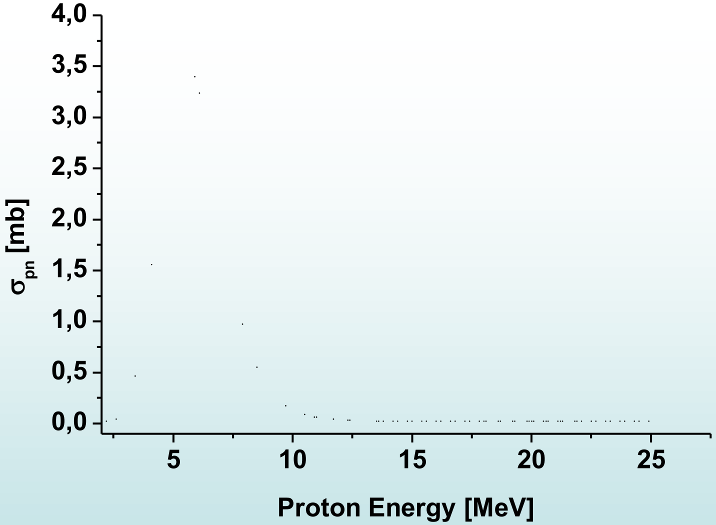
All Figures

Direct Processes on Discrete Levels

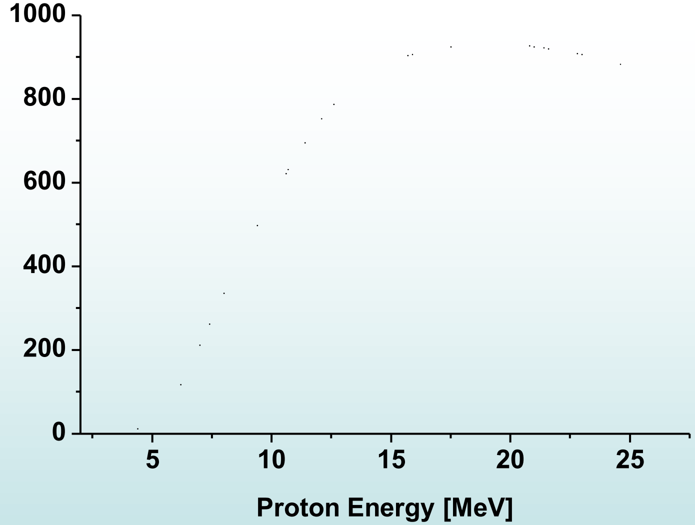


Direct Processes on Continuum States



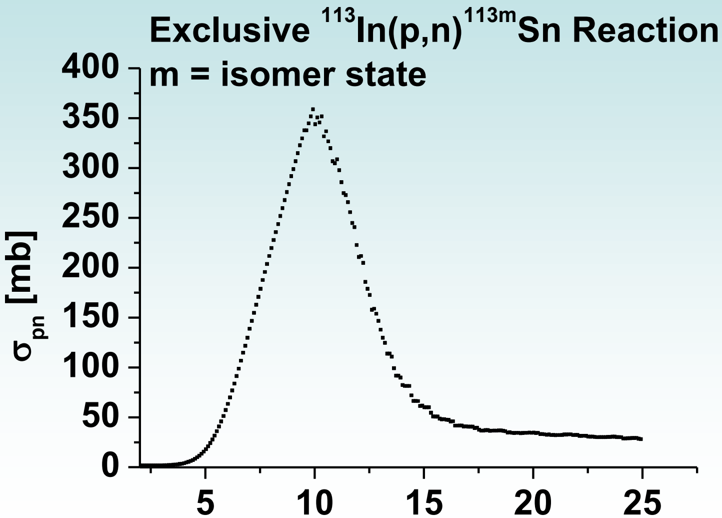


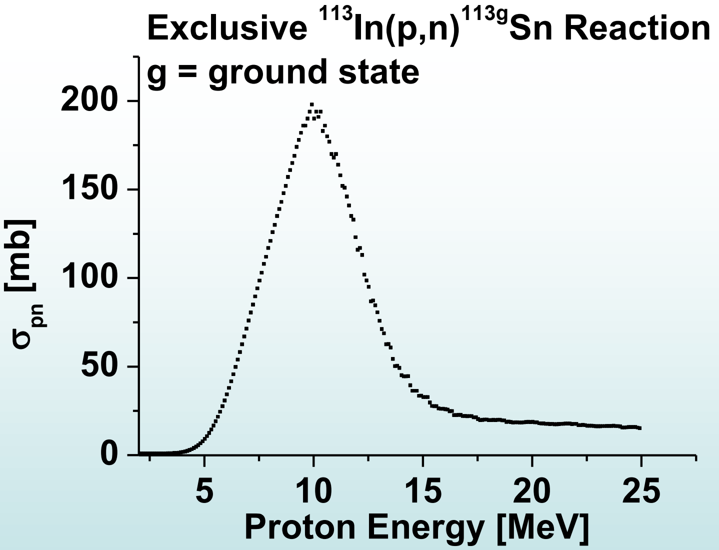
Compound Processes on Discrete Levels



Compound Processes on Continuum States

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

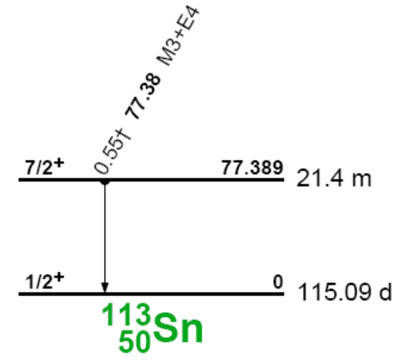




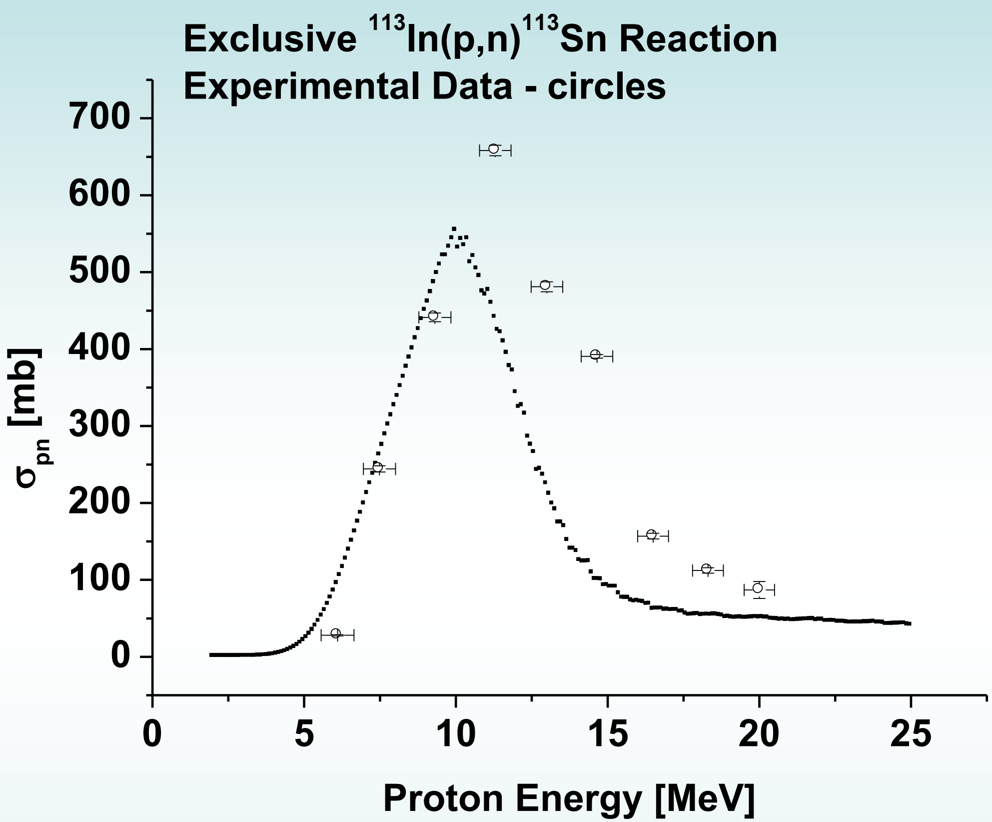
Exclusive Cross Section

- In our case (p,n)
- Measured all neutrons only from $^{113}In(p,n)^{113}Sn$
- These Cross Sections are used for Isomer Ratio Calculation According with the Relation

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



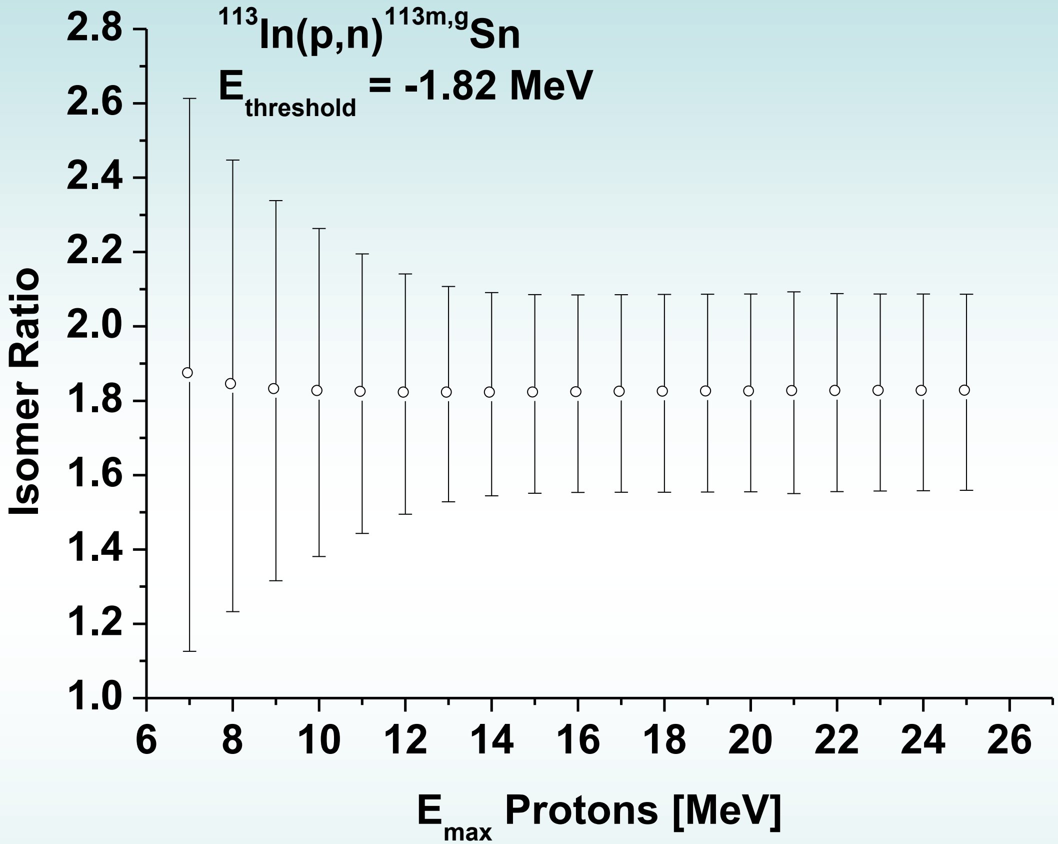
Results. Total ^{113}Sn nucleus production. Experimental Data



Exclusive Cross Section

- 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 other 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 Cross Section is satisfactorily described it is possible to evaluate the Isomeric Ratio

Results. Evaluated Isomeric Ratio



Incident proton flux

$$\phi\left(E_p\right)=1$$

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

Results. ^{113}In(p,n)^{113m,g}Sn. WS Parameters

Talys - Standard Input - Parameters

	V_V[MeV]	W_v[MeV]	r_V[fm]	a_v[fm]
n	62	0.11	1.22	0.661
p	51	0.14	1.22	0.661

Volume Central

	V_D[MeV]	W_D[MeV]	r_D[fm]	a_D[fm]
n	0	4.04	1.266	0.576
p	0	4.25	1.266	0.578

Surface Central

	V_{SO}[MeV]	W_{SO}[MeV]	r_{SO}[fm]	a_{SO}[fm]
n	6.06	-0.01	1.052	0.590
p	6.09	-0.01	1.220	0.661

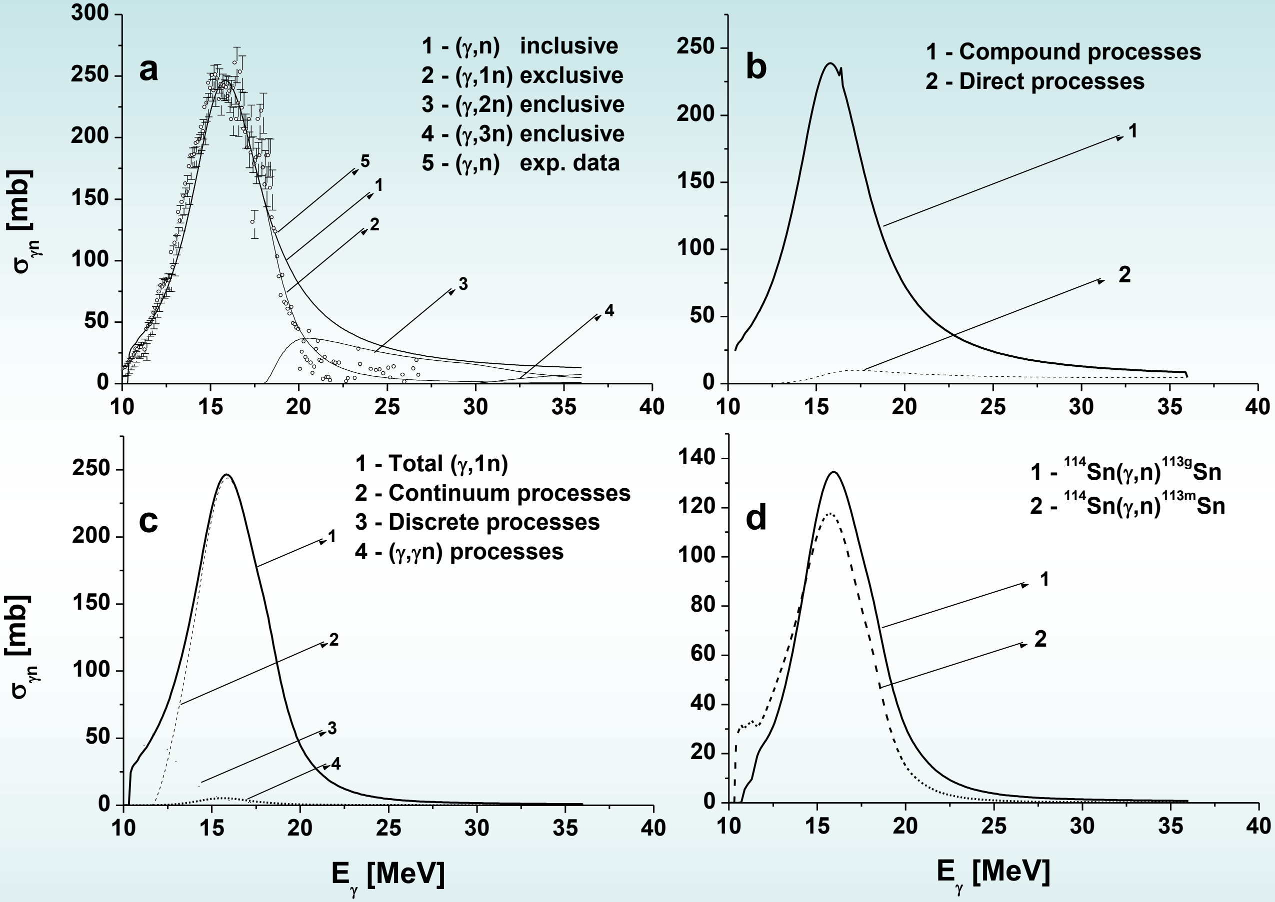
Spin Orbit

Results. PhotoNeutron Reactions. Natural Sn(γ,n)

Cross section and isomeric ratio analyzed with Talys

	Reaction	Isotope	Isomeric Ratio R	Isomer (m)		Ground (g)	
				J^π	τ_m	J^π	τ_m
1	**$^{114}Sn(\gamma,n)^{113m,g}Sn$**	**^{113}Sm**	**Y^{113mSn}/Y^{113gSn}**	**$(7/2)^+$**	**21.40 m**	**$(1/2)^+$**	**115.9d**
2	$^{118}Sn(\gamma,n)^{117m,g}Sn$	^{117}Sm	Y^{117mSn}/Y^{117gSn}	$(11/2)^-$	13.60 d	$(1/2)^+$	stable
3	**$^{120}Sn(\gamma,n)^{119m,g}Sn$**	**^{119}Sm**	**Y^{119mSn}/Y^{119gSn}**	**$(11/2)^-$**	**293.1 d**	**$(1/2)^+$**	**stable**
4	$^{122}Sn(\gamma,n)^{121m,g}Sn$	^{121}Sm	Y^{121mSn}/Y^{121gSn}	$(11/2)^-$	55.00 y	$(3/2)^+$	27.06 h
5	$^{124}Sn(\gamma,n)^{123m,g}Sn$	^{123}Sm	Y^{123mSn}/Y^{123gSn}	$(3/2)^+$	40.60 m	$(11/2)^-$	129.2 d

Results. $^{114}Sn(\gamma,n)^{113m,g}Sn$



a) binary (γ,n) inclusive cross section (c.s.) with the contribution of each (γ,xn) exclusive processes

- compared with exp. data

b) Compound and direct processes

c) Continuum and discrete proc.

d) c.s. of m ang states production – used for IR evaluation

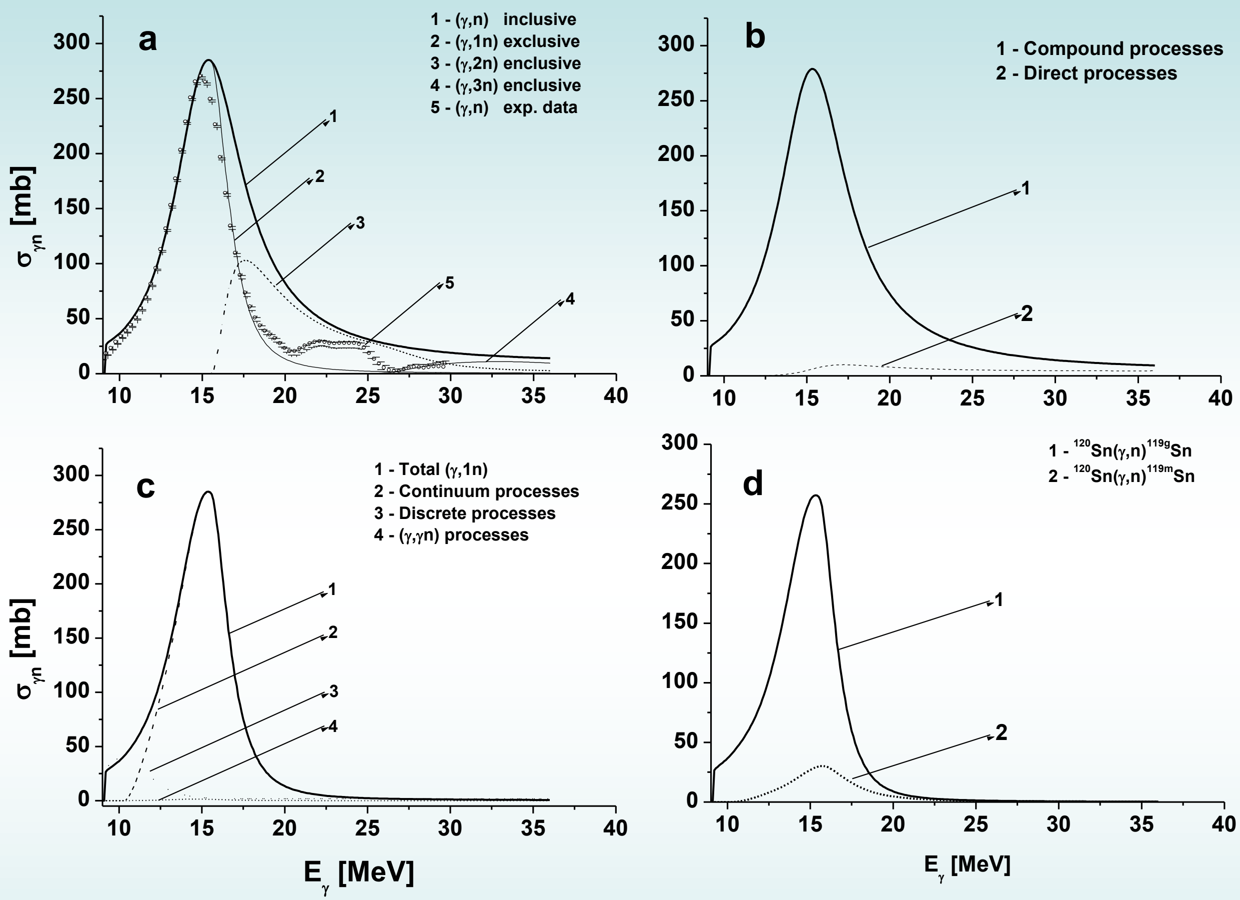
- good agreement with experimental data ; (γ,1n) exclusives are dominant (a)

- compound proc. are the main; direct proc. become important at higher energy (b);

- with the increasing of the energy contribution of continuum processes is also increasing (c)

- σ_m, σ_g used for IR evaluation (d)

Results. $^{120}Sn(\gamma,n)^{119m,g}Sn$



a) binary (γ,n) inclusive cross section (c.s.) with the contribution of each (γ,xn) exclusive processes

- compared with exp. data

b) Compound and direct processes

c) Continuum and discrete proc.

d) c.s. of m ang states production – used for IR evaluation

- good agreement with experimental data ; $(\gamma,1n)$ exclusives are dominant (a)
- compound proc. are the main; direct proc. become important at higher energy (b);
- with the increasing of the energy contribution of continuum processes is also increasing (c)
- σ_m, σ_g used for IR evaluation (d)

Results. Natural Sn(γ,n). Isomer Ratios

	Reaction	R_1	R_2	R_3
1	$^{114}Sn(\gamma,n)^{113m,g}Sn$	1.142 ± 0.203	1.121 ± 0.173	0.995 ± 0.159
2	$^{118}Sn(\gamma,n)^{117m,g}Sn$	0.081 ± 0.015	0.0768 ± 0.012	0.0616 ± 0.010
3	$^{120}Sn(\gamma,n)^{119m,g}Sn$	0.131 ± 0.025	0.126 ± 0.022	0.104 ± 0.018
4	$^{122}Sn(\gamma,n)^{121m,g}Sn$	0.258 ± 0.052	0.243 ± 0.045	0.170 ± 0.030
5	$^{124}Sn(\gamma,n)^{123m,g}Sn$	4.075 ± 0.532	4.187 ± 0.785	5.078 ± 0.954

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

Isomer ratios calculated for Sn isotopes obtained in (γ,n) reaction.

1) $\phi = 1; E_m = 35$ MeV;

2) $\phi = 1; E_m = 25$ MeV;

3) $\phi \sim (E_0 - E_g)/E_g$ (6); $E_m = 25$ MeV; $E_0 = 30$ MeV

$$\phi(E_\gamma) \sim I_c = i_b Z (E_0 - E_\gamma) E_\gamma^{-1}$$

Kramers relation for brehmstrahlung source

I_c = intensity of gamma quanta; i_b = electrons beam current;

E_0 = energy of accelerated electrons; Z = charge of stopping element.

Possibility of our facility (IREN, MT-25)

$E_0 = 30$ MeV

In order to have enough statistics $E_m = 25$ MeV

DISCUSSIONS AND CONCLUSIONS

Cross sections (CS) induced by fast protons and gammas

- were evaluated by Talys

- possibility to calculate inclusive and exclusive cross sections

- quite good agreement with experimental data

- select new potentials parameters for better description of experimental CS

Proton Induced

- for low energies compound processes are dominant but the direct processes become important with the increasing of incident protons energy

Photon Induced - Compound Processes are dominant

Isomer Ratios (IR)

- tendency of the IR is respected – IR becomes constant with the increasing of maximal energy E_{max}

- New Evaluations -> proposal of new measurements of fast protons and gammas CS and IR on In and Sn nuclei at JINR facilities

THANK YOU VERY MUCH FOR YOUR ATTENTION! ☺