Fast Neutron Processes on Molybdenum Isotopes

Cristiana Oprea, Ioan Alexandru Oprea

Joint Institute for Nuclear Research,
Frank Laboratory of Neutron Physics
6 Joliot-Curie, 141980 Dubna, Russian Federation

Molybdenum nucleus has many natural and artificial isotopes important for fundamental and applicative researches. ^{94}Nb nucleus, important in nuclear technology, can be obtained in ^{94}Mo(n,p) and ^{95}Mo(n,np) processes. Cross sections, angular correlations and isomer ratios in fast neutrons induced reactions up to 20 MeV were evaluated using codes realized by authors as well as dedicated software. Contributions of different nuclear reaction mechanisms in the cross sections were also determined. Parameters of nuclear optical potential, density levels and radius channels were extracted. Theoretical evaluations were compared with existing experimental data. The results of present work were realized in the frame of the fast neutrons scientific program at FLNP basic facilities (IREN and EG5) and are necessary for future experiment preparation .

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STRUCTURE OF THE PRESENTATION

1. INTRODUCTION
2. THEORETICAL BACKGROUND
3. COMPUTER CODES
4. RESULTS
5. DISCUSSION
6. CONCLUSIONS

1. INTRODUCTION – FAST NEUTRON PROCESSES

FAST NEUTRONS ACTIVATION ANALYSIS

- COMPLEMENTARY TO ACTIVATION WITH SLOW NEUTRONS

- POSSIBILITY TO CREATE BETTER GAMMA EMITTERS COMPARED WITH SLOW NEUTRONS

- POSSIBILITY TO INVESTIGATE LARGE SAMPLE DUE TO:

  - PENETRATION DEPTH OF NEUTRONS
  - ESCAPE FROM SAMPLE OF EMITTED GAMMAS

PROCESSES

- (n,n’), (n,n’γ), (n,2n), (n,p), (n,np), (n,α), (n,nα) etc

DIFICULTIES

- HIGH BACKGROUND

METHODS OF BACKGROUND REDUCTION

- NEUTRONS TAGGING

1. INTRODUCTION – FAST NEUTRONS PROCESSES – ANALYZED ELEMENTS

GENERAL

Precise nuclear data for:

- Nuclear energy – existing fission reactors ; future fusion reactors
- Long lived radioactive waste
- Reprocessing of U and Th (Transmutation and Energy)
- Accelerated Driven Systems (ADS)

FAST NEUTRONS REACTIONS – ^{94}Nb PRODUCTION

Processes:

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

Fast Neutrons with Emission of Charged Particles

- Nuclear reaction mechanisms
- Nuclear Data for Structural Material needed to estimate gas production by (n,p) and (n,α) reactions

2. THEORETICAL BACKGROUNDS

Cross Sections Evaluations

-CS calculated with Talys

Incident energy - from threshold up to 20 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

Levels Density – Constant Temperature Fermi Gas Model

2. THEORETICAL BACKGROUNDS – HAUSER FESHBACH APPROACH

Cross section

$$\sigma_{\alpha\beta} = \pi \lambda_\alpha^2 \frac{T_\alpha T_\beta}{\sum_c T_c}$$

→ **Historically first HF expression**

$$\sigma_{\alpha\beta} = \pi \lambda_\alpha^2 \frac{T_\alpha T_\beta}{\sum_c T_c} W_{\alpha\beta}$$

→ **Hauser - Feshbach**

$W_{\alpha\beta} =$ **Widths Fluctuation Factor (WFC)**

WFC

- **Indicates a correlation between the ingoing channel (incident) and outgoing channels**
- **At low energies (<1 MeV) WFC=1 - no correlation between *in* and *out* channels**
- **Decreases slowly with the energy**
- **It is calculated by complicate procedures (ex Moldauer expression)**

2. THEORETICAL BACKGROUNDS – ISOMER RATIO

$$R = \frac{Y^m}{Y^g} =$$ 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 particle

2. THEORETICAL BACKGROUNDS – ACTIVITY

$$A_{obs} = \frac{N\sigma\varphi a\varepsilon}{\lambda}\left[1 - Exp\left(-\lambda t\right)\right]Exp\left(-\lambda T\right)\left[1 - Exp\left(-\lambda\Delta T\right)\right]$$

Where:

N = Number of atoms of the isotope of the element
σ = cross section
a = γ-ray abundance
φ = Neutron Flux
ε = Detector efficiency
λ = Decay constant
t = Irradiation time
T = Cooling time
ΔT = Counting time

Yields and Activities – features not implemented yet in Talys

3. THEORETICAL BACKGROUNDS – 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

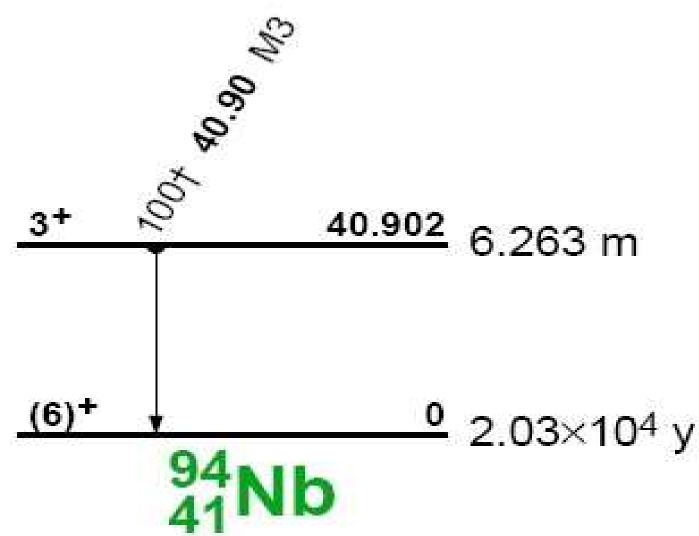
4. RESULTS.

FAST NEUTRON REACTIONS WITH CHARGED PARTICLES EMISSION
CASE OF $^{94}Mo(n,p)^{94}Nb$ Reaction ; Q_{np} = -1.26 MeV

Importance – Obtaining of ^{94}Nb Nucleus
Natural Molybdenum: Mo Z=42
Natural Isotopes of Mo with their abundance (%):
- ^{92}Mo(14.65), ^{94}Mo(9.19), ^{95}Mo(15.87), ^{96}Mo(16.67), ^{97}Mo(9.58), ^{98}Mo(24.29) - stables
- ^{100}Mo(9.74) – Decay $\beta^- \beta^-$ to ^{100}Ru

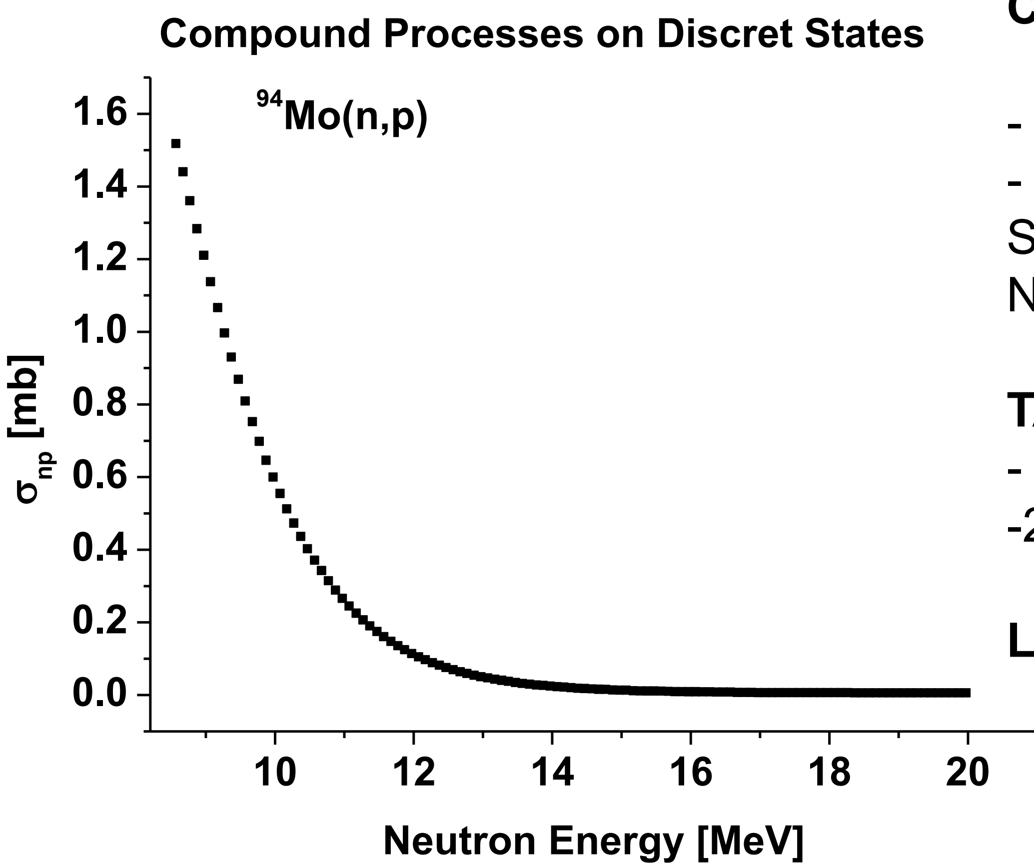
Density of Natural Mo: 10.28 g/cm^3 :
Spin and Parity of ^{94}Mo: 0^+

Isomers in $^{94}Mo(n,p)^{94m,g}Nb$ Reaction



Results on:
- Inclusive and Exclusive Cross Sections
- Production of isomer and ground states of ^{94}Nb (m and g states)
- Parameters of Nuclear Potentials in incident ar exit channels
- Activities and other Concurrent Processes

4. RESULTS. INCLUSIVE REACTIONS



CROSS SECTION (CS) ANALYSIS CONTRIBUTION OF:

- NUCEAR REACTION MECHANISM
- DISCRETE AND CONTINUUM STATES OF THE COMPOUND NUCLEUS

TAKEN INTO ACCOUNT:

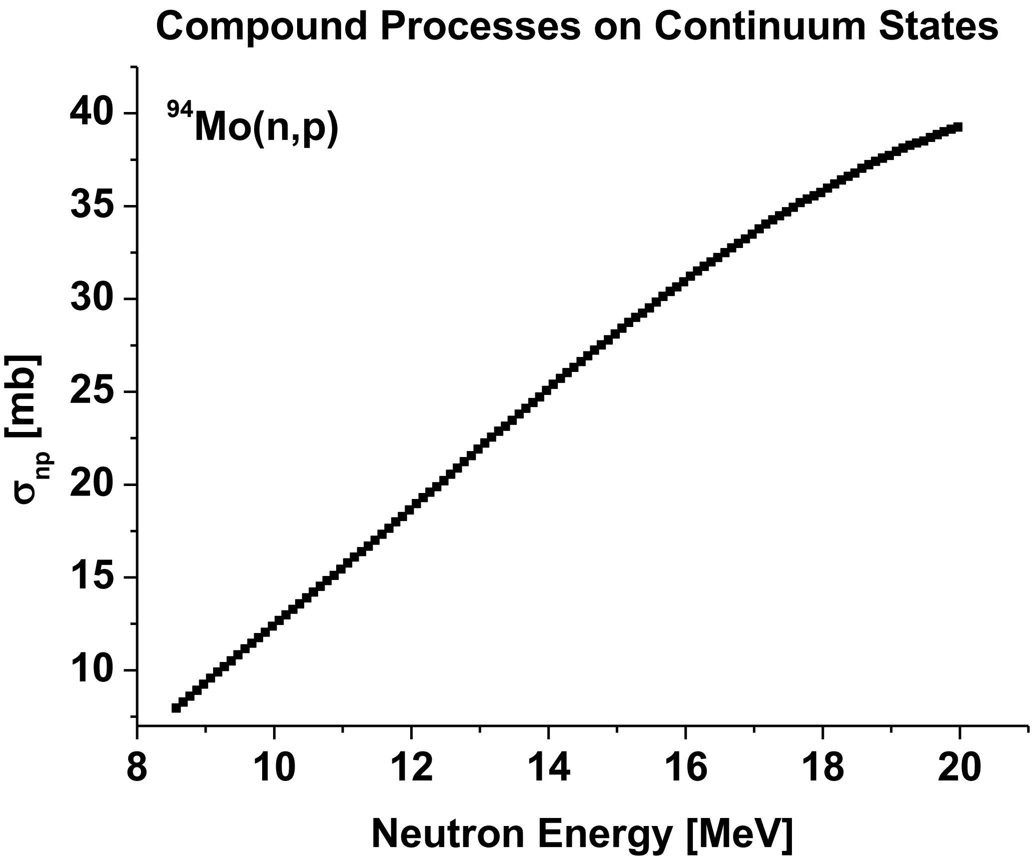
- 10 DISCRETE STATES FOR (n,x)
-20 DISCRETE STATES FOR (n,n')

LOW CONTRIBUTION TO THE CS

OBSERVATION:

- CONTRIBUTION OF DIRECT PROCESSES ON DISCRET STATES NEGLECTED BECAUSE THEY ARE ABOUT 10 TIME LOWER THAN THE RESULTS FROM THE FIGURE

4. RESULTS. INCLUSIVE REACTIONS

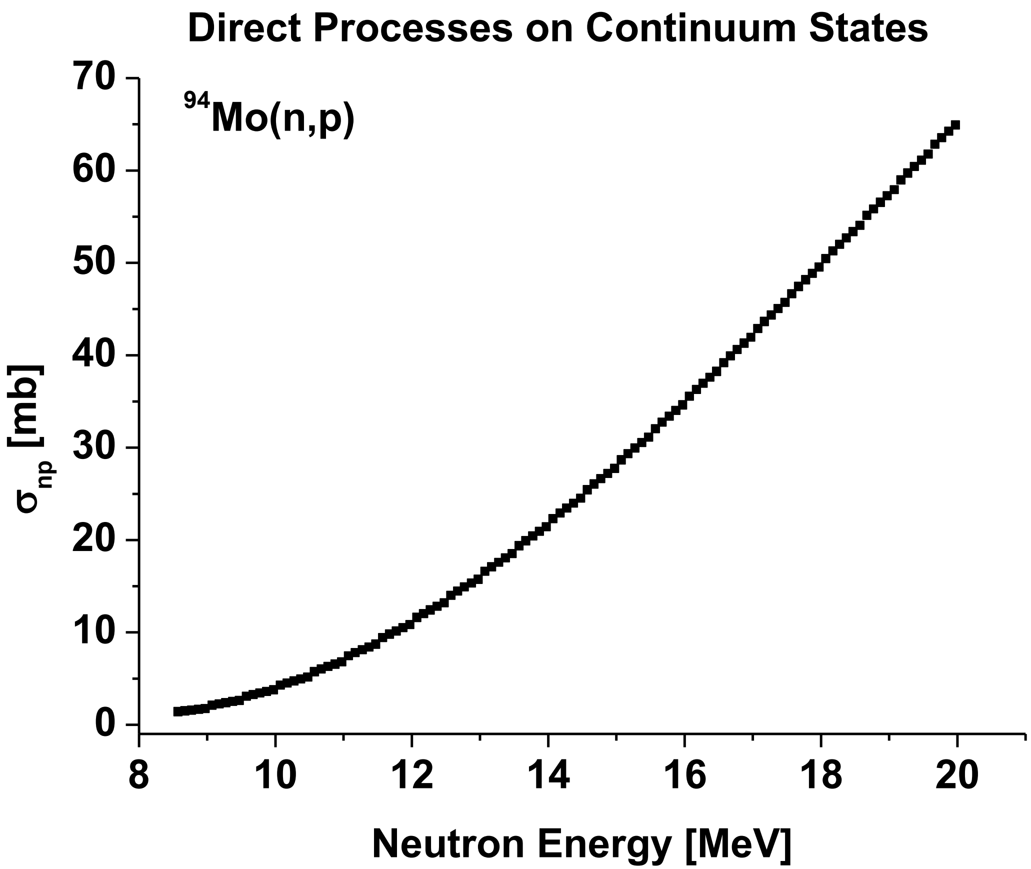


CS HAS THE EXPECTED SHAPE
- IT WILL INCREASES UP TO SOME MAXIMUM AND AFTER THAT WILL SLOWLY DECREASE (NOT REPRESENTED

CONTINUUM STATES - IMPORTANT

- COULOMB BARIER FOR CHARGED PARTICLES

4. RESULTS. INCLUSIVE REACTIONS

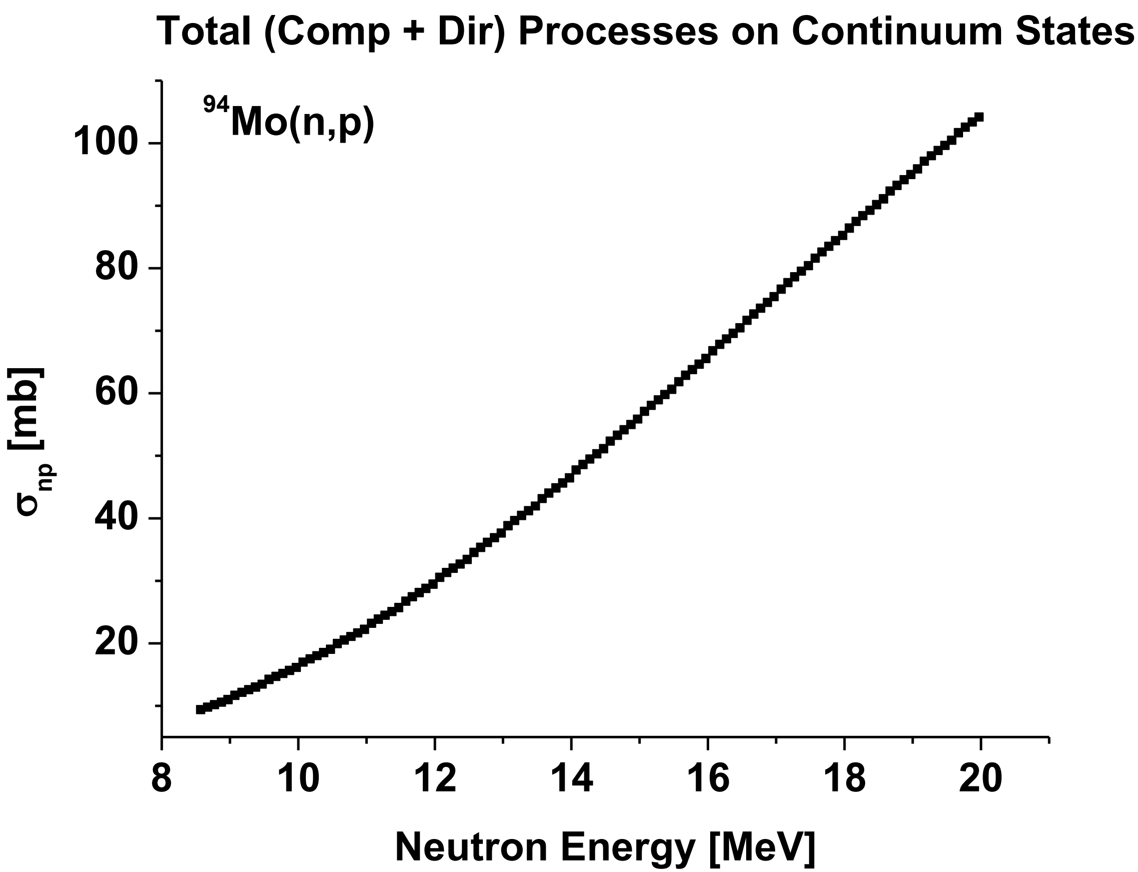


DIRECT PROCESSES

- THEIR CONTRIBUTION TO CS IS INCREASING WITH THE INCIDENT ENERGY

- IN THE ANALYSED REACTION DIRECT PROCESSES BECOME DOMINANT WITH THE INCREASING OF THE ENERGY

4. RESULTS. INCLUSIVE REACTIONS

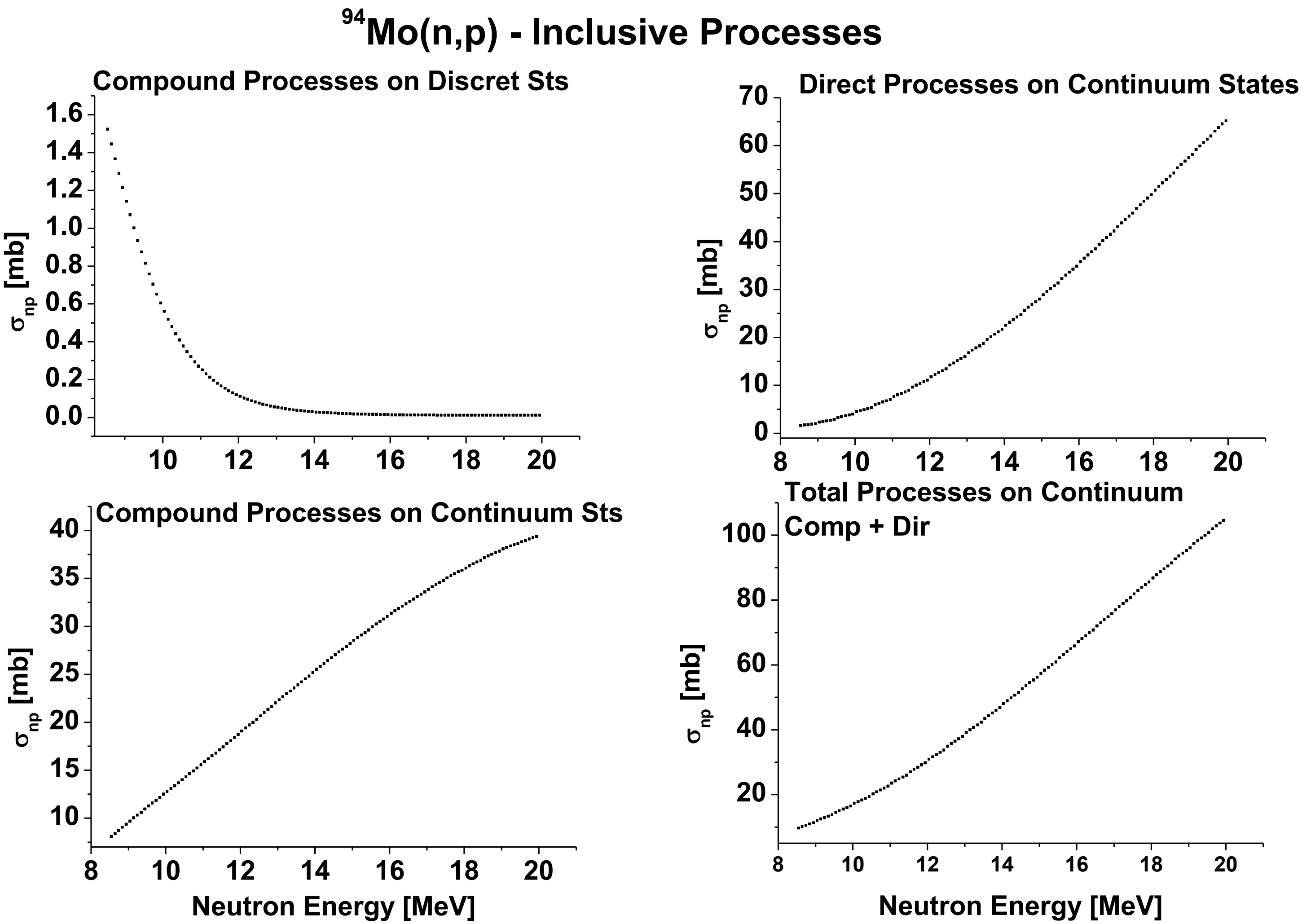


TOTAL CONTRIBUTION TO INC. CROSS SECTION

- NEGLECTED DISCRETE STATES

- CONSIDERED CONTINUUM STATES

4. RESULTS. INCLUSIVE REACTIONS. ALL EVALUATIONS



THE NUCLEAR REACTION $^{94}Mo(n,p)^{94}Nb$:

DIRECT AND COMPOUND MECHANISM ORIGINATED MAINLY BY PRE – EQUILIBRIUM PROCESSES

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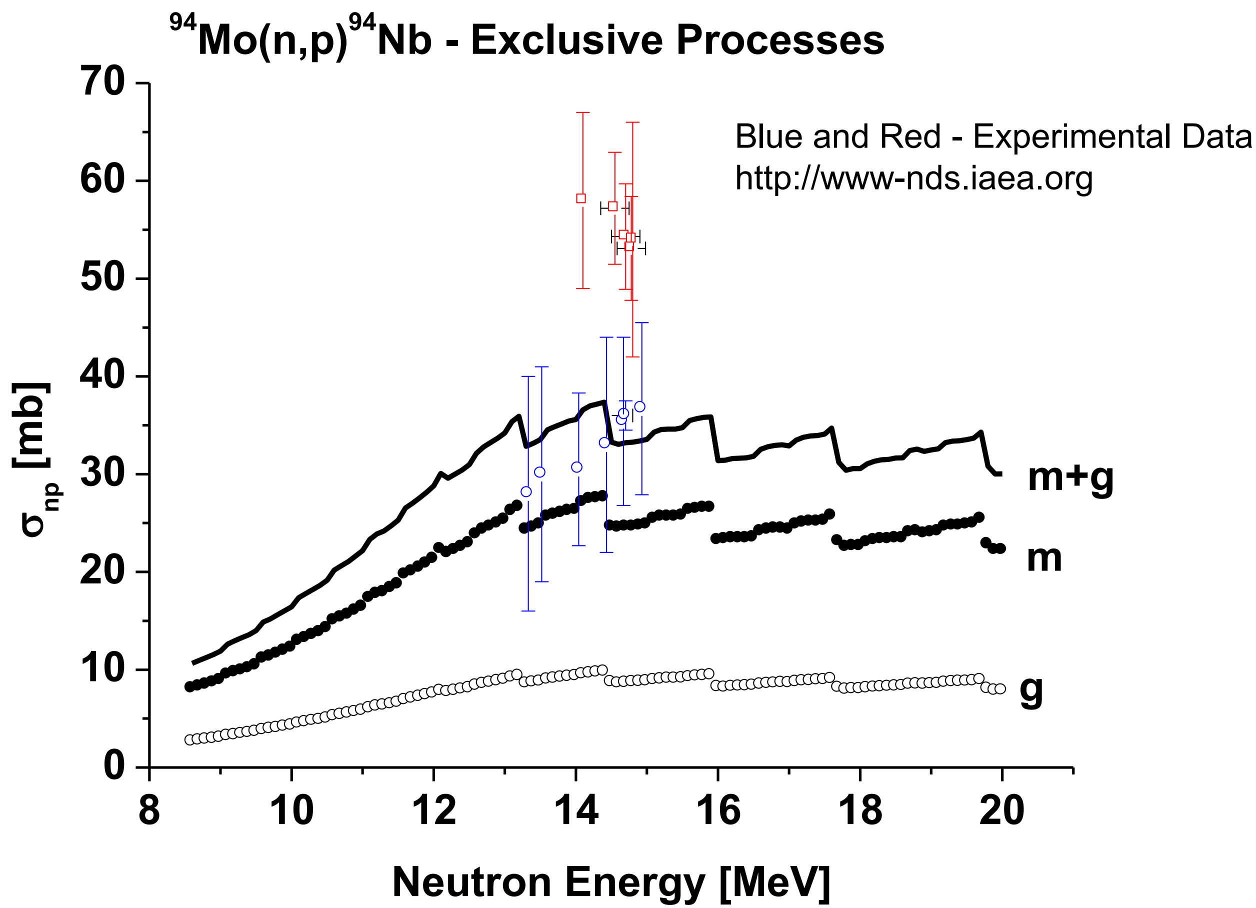
4. RESULTS. EXCLUSIVE REACTIONS



Isomer Ratio

R = 2.852 ⌖ 0.013 – Incident Neutron Flux =1

R = 2.860 ⌖ 0.010 – Incident Neutron Flux ~$1/E^{0.9}$

Gamma Transitions E_γ = 0.0409 MeV

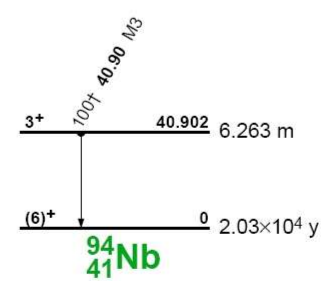
PRODUCTION OF:

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

Standard Talys Input:
- Potentials
- Density Levels

Experimental Data:
- Described Well
- Further Analysis of Experimental Data and Talys Input Parameters

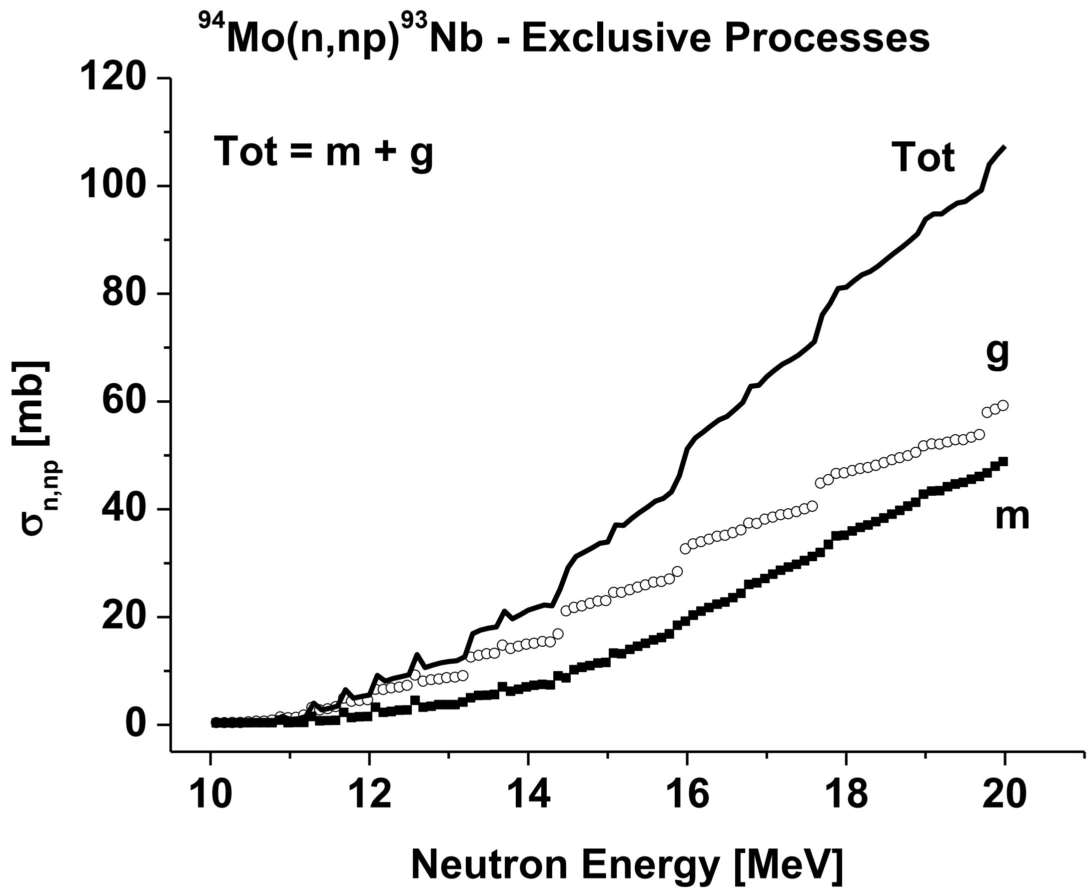
Cross Section of Isomer and Ground States of ^{94}Nb



4. RESULTS. EXCLUSIVE REACTIONS. CONCURENT PROCESSES

In the ^{94}Mo(n,p)^{94}Nb Reactions for Incident Neutrons from Threshold up to 20 MeV many channels are open

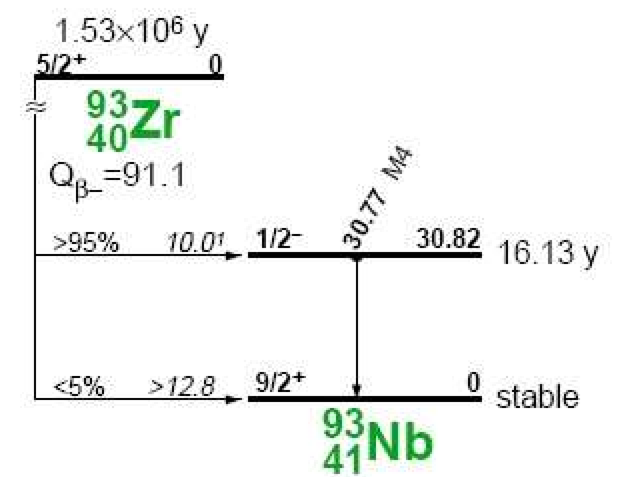
- 2 channels: ^{94}Mo(n,np)^{93}Nb (Q=-8.49 MeV) and ^{94}Mo(n,2n)^{93}Mo (Q=-9.67 MeV)



R = 1.51 ⌖ 0.025 – Neutron Flux =1

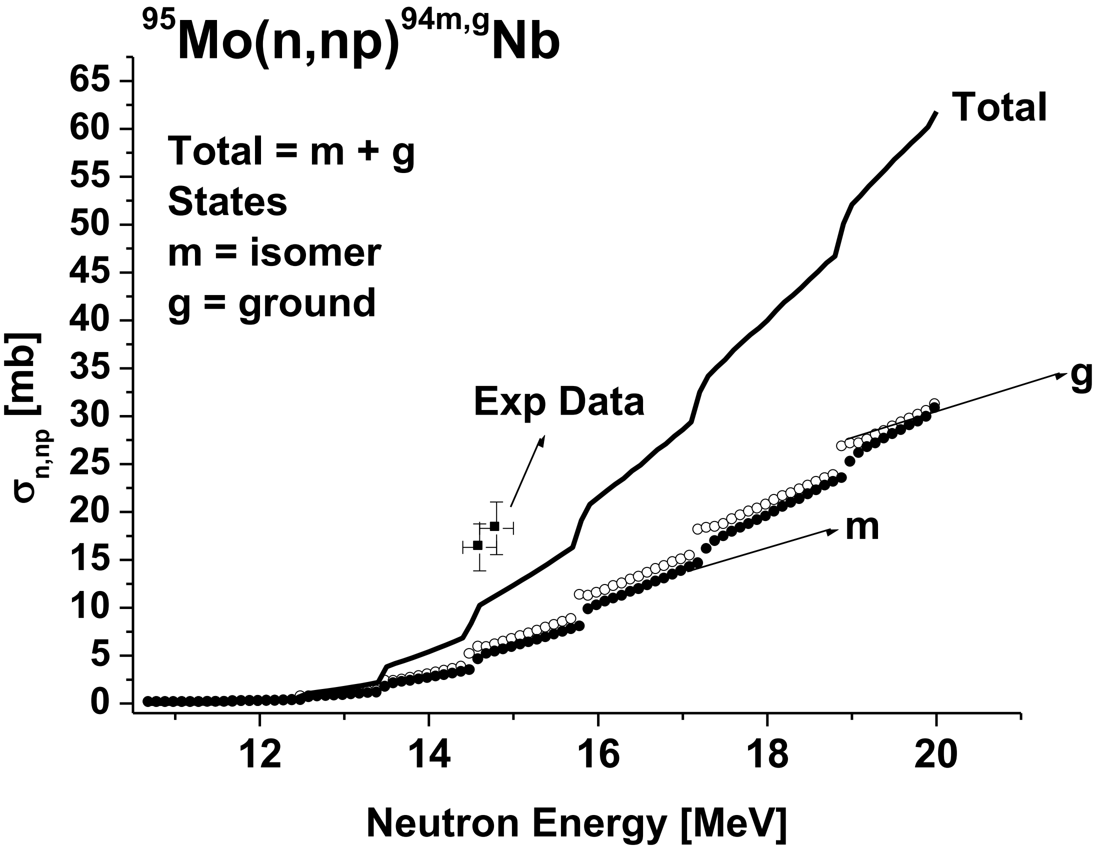
CS of (n,p), (n,np) and (n,2n) are of the same order of magnitude

Gamma Transitions E_γ = 0.0307 MeV



4. RESULTS. EXCLUSIVE REACTIONS. SECOND WAY OF ^{94}Nb PRODUCTION

^{94}Nb isotopes – obtained by ^{95}Mo(n,np)^{94}Nb reaction (Q= - 8.63 MeV)
Realized an analyze of Inclusive and Exclusive Reactions
Presented only the main Results on Exclusive Reactions



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

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

High Energy part dominated by Direct Processes -> Increasing of High Energy Region

Isomer Ratio
- Neutron Flux =1
R = 0.927 ⊕0.019
- Neutron Flux ~ $1/E^{0.9}$
R = 0.923 ⊕0.018

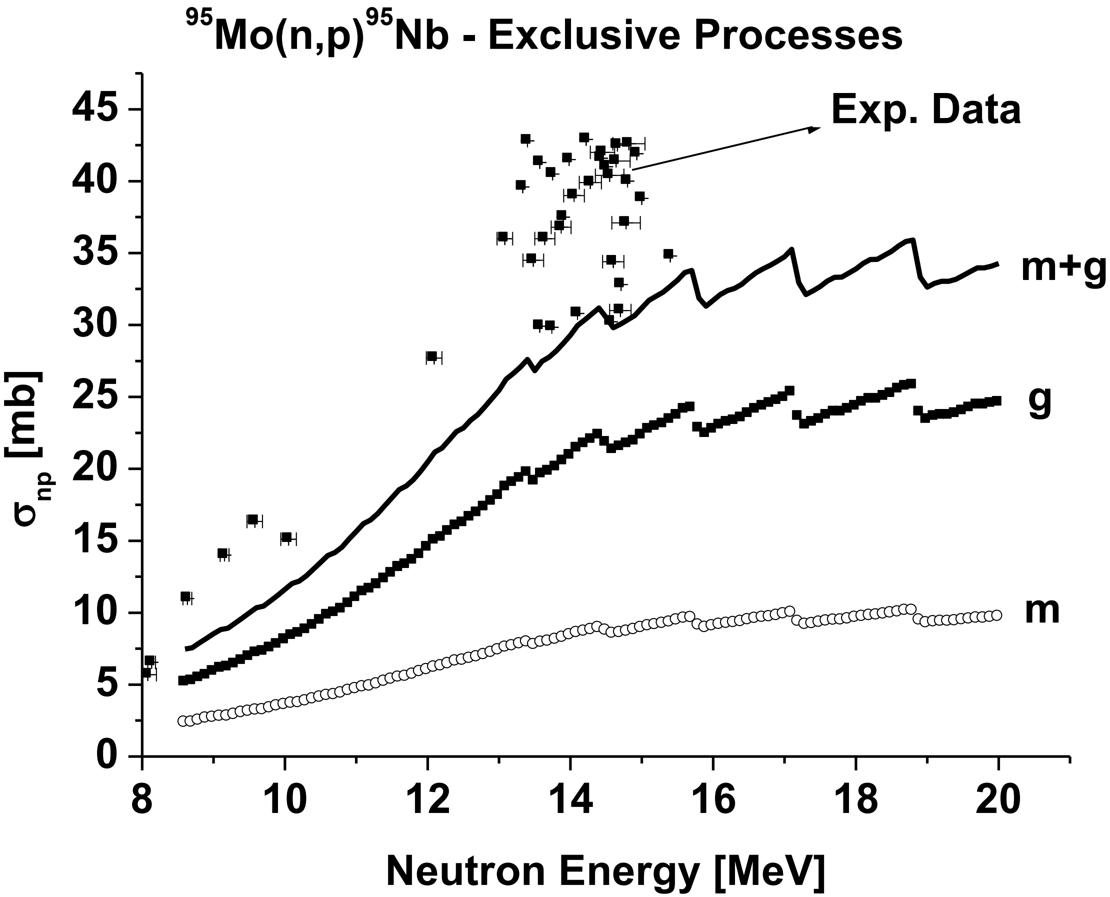
4. RESULTS. EXCL REACTIONS. ^{94}Nb PRODUCTION. CONCURENT PROCESSES

Concurrent Processes:

^{95}Mo(n,p)^{95}Nb (Q = - 0.1432 MeV);

^{95}Mo(n,2np)^{93}Nb (Q = -15.857 MeV)

Exclusive Processes for ^{95}Mo(n,p)^{95}Nb



Production of ^{95}Nb

Standard Talys Input – Acceptable Description of Experimental Data

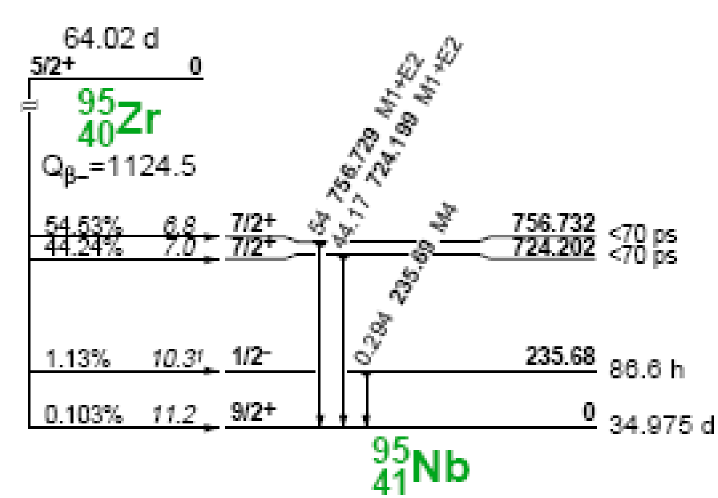
Isomer Ratio

Neutron Flux =1

R = 0.4024 ⌖ 0.025

Gam. Tr. E_γ = 0.2356 MeV

(n,2np)–importance at 17–20 MeV



4. RESULTS. EXCL 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

4. RESULTS. EXCL 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

4. RESULTS. ACTIVITIES. ISOMER RATIO MEASUREMENTS

MODEL - REAL TARGET OF 1 CM X 1 CM X 0.1 CM
DESINSITY – 10.28 g/cm^3
Goal – Activity obtained in Experiment at Different Energies

	$^{95}Mo(n,np)^{94m}Nb$		$^{95}Mo(n,np)^{94g}Nb$		$^{95}Mo(n,p)^{95m}Nb$		$^{95}Mo(n,p)^{95g}Nb$	
E_n [MeV]	σ [mb	A_{obs} [dez]	σ [mb	A_{obs} [dez]	σ [mb	A_{obs} [dez]	σ [mb]	A_{obs} [dez]
14.1	5.76	$1.86 \cdot 10^6$	3.09	$1.7 \cdot 10^{-3}$	8.56	9818	6.95	7
20	61.8	$2.00 \cdot 10^7$	31.1	$1.7 \cdot 10^{-2}$	9.67	1109	48.5	47

τ_m = 6.263m; τ_g=2.03 · 10^{6}y

τ_m = 86.6 h ; τ_g = 34.975 d

Irradiation time = 3 min; Cooling time = 3 min; Counting time = 5 min

4. RESULTS. ACTIVITIES. ISOMER RATIO MEASUREMENTS

MODEL - REAL TARGET OF 1 CM X 1 CM X 0.1 CM
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$^{94}Mo(n,p)^{94m}Nb$			$^{94}Mo(n,p)^{94g}Nb$		$^{94}Mo(n,np)^{93m}Nb$		$^{94}Mo(n,np)^{93g}Nb$	
E_n [MeV]	σ [mb	A_{obs} [dez]	σ [mb	A_{obs} [dez]	σ [mb	A_{obs} [dez]	σ [mb]	A_{obs} [dez]
14.1	27.1	$8.75 \cdot 10^6$	9.48	$6.4 \cdot 10^{-3}$	6.95	0	6.95	0
20	22.2	$7.17 \cdot 10^5$	7.83	$4.3 \cdot 10^{-3}$	9.67	0	48.5	0

τ_m = 6.263m; $\boldsymbol{\tau_g}$**=**2.03 · 10^{6}y

τ_m = 16.13 y ; $\boldsymbol{\tau_g}$ **=** stable

Irradiation time = 3 min; Cooling time = 3 min; Counting time = 5 min

Talys – for gamma and neutrons induced reactions activities and yields calculations on sample target are not implemented
Activities are evaluated by us – simple model of isomer ratios measurements

Results suggest the possibility of the isomer ratio measurements

5. DISCUSSIONS

Analyzed Nuclear Reactions Induced by Fast Neutrons for:
Fast Neutrons Activation and Isomer Ratio Evaluation
Reactions: $^{94}Mo(n,p)^{94}Nb$ and $^{95}Mo(n,np)^{94}Nb$

For mentioned Processes were Evaluated with Talys:
- Cross Sections (Inclusive and Exclusive)
- Isomer Ratios
- Activities and Yields on Simple Modeled Measurements

Comparison with Existing Experimental Data
- using a Standard Talys Input the CS Evaluation are in well and / or acceptable Accordance with Existing Experimental Data
- For many Evaluations like CS productions of isomer and isotopes and Isomer Ratios – no experimental data
- Obtained New Nuclear Data on Potential and Level Densities Parameters

Cross Sections – by Talys

6. CONCLUSIONS

Talys – Rapid and Efficient Codes for Evaluation of Nuclear Data
(Reaction Models ->Cross Section and Nuclear Structure)

Necessary a Better Description of Experimental Data on Analyzed Processes

Fast Neutrons – Obtained New Theoretical Evaluation on Isomer Production and Isomer Ratios - > New Measurements and Experiments

Improvement of Experimental and Theoretical Data for Tagged Neutrons Method
Necessary to test New Elements

Necessary ot use Computer Codes for Experiment Simulations – GEANT4
- Activities, Yields and other

Present Evaluations
- Experiment Proposal at JINR Dubna Facilities
- LNF JINR Dubna Facilities – IREN, IBR-2
- LNR JINR Dubna – Microtron MT-25

THANK YOU VERY MUCH

FOR YOUR ATTENTION! ☺