Fast proton-induced fission of ^{238}U from threshold to 70 MeV

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ABSTRACT

The fast proton-induced fission cross-sections of ^{238}U have been analyzed from the threshold up to 70 MeV. Calculations were performed on fission variables such as cross-sections, mass distributions, and prompt neutron emission.

For the analysis, Talys and programs written by authors were used to describe the fission process using a Brosa model. As a result, we estimate the contribution of different nuclear reaction mechanisms (direct, pre-equilibrium, compound nucleus) to cross-sections, prompt neutron production, and other fission parameters.

Different nuclear reaction mechanisms contribute to the interaction of fast protons with any target nucleus, excited residual nuclei by mean of (p,p’), (p,xn), (p,xp), (p,xa) (x=1,2,…,n) and other processes. In the case of ^{238}U, excited residual nuclei can also fission, contributing in this way to the investigated variables and isotope production.

Theoretical results were compared with previous experimental data found in the literature. The comparison allowed us to extract parameters of the optical potential, fission barrier height and width, and type of nucleus deformation. Fission cross sections and yields for produced fission isotopes (as Mo, I, Xe, Sr and other fission fragments) along the whole energy range were determined for all types of incident channels and then agreed with available data from the EXFOR database.

OUTLINE

INTRODUCTION

ELEMENTS OF THEORY

RESULTS AND DISCUSSIONS

CONCLUSIONS

INTRODUCTION

URANIUM

Natural Uranium: abundance - ^{234}U - 0.0054%; ^{235}U - 0.7204%; ^{238}U - 99.2742%

Isotopes: Z = 92; A = 214 to 242

Properties of Uranium isotopes – All isotopes of U are unstable and therefore undergoing to stable configuration by spontaneous fission, alpha, beta and more rarely by double beta and cluster decay.

Fission – >a real solution to the global energy challenge of the future

- Hydrocarbon based energy will be finished in a few decades
- Wind energy – still expensive and not effective
- Nuclear energy obtained by fission of ^{235}U is also limited

INTRODUCTION

Fundamental Researches

Fission - investigation of the configuration of fissionable system near scission point. It gives information on: measurements of anisotropy, emitted gamma rays, fission product ground states

Applicative Researches

Fission – important for transmutation and nuclear energy projects, new generation nuclear reactors

Isotope and Isomer production for a wide range of applications in medicine, electronics, engineering etc

Goal and objectives

Fission process induced by fast protons up to 40 MeV energy on ^{238}U was analyzed;

Experimental observables as cross sections, fragment mass distribution, yields of some nuclides of interest and average prompt neutrons multiplicity characterizing ^{238}U fission were theoretically evaluated by using TALYS-1.95 software;

This study represents a research proposal for fast proton induced fission investigations and isotope production at basic facilities in Romania and EU

CODES AND ELEMENTS OF THEORY

TALYS

Freeware soft working under LINUX – dedicated to nuclear reactions, fission and nuclear structure calculation
Codes for nuclear reaction mechanisms and nuclear structure calculations
Implemented compound, direct and pre-equilibrium processes
Wide data of nuclear data - energy levels, density levels, spins, parity, optical potential parameters for many nuclei

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

Fast Proton Induced Fission

Cross section -> compound processes (main)
Mass distribution of fission fragments – evaluated in the frame of Brosa model
Density levels – Constant temperature with Fermi gas model

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, 211 (2008)

CODES AND ELEMENTS OF THEORY

Hauser – Feshbach Approach

Cross Section (XS)

$$\sigma_{\alpha\beta} = \pi \bar{\lambda}_{\alpha}^{2} \frac{T_\alpha T_\beta}{\sum_c T_c}$$

Historically first HF expression

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

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

W. Hauser, H. Feshbach, Phys. Rev. vol. 87, no. 2, p. 366 (1952)

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)

CODES AND ELEMENTS OF THEORY

Transmission coefficients **=** probability of a particle to pass trough a potential barrier

For discrete states $T(l,E)=1-\left|U_l(E)\right|^2$ **Quantum mechanical approach**

For continuum states $T_{eff}(U)=\int_{E_{\min}}^{E_{\max}}\rho(\varepsilon)T(\varepsilon)d\varepsilon$ **Effective transmission coefficient**

For Fission – Bohr – Wheeler relation $T_f(E_x)=\dfrac{1}{1+Exp\left[-2\pi\dfrac{E_x-B_f}{h\varpi_f}\right]}$

Level density $\rho(E_x,J,\Pi)=\dfrac{1}{2}\dfrac{2J+1}{2\sqrt{2\pi}\sigma^3}Exp\left[-\dfrac{\left(J+\dfrac{1}{2}\right)^2}{2\sigma^2}\right]\dfrac{\sqrt{\pi}}{12}\dfrac{Exp\left(2\sqrt{aU}\right)}{a^{\frac{1}{4}}U^{\frac{5}{4}}}$

$E_x=U-\Delta$ **Effective excitation energy**

$E_x=$ **Excitation energy**

$a=$ **Level density parameter**

$B_f=$ **Barrier height**

$h\omega_f=$ **Barrier width**

$J=$ **Spin**

$\sigma=$ **Spin cut-off parameter**

CODES AND ELEMENTS OF THEORY

Fission XS for a given fission fragment (FF) mass

$$\sigma(A_{FF}) = \sum_{Z_{FS}, A_{FS}, E_x} \sigma_F(Z_{FS}, A_{FS}, E_x) Y(A_{FF}; Z_{FS}, A_{FS}, E_x)$$

A_{FF} = FF mass; $\sigma_F(Z_{FS}, A_{FS}, E_x)$ = cross section of fissionable system (FS)
Y (A_{FF} ;Z_{FS}, A_{FS}, E_x) = relative yield of FF with mass A_{FF} coming from a FS with mass A_{FS} and charge Z_{FS}
Z_{FS}, A_{FS} = charge and mass of FS; E_x = excitation energy

XS Production of FF with given mass (A_{FF}) and charge (Z_{FF})

$$\sigma_{prod}(Z_{FF}, A_{FF}) = \sum_{Z_{FS}, A_{FS}, E_x} \sigma_F(Z_{FS}, A_{FS}, E_x) Y(A_{FF}; Z_{FS}, A_{FS}, E_x) Y(Z_{FF}; A_{FF}, Z_{FS}, A_{FS}, E_x)$$

Y (Z_{FF} ;A_{FF} ,Z_{FS}, A_{FS}, E_x) = relative yield of FF with charge Z_{FF} and mass A_{FF} coming from a FS with mass A_{FS} and charge Z_{FS}

CODES AND ELEMENTS OF THEORY

FF mass distribution

$$Y(A_{FF};Z_{FS},A_{FS},E_x)=\sum_{FM=SL,STI,STII} W_{FM}(Z_{FS},A_{FS},E_x)Y_{FM}(A_{FF};Z_{FS},A_{FS},E_x)$$

W_{FM} (Z_{FS}, A_{FS}, E_x) = weight of fission mode (FM);
Y_{FM} (A_{FF} ;Z_{FS}, A_{FS}, E_x) = mass distribution;
FM = SL = superlong; STI, II = standard I, II

FM weight

$$W_{CFM}(Z_{FS},A_{FS},E_X)=\frac{T^B_{f,CFM}}{T^B_{SL,CFM}+T^B_{STI,CFM}+T^B_{STII,CFM}}$$

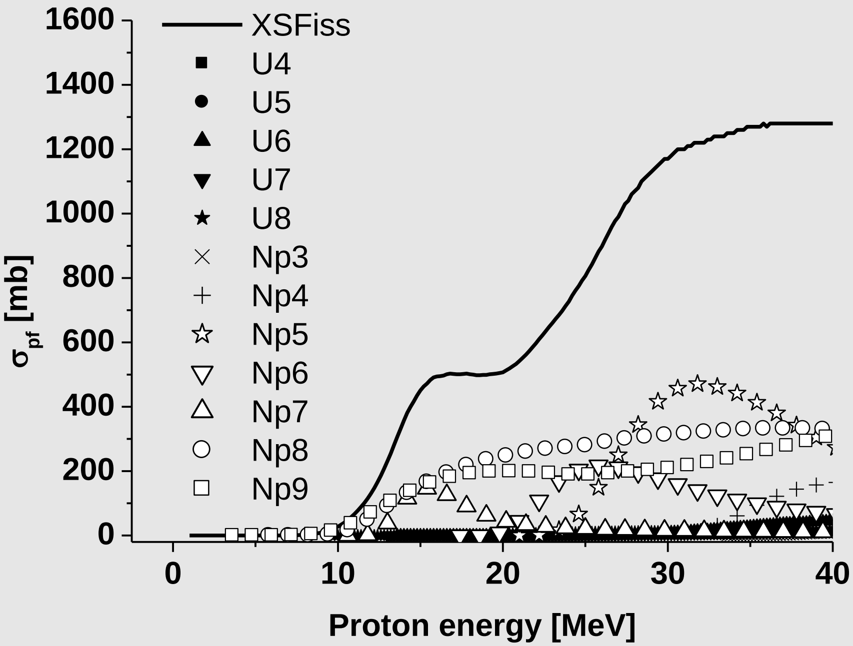
CFM = SL, STI, STII; $T_{f,\,CFM}$ = transmission coefficient (Hill – Wheeler);
B = second barrier

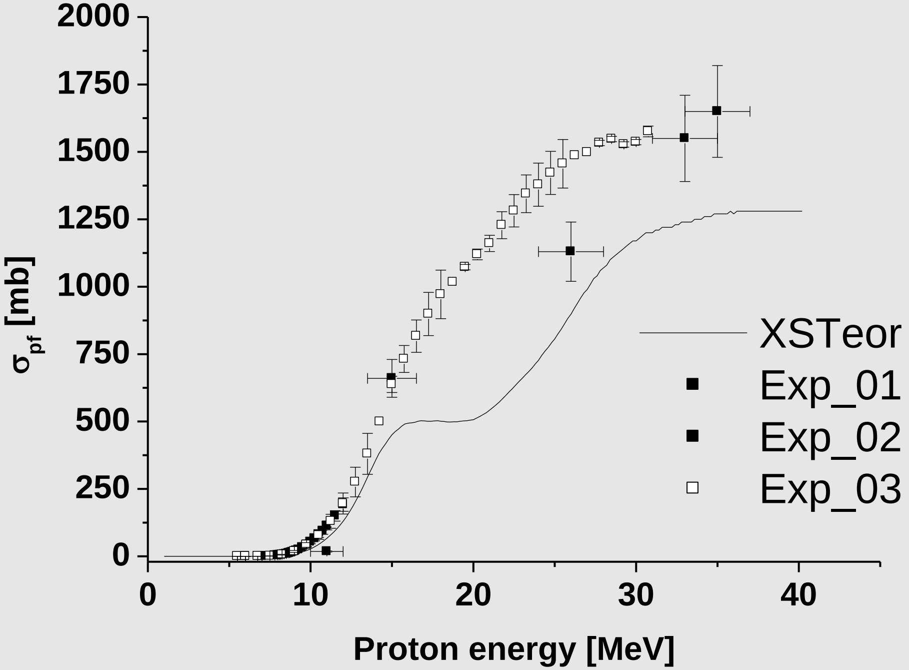
M. C. Duijvestijn, A. J. Koning, and F. -J. Hambsch, Phys. Rev. C **64**, 014607 (2001)
A. J. Koning, S. Hilaire and M. C. Duijvestijn, TALYS-1.0., *Proceedings of the International Conference on Nuclear Data for Science and Technology*, April 22-27, 2007, Nice, France, editors O. Bersillon, F. Gunsing, E. Bauge, R. Jacqmin, and S. Leray, EDP Sciences (2008) 211-214

U. Brosa, S. Grossmann, A. Muller, Phys. Rep, **197**, 167-262 (1990)

RESULTS AND DISCUSSIONS. Cross Section (XS)

Total Fission Cross Sections



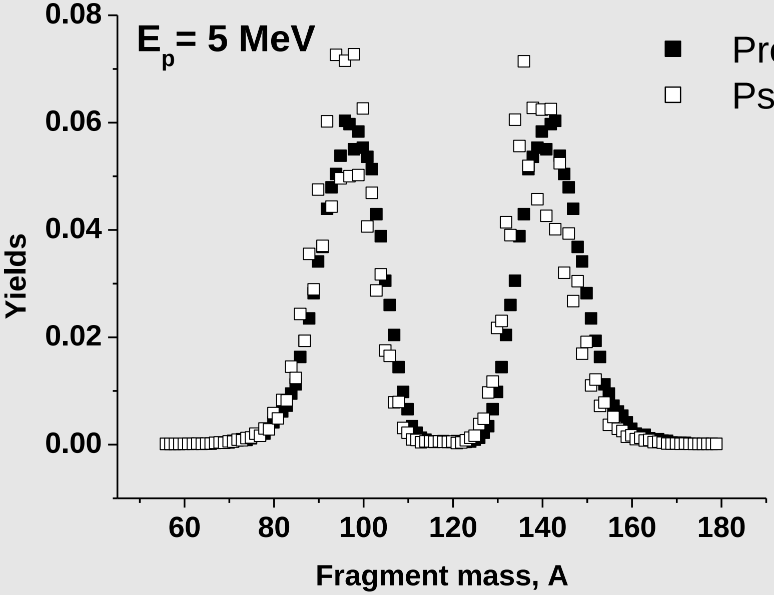


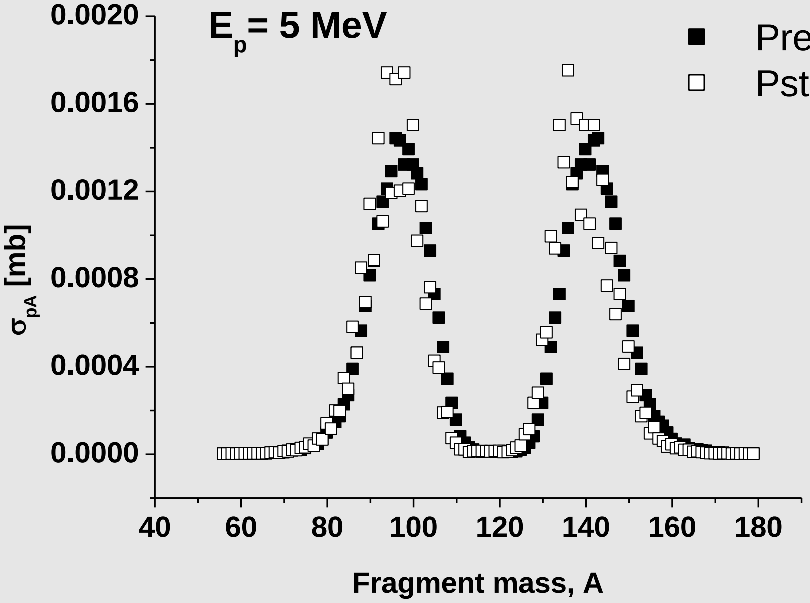
Experimental and Theoretical Data - compared in an energy interval up to 40 MeV
- Contribution of other fissionable nuclei are given / Total Fission XS – Sum off all
- Experimental data are described approximately well – (p,pxf) channel practically neglected / Main contributions given by Np isotope fission

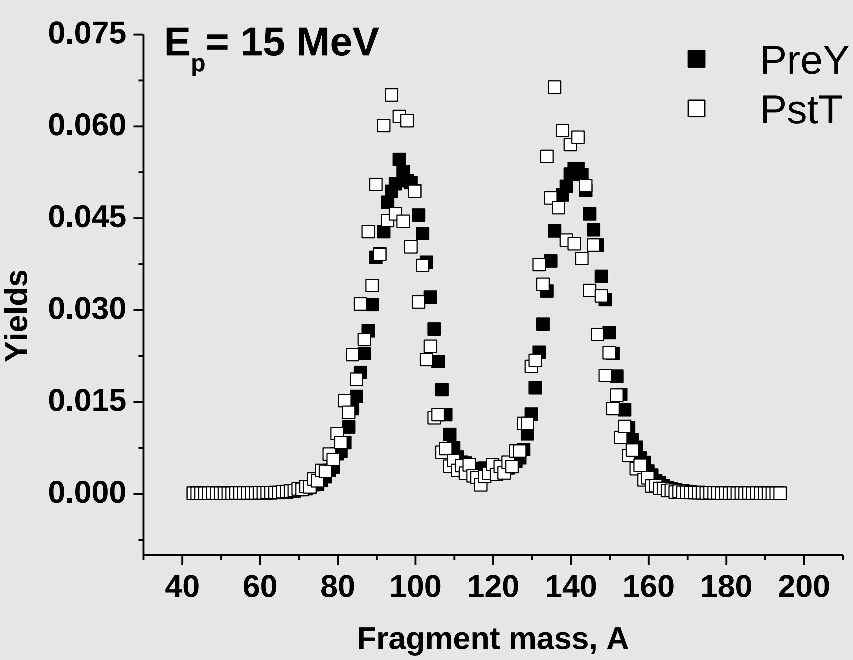
The experimental data – 3 sets of data

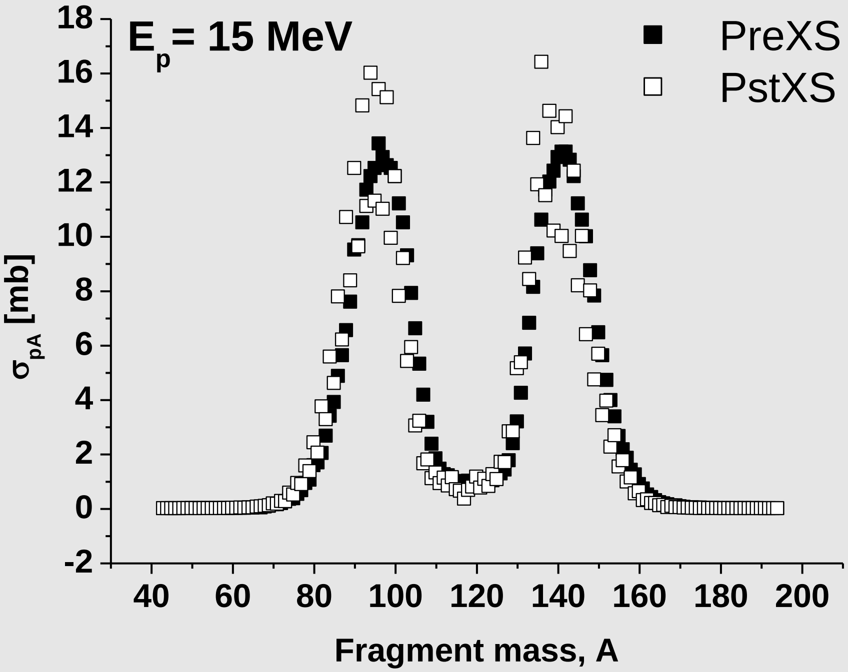
Experimental Data – EXFOR

Fission Fragment Mass Distribution. Yields and Cross Sections (I)

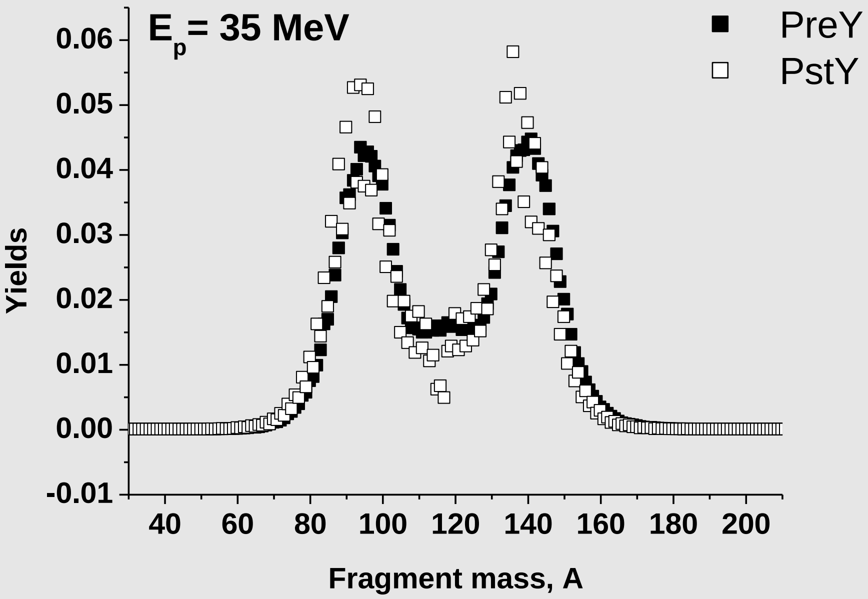


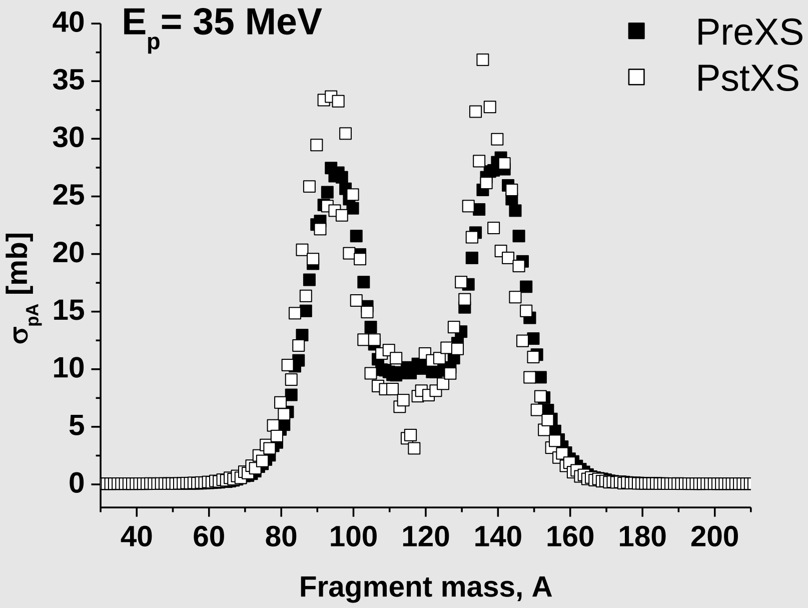






Fission Fragment (FF) Mass Distribution (MD). Yields and Cross Sections (II)

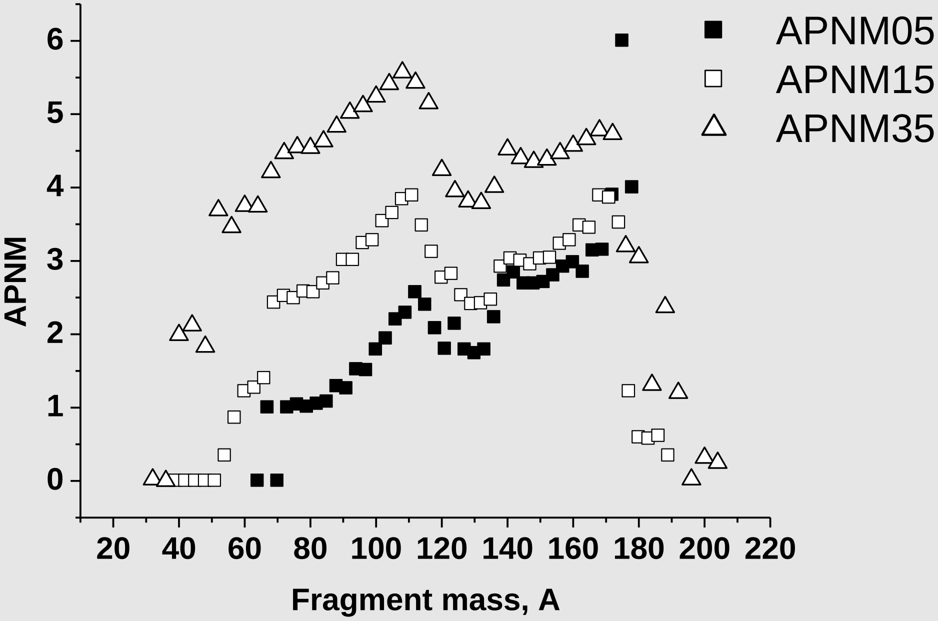


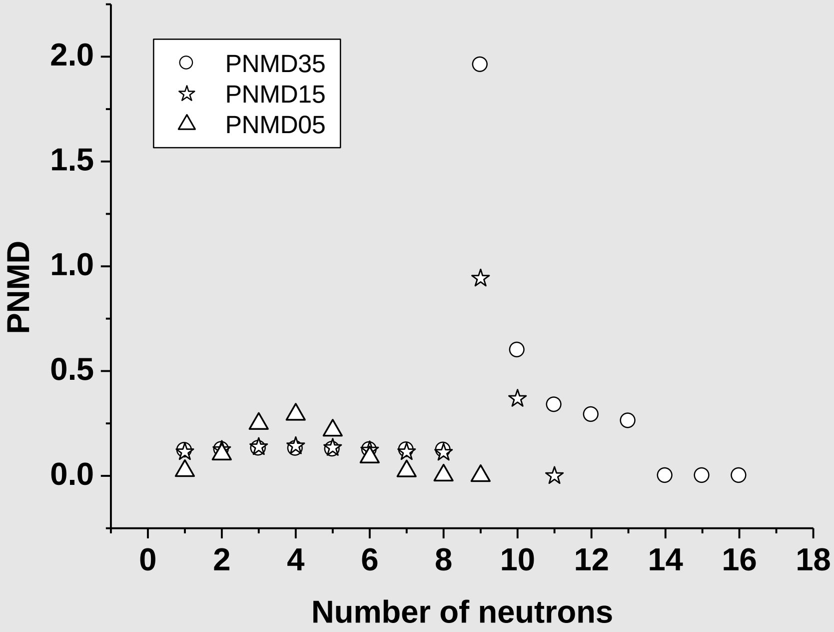


Relative Yields of FF Distribution for Fast Protons / From 5 up to 40 MeV / Pre and Post Neutron Emission

With the increasing of the incident energy the number of produced nuclei is increasing
The MD becomes more symmetric by increasing the incident proton energy; the magnitude of MD (Yields and XS) is slowly increasing
XS is slowly increasing with incident energies

PROMPT NEUTRONS





Average Prompt Neutron Multiplicity (APNM)

- nubar-prompt is increasing
-distribution is enlarging with FF mass
- number of emitted neutrons is increasing
- XS is decreasing - number of prompt neutrons increases – due to high excitation energy

Prompt Neutron Multiplicity Distribution (PNMD)

- increasing with neutron incident energy but limited by excitation energy

$$\bar{\nu}_{pr}(E_p = 5MeV) = 3{,}85$$

$$\bar{\nu}_{pr}(E_p = 15MeV) = 3{,}93$$

$$\bar{\nu}_{pr}(E_p = 35MeV) = 6{,}77$$

Isotope Production

In fission process a large number of artificial nuclei are produced which are of a great interest in many applications

Results of some isotopes of interest like ^{99}Mo, ^{131}I and ^{133}Xe are obtained

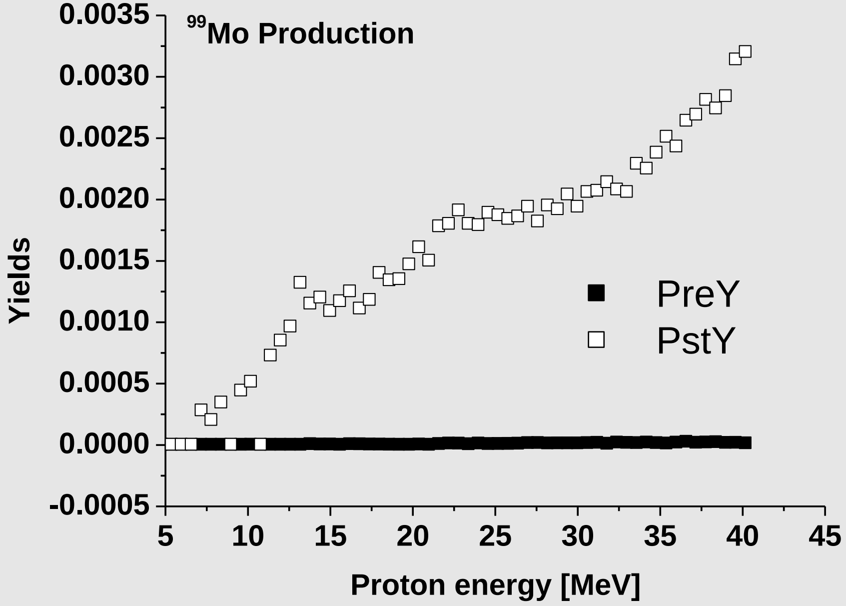
^{99}Mo – very important for medicine in cancer therapy

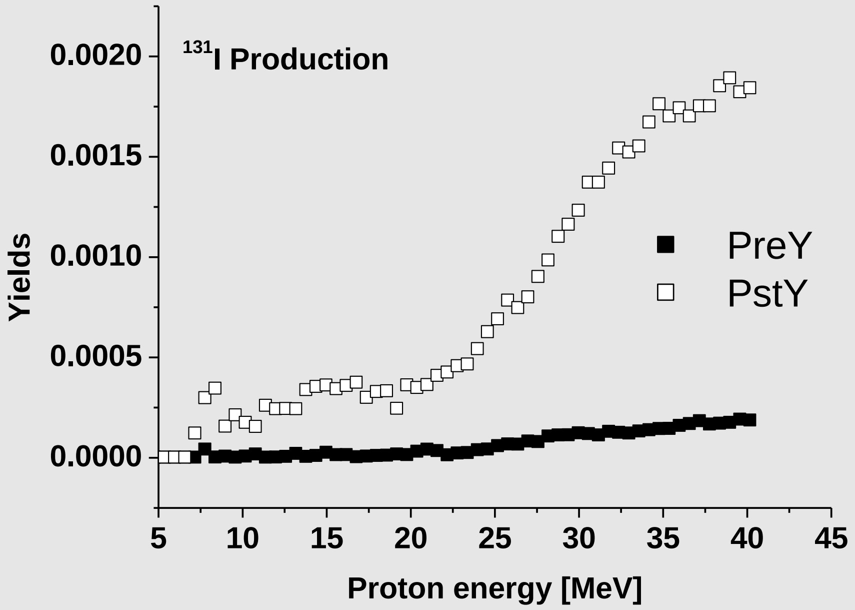
^{131}I – major fission product of Uranium and Plutonium
- important in radiobiological protection, nuclear medicine and industry as tracer

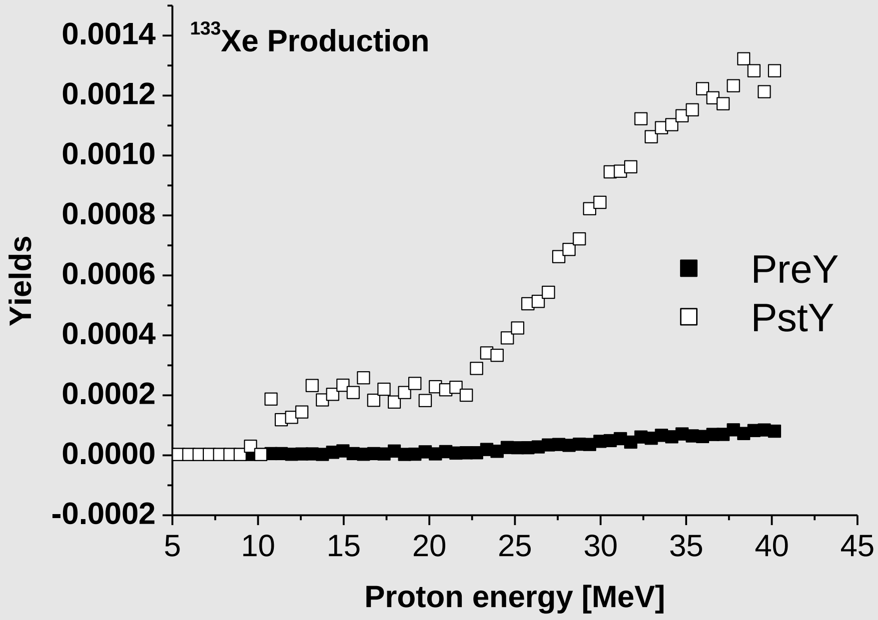
^{133}Xe – for medicine applications

^{135}Xe – important in nuclear reactor technology – a high neutron absorption ~ 2×10^6 b

Isotope Production. ^{99}Mo, ^{131}I, ^{133}Xe. Relative Yields



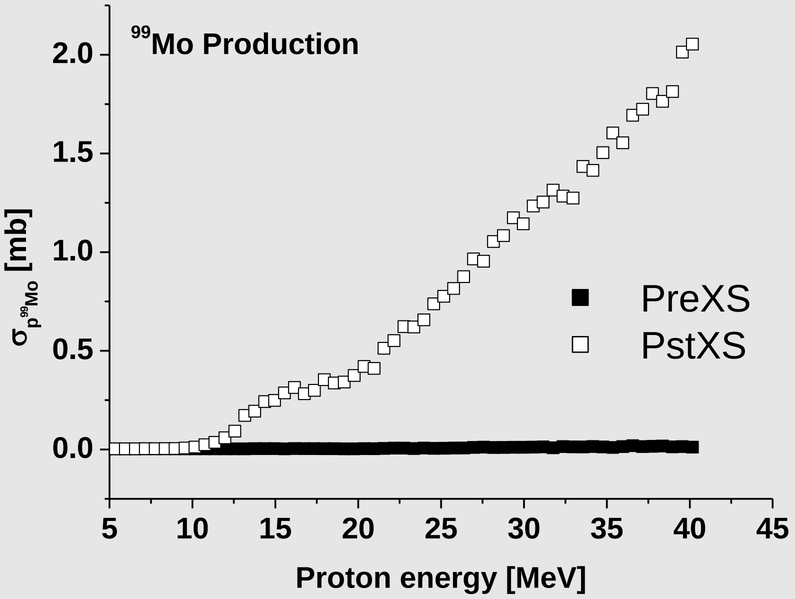


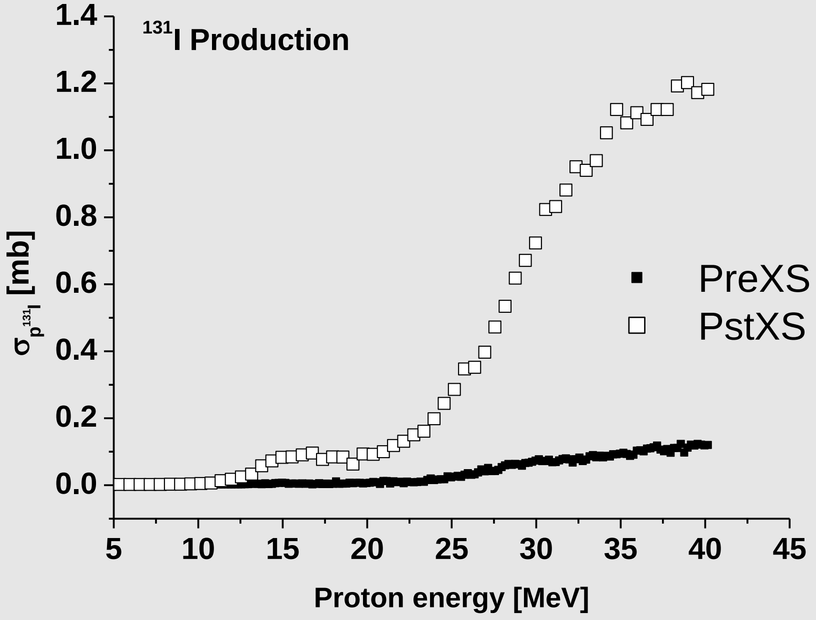


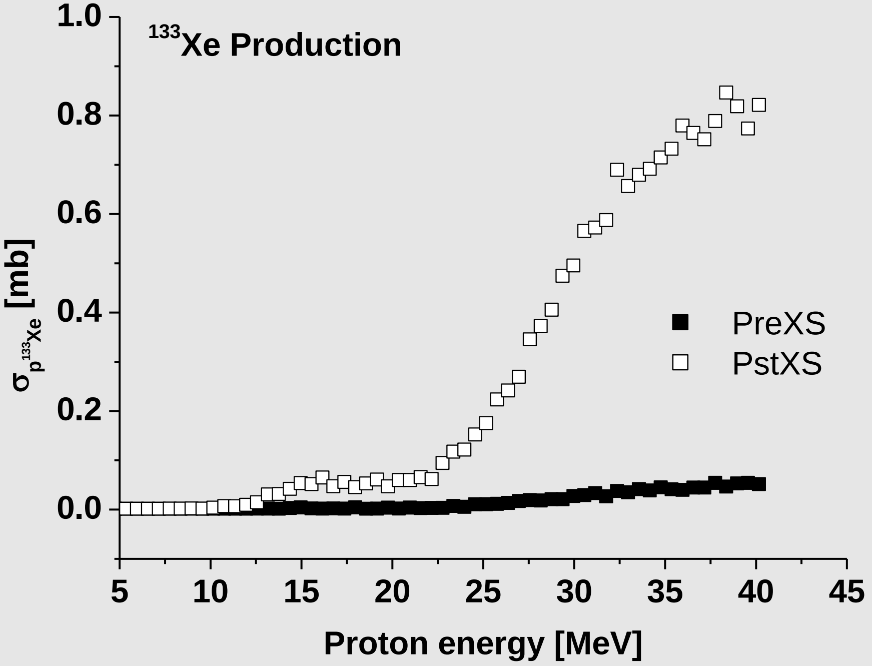
Relative yields of ^{99}Mo, ^{131}I and ^{133}Xe

- Relative Yields were evaluated for a large number of isotopes
- With a standard input these yields are not obtained because they are very low
- It is necessary to increase the precision of calculation in order to obtain parameter evaluations which by default are neglected
- It is opening the possibility to investigate isomer ratios obtained in fission

Isotope Production. ^{99}Mo, ^{131}I, ^{133}Xe. Cross sections



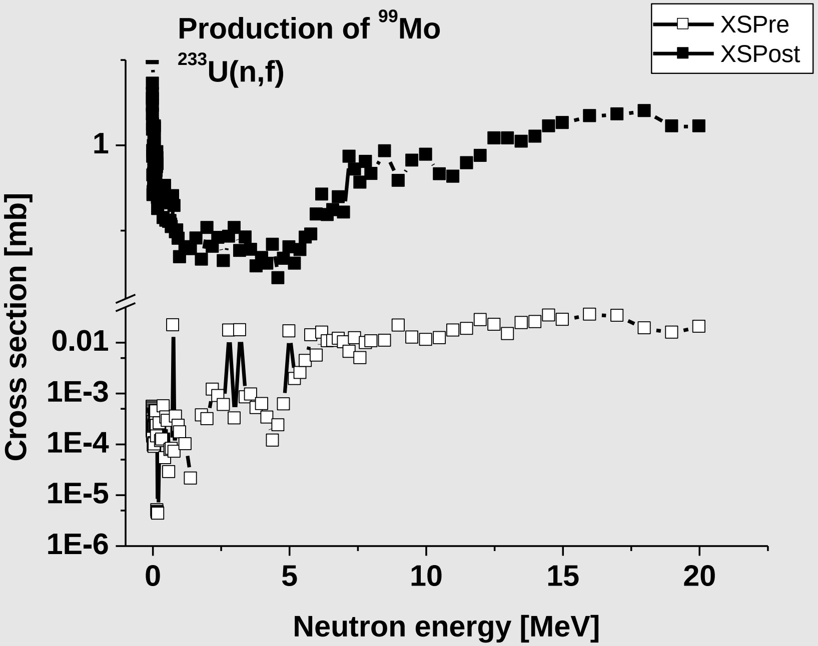


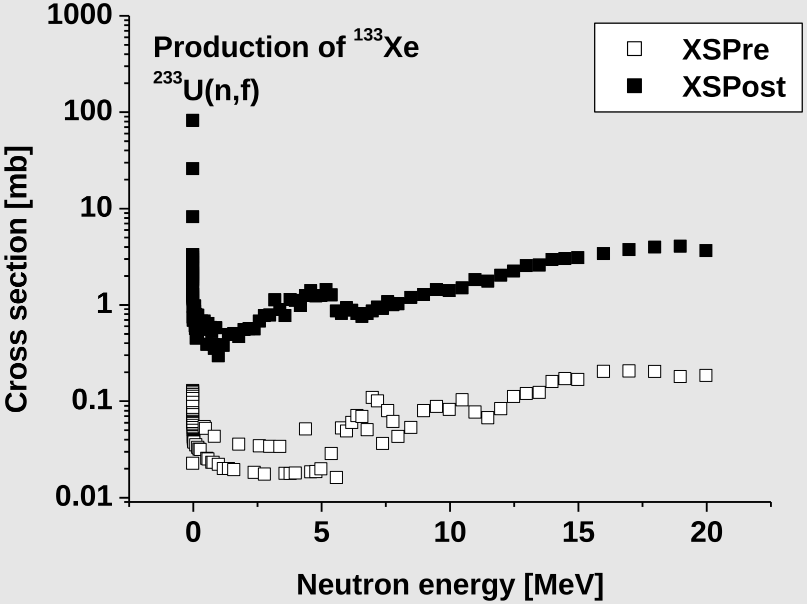


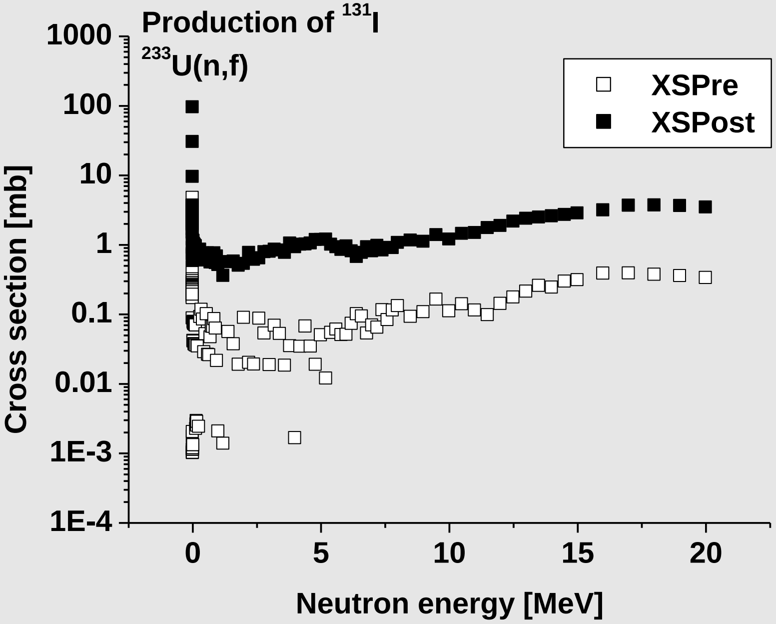
XS Production of ^{99}Mo, ^{131}I and ^{133}Xe as Function of Incident Energy

- XS obtained by increasing Talys precision calculation
- XS for ^{99}Mo are low -> difficult to separate especially due to the isotope time of life
- Same precision for ^{131}I and ^{133}Xe
- For ^{131}I, ^{133}Xe – High XS for slow neutrons
- Possible explanation – these nuclei are closer to stable magic nuclei

Isotope Production. ^{99}Mo, ^{131}I, ^{133}Xe. XS. Comparison with U^{233}(n,f)



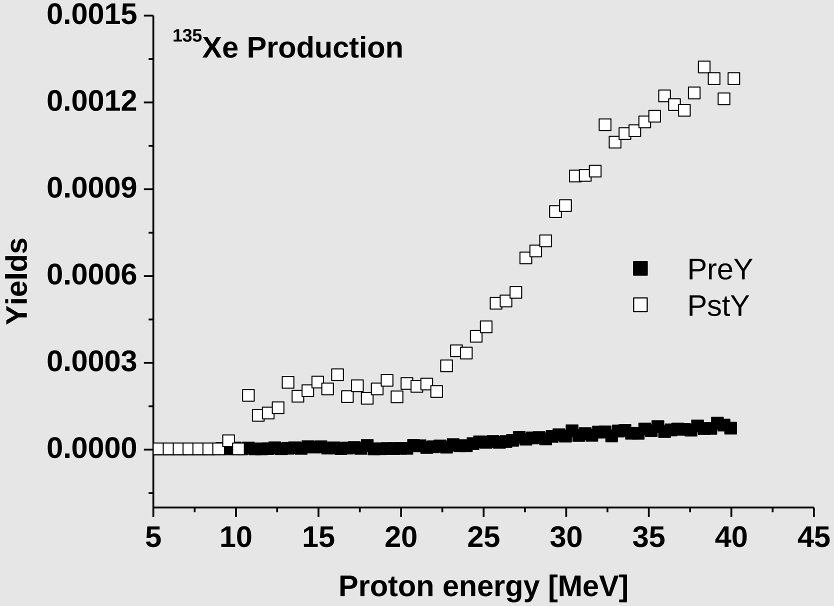


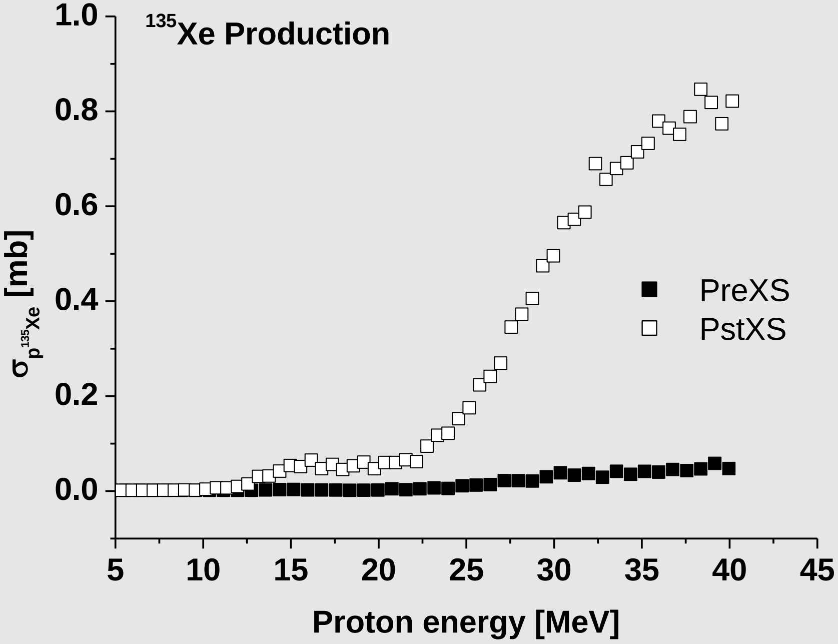


XS Production of ^{99}Mo, ^{131}I and ^{133}Xe

- Large values at slow energies
- XS obtained by increasing Talys precision calculation
- XS for ^{99}Mo are very low -> difficult to separate especially due to the isotope time of life – requires higher precision than ^{131}I and ^{133}Xe
- For ^{131}I, ^{133}Xe – High XS for slow neutrons
- Possible explanation – these nuclei are closer to stable magic nuclei

Isotope Production. ^{135}Xe. Yields and XS





^{135}Xe – neutron absorber -> reactor technology

- ^{135}Xe major neutron induced fission product

- neutron induced fission yields and XS are of the same order of magnitude for ^{99}Mo, ^{131}I and ^{133}Xe

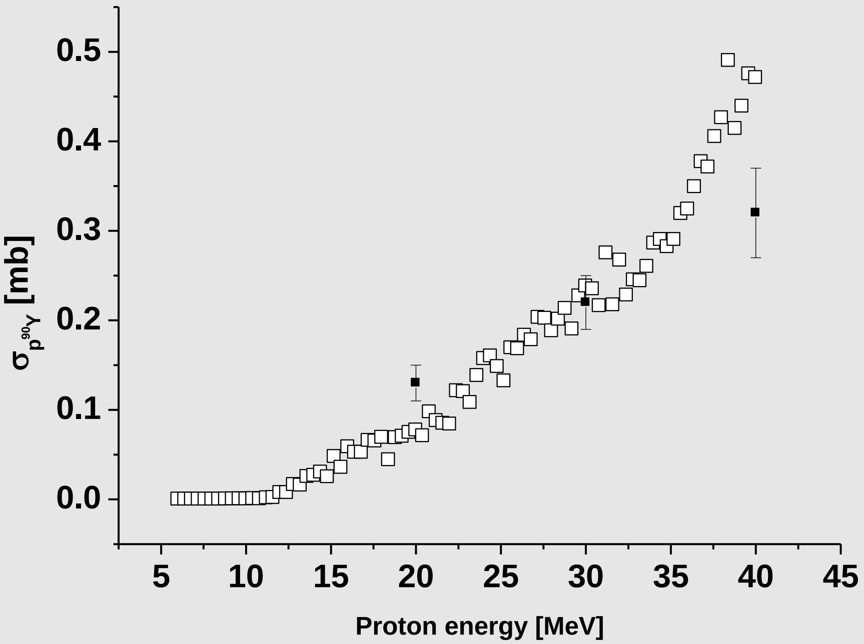
Relative yields, XS production and parameters of potential and level density variation

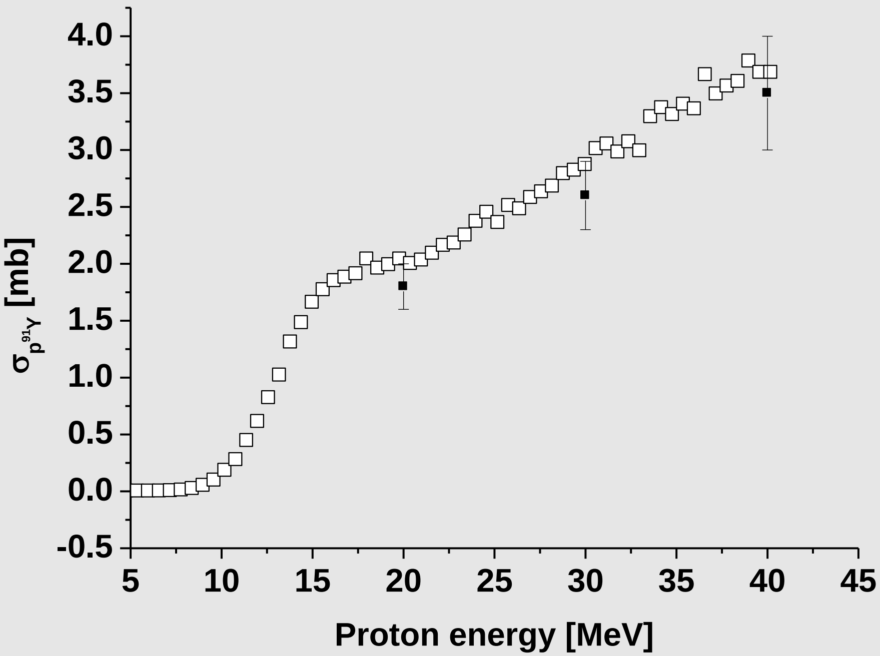
XS Production is lower than in the case of neutron induced fission

^{135}Xe is not a major fission product in fast proton induced fission

Analogue XS were obtained for a large number of isotopes

Yttrium Isotope Production. Theory and Experiment





Production of ^{90}Y (left) and ^{91}Y (right)

^{89}Y - single natural isotope / Other Y isotopes are fission products

- ^{90}Y – of interest for medicine, superconductors, Lithium batteries etc
- Yields and XS isotopes production is proportional with fission XS
- Low XS values
- Well description of cross sections
- Many other comparisons are obtained

RESULTS. Simulation of Isotope Production

Reaction: p + ^{238}U Production of ^{239}Np was chosen

Area of ^{238}U Target – 1 cm^2

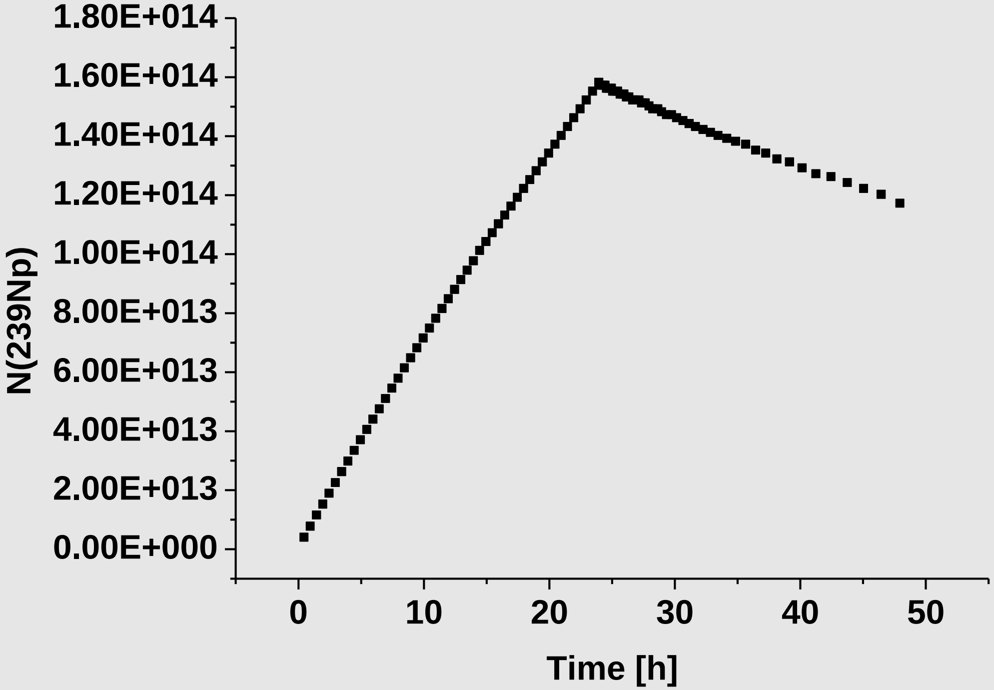
Thickness of the target – 1.85 mm

Density – 19.1 g/cm^3

Proton beam intensity – 0.150 mA

Initial proton energy – 40 MeV

Proton energy loss considered



N(^{238}U) = 8.94 × 10^{21} nuclei

Time of irradiation – 48 h

Cooling time – 24 h

Cross Sections. Yields. Isotope Production. Talys input data

Fission calculations
p+^{238}U – double humped barrier

First barrier
Height: 4.35 MeV; Width: 0.8 MeV
Type of axiality: axial symmetry

Second barrier
Height: 5.5 MeV; Width: 0.8 MeV
Type of axiality: left: right asymmetry

Fission model – chosen experimental fission barrier (Maslov)

Fission model yields – Brosa

Level density model – Constant temperature + Fermi gas

RESULTS. Isotope Production. Talys input data

Optical model parameters – p+^{233}U incident channel
Wood – Saxon Potential

Central	U[MeV]	r[fm]	a[fm^{-1}]
Real	46.75	1.245	0.660
Imaginary	0.09	1.248	0.594
Surface			
Real	0	0	0
Imaginary	2.46	1.208	0.614
Spin-Orbit			
Real	5.680	1.121	0.590
Imaginary	0	0	0

In the evaluation
30 discrete levels for target nucleus
10 discrete levels for residual nucleus
5 excited rotation levels

CONCLUSIONS

- Observables and parameters of proton induced fission process on ^{233}U were investigated
- Cross sections, mass distributions, dependence of average prompt neutron multiplicity on fission fragment mass, isotope production were obtained for incident proton energy starting from 5 up to 45 MeV; the other obtained data up to 70 MeV need more analyses
- Calculations were compared with existing experimental data
- Cross sections well described for fast neutrons

Future plans

- New experimental data on fast protons and neutrons fission of ^{233}U are planned and are necessary
- Project proposals for experiment were performed
- Improvement of theoretical evaluations and computer simulations

THANK YOU FOR YOUR ATTENTION! ☺