EPJ Web of Conferences **111**, 11002 (2016)
DOI: 10.1051/epjconf/201611111002

Neutron Induced Capture and Fission Processes on ^{238}U nucleus

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Abstract. Nuclear data on Uranium isotopes are of crucial interest for new generation of nuclear reactors. Processes of interest are the nuclear reactions induced by neutrons and in this work mainly the capture and the fission process on ^{238}U will be analyzed in a wide energy interval. For slow and resonant neutrons the many levels Breit – Wigner formalism is necessary. In the case of fast and very fast neutrons up to 200 MeV the nuclear reaction mechanism implemented in Talys will be used. The present evaluations are necessary in order to obtain the field of neutrons in the design of nuclear reactors and they are compared with experimental data from literature obtained from capture and (n,xn) processes.

1 Introduction

In the middle of XX century the scientists had already demonstrated that the classical fossil hydrocarbon fuel (gas, coal, oil) will be finished in approximately one century taking into account the predicted temps of world economic development. The nuclear power based on the fission of the ^{235}U induced by slow neutrons as solution for the energetically sustainable development was considered until now. It is well known that this is not a long term solution, because the amount of ^{235}U in natural Uranium is about 0.7% and considering the energy demand of world economy, the planet reserves of ^{235}U will be finished practically in the same time with the fossil fuel [1]. A perspective direction of the development of nuclear energy is the possibility to transform the fissionable nuclei ^{238}U, ^{232}Th and others in nuclear fuels which requires the design and construction of new type of nuclear reactors. Then the energy demand of the world could be ensured for millions years even if the energy request of the planet would be increased by 50-100 times compared with nowadays demand [1,2].

In many countries national programs of research and development of subcritical systems and new generation nuclear reactors based on the fission of ^{238}U induced by fast neutrons are already started or in progress. The experimental, theoretical, computer simulations and numerical results provided by these programs have demonstrated the feasibility of the developed methods based on ^{238}U, natural Uranium and without using ^{235}U, Thorium and spent fuel elements from nuclear plants [3,4].

The fission and capture processes are regarded as concurrent processes in the neutron reactors. The neutron fields can be measured by threshold detectors based on (n,xn) reactions on ^{89}Y. The neutron

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multiplicity and mass distributions are important and necessary elements for calculation of fission reaction chain.

In the present work the cross sections of fission and capture processes induced by fast neutrons on ^{238}U and of the (n,xn) reactions on ^{89}Y nucleus, the mass distributions and neutron multiplicity are evaluated.

2 Theoretical backgrounds

Bohr and Wheeler [5] and Frenkel [6] were the first who have explained quantitatively the fission process in terms of liquid drop model. The authors regarded the nucleus like a classical liquid drop with volume energy and surface tension and on this basis the normal modes of vibration of the drop can be interpreted as excited states of nucleus in a potential barrier. The fission cross section is rising rapidly if the excitation energy is higher than the barrier height or the fission threshold, although the fission is not a threshold process in a conventional way because fission is possible at any excitation energy by barrier tunneling.

The neutron induced fission and (n,xn) cross sections, the mass distribution and neutron multiplicity obtained in the present work were calculated with Talys codes [7]. Fission cross section induced by neutrons with energy from 1 MeV up to 200 MeV was calculated in the frame of a phenomenological approach based on experimental data of fission barrier height and widths with axial asymmetry of the compound nucleus, provided by Talys database [7] and other nuclear data bases from the net.

For the cross sections of neutron capture process by ^{238}U and (n,xn) reactions on ^{89}Y nucleus, in the wide incident neutrons energy range from 2 MeV up to 200 MeV, it is necessary to consider all nuclear reactions mechanisms i.e. the statistical, pre-equilibrium and direct model. Compound processes, which are dominant in the low energy range of 10-20 MeV, by the statistical model of nuclear reactions and Hauser – Feshbach formalism are described [8]. The contribution to the cross section of pre-equilibrium processes is obtained according with the simple two-component exciton model [9]. For the direct processes the Distorted Wave Born Approximation (DWBA) was used [10].

In the cross sections evaluations a local type Wood – Saxon optical potential with all components (volume-central, surface-central, spin-orbit) was considered mainly extracted from experimental data. In the case of no experimental data Talys permits also to define global optical potential according with reference [11]. The mass distribution of the fission fragments and the neutron multiplicity for different energies of incident neutrons, in the cases of pre-neutrons and post-neutrons emission, were obtained using the GEF model (**GE**neral **F**ission model) created by Schmidt and Jurado [12]. This model is founded on some general theoretical ideas with rather general character. It is avoiding microscopic calculation with corresponding approximations and limitations. The GEF model is complemented by a wide volume of empirical information and it is able to give quantitative predictions of fission observables for a large number of fissionable systems.

3 Results and discussions

We have evaluated the cross sections of the ^{238}U(n,f) and ^{238}U(n,γ)^{239}U processes for incident neutrons energy from 1 MeV up to 200 MeV using the standard Talys input. The results are shown in the Figure 1.a and 1.b. The theoretical evaluation of neutron capture and fission reactions are compared with existing experimental results from Internet nuclear data bases [13]. Since the capture and fission cross sections are time consuming the step for the calculations is 10 MeV. From Figures 1.a and 1.b it results that at high neutrons energies the fission process is dominant comparing with the capture process of type ^{238}U(n,γ)^{239}U. We note that the total gamma production is larger with one order of magnitude and it represents the contributions from all processes in which gamma quanta are involved in the exit channels.

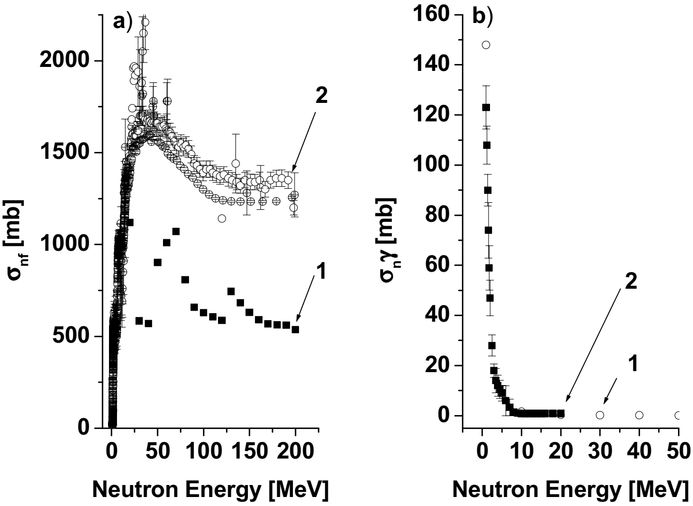

Figure 1. Cross section: a) Neutron induced fission of ^{238}U nucleus; b) Capture ^{238}U(n,γ)^{239}; 1- Talys evaluation; 2- Experimental data.

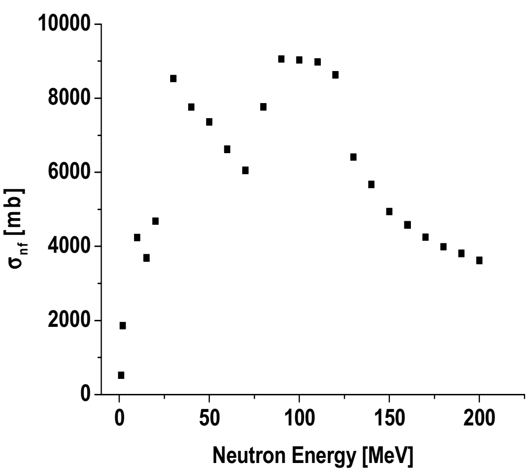

Figure 2. Total gamma production in the neutron capture by ^{238}U nucleus.

The total gamma production in the neutron capture by ^{238}U nucleus is represented in the Figure 2. The comparison of fission theoretical and experimental data can be considered satisfactorily (Figure 1.a). The capture experimental and theoretical data are in a better agreement than the fission data but it's necessary to extend the measurements higher than 20 MeV (Figure 1.b). The Figure 2 suggests that the measurements of the neutron capture of type ^{238}U(n,γ)^{239}U will be very difficult and affected by a large background.

Another interesting features of the fission process are the mass distribution of fission fragments and the neutron multiplicity at a given incident neutron energy before and after neutron emission by fission fragments. In Figures 3.a and 3.b we have the mass distribution at given incident neutron energies, 10 MeV and 100 MeV, respectively. One can observe that the mass distribution becomes more symmetrical with the increasing of the incident neutron energy.

The neutron multiplicity results are shown in the Figures 4.a and 4.b for 10 MeV and 100 MeV, respectively.

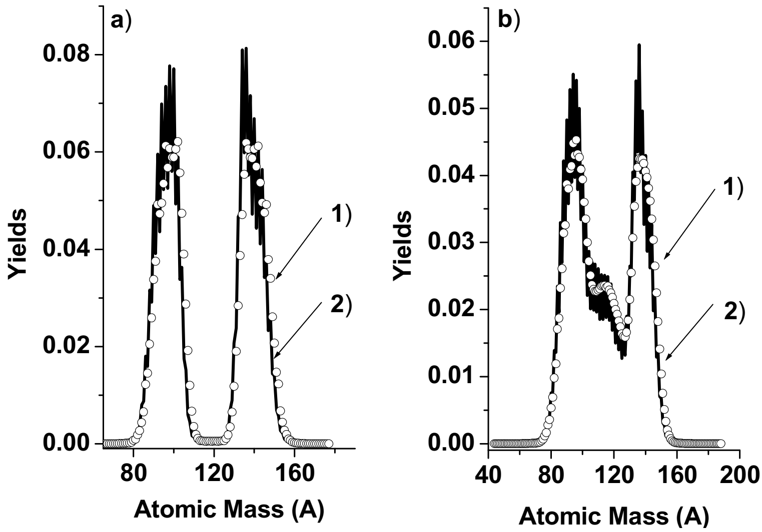

Figure 3. Mass distribution of fission fragment in $^{238}U(n,f)$ process at given incident neutron energy (E_n) before (1) and after (2) neutron emission; a) E_n = 10 MeV; b) E_n = 100 MeV.

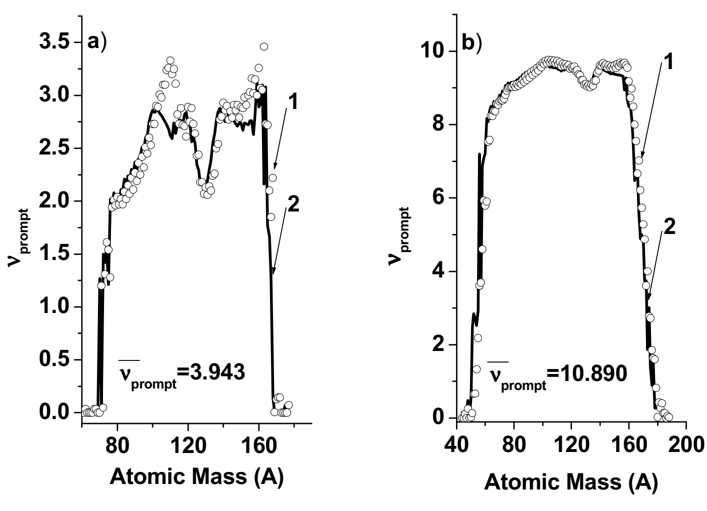

Figure 4. Average prompt neutron multiplicity as a function of mass at given incident neutron energy (E_n) before (1) and after (2) neutrons emission; a) – E_n=10 MeV; b) – 100 MeV.

The ^{89}Y nucleus has no isotope, and in many studies of new reactors, it is used in the design of threshold neutron detectors necessaries for the determination of fast neutrons energy spectrum. We have evaluated the cross sections of $^{89}Y(n,xn)$ reactions (x=1,2,3,4) with standard Talys parameters input. For $^{89}Y(n,2n)^{88}Y$ and $^{89}Y(n,2n)^{87}Y$ reactions the results are compared with experimental data and are shown in the Figure 5. In the case of production of ^{88}Y nucleus the agreement between theoretical and experimental data is very good (Figure 5.a). For ^{87}Y production in the $^{89}Y(n,3n)$ reaction our calculations from Figure 5.b are compared with two sets of experimental data. With the experimental data set noted by 2 in Figure 5.a there are serious differences as compared with theoretical one but with the data set noted with 3 there is a quit good agreement. The experimental data from Figures 5.a and 5.b are taken from [13, 14] and [13, 15, 16], respectively.

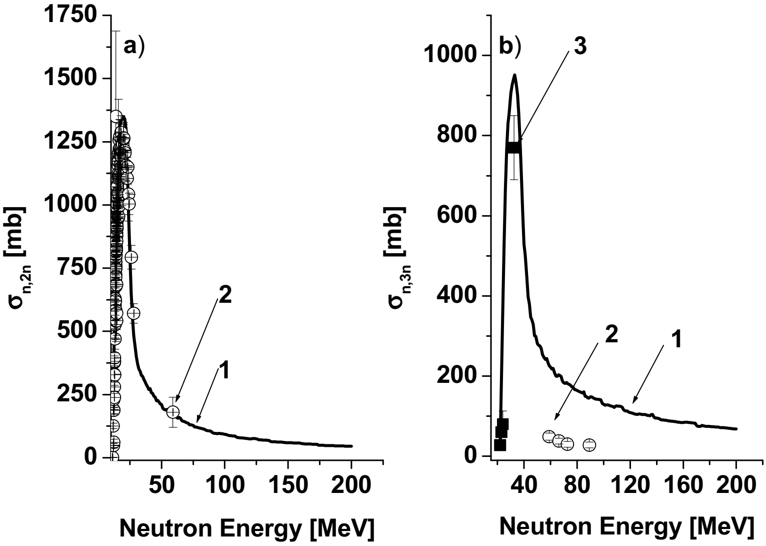

Figure 5. Production of ^{88}Y and ^{87}Y nuclei in: a) $^{89}Y(n,2n)^{89}Y$; b) $^{89}Y(n,3n)^{87}Y$; 1- Talys evaluation compared with experimental data – 2, 3.

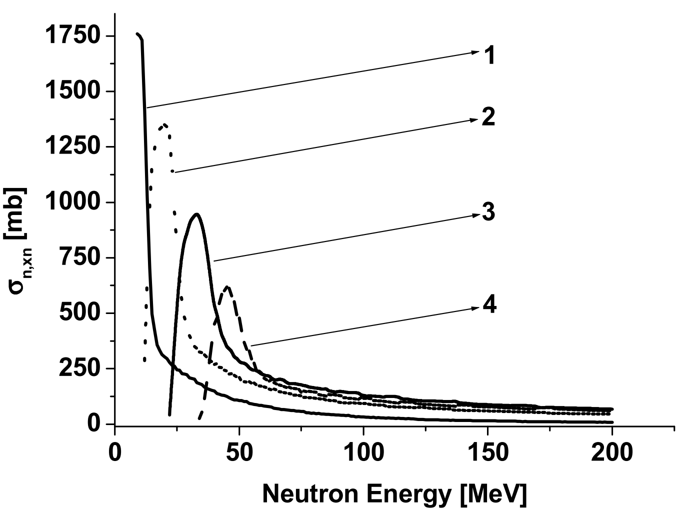

Figure 6. Talys evaluations of $^{89}Y(n,xn)$ reactions (x=1,2,3,4); Production of: 1 – ^{89}Y; 2 – ^{88}Y; 3 – ^{87}Y; 4 – ^{86}Y.

The quit good agreement between experimental and evaluated data of cross sections suggested to the authors to estimate (n,n') and (n,4n) cross sections where the experimental data are lacking or very poor. In Figure 6 the cross sections of production of $^{89,88,87,86}Y$ nuclei in (n,xn) reactions are represented. The cross sections calculations with standard Talys input had showed that in the low energy part of incident neutrons near the threshold, the compound processes are dominant first on discrete states of residual nuclei and step by step with the increasing of energy the discrete states are replaced by continuum ones. Going further on energy after the maximum is passed the contribution in the cross sections of compound processes is decreasing and gradually the pre-equilibrium and direct processes, respectively, become dominant in the cross sections.

4 Conclusions

We have evaluated the cross sections of neutron induced fission and capture on ^{238}U and of the (n,xn) reactions on ^{89}Y nucleus (x=1,2,3,4) from 1 MeV up to 200 MeV by using the Talys code. In the mentioned incident neutron energy interval the nuclear potential, density levels and other parameters (mainly extracted from experimental data practically for all nuclei) necessaries in the evaluations are locally defined. Talys software allows calculations in principle up to 1000 MeV with the so called global defined parameters. In the future the calculations should to be extended higher than 200 MeV up to some GeV as it is requested in the researches dedicated to the fast neutrons reactors of new generation.

On the other hand the energy range lower than 1 MeV, corresponding to the slow and resonant neutrons, is also of interest requesting treatment in the frame of other approaches and formalisms like Multilevel Breit- Wigner, R and/or S matrix.

The mentioned formalisms and computer codes dedicated to nuclear reactions are necessary to be combined with simulation software of the physical experiment as a new and interesting direction of development of the present research.

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