Nuclear Reactions with 14 MeV Neutrons on Molybdenum Isotopes

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Abstract. Molybdenum and Niobium are important chemical elements in many fundamental and applicative researches. The cross sections of fast neutron induced reactions with emission of charged particles in the ^{94}Mo(n,p)^{94}Nb reaction were evaluated. For each process, the contribution of compound, direct and pre-equilibrium nuclear reaction mechanism and the corresponding nuclear data (parameters of nuclear potential, density states and others) were extracted. The present evaluations were done in order to realize new fast neutron measurements at IREN neutron source from FLNP JINR Dubna.

INTRODUCTION

Molybdenum is a chemical element with protons number, Z= 42, it has a total number of 33 isotopes with six natural ones (A= 92, 94, 95, 96, 97, 98) and four isomers. The Mo isotope with mass A= 100 is a fission product and is very important for medicine [1,2].

Nuclear reactions induced by fast neutrons with emission of charged particles like (protons and alphas) are of interest for fundamental and applicative researches. Relative to fundamental studies, these reactions furnish new information about structure of atomic nuclei and nuclear reactions mechanisms. In the applicative researches, (n,p) and (n,α) reactions are of great importance in the material sciences. Due to these processes, in time, in the walls and vessels take place a process of accumulation of Hydrogen and Helium which will modify their physical properties. Further, these reactions provide precise data for nuclear technology, reprocessing of U and Th for future projects of transmutation and energy, processing of long live waste, accelerated driven systems, fast neutron activation analysis etc [3,4].

In the present work the ^{94}Mo(n,p)^{94}Nb reactions with fast neutrons, starting from protons threshold (Q= –1.26 MeV) up to 20 MeV will be analyzed. Residual nucleus ^{94}Nb, obtained in this reactions, has the time of life $T_{1/2}$= 20300 years and can be found in the radioactive waste. Due to its large time of life, the ^{94}Nb isotope contributes to the low level activity of environment caused by buried waste [5]. For this reaction, cross sections were evaluated with Talys. Contributions to the cross sections of different nuclear reactions mechanisms given by discrete and continuum states were separated. Using cross sections theoretical evaluations, isomer ratios were also calculated, parameters of nuclear potential were extracted and finally, some activities were obtained for planned experimental measurements.

THEORETICAL BACKGROUND

Talys represents a freeware computer codes destined for nuclear reactions and structure of atomic nuclei evaluations, working mainly under Linux operation system. In Talys are implemented the main nuclear reaction mechanisms (compound, direct and pre-equilibrium) and large nuclear database which includes information about levels, states densities and parameters of nuclear potentials. This software allows to calculate inclusive and exclusive cross sections. Considering a binary nuclear reaction, A(a,b)B, inclusive cross sections are defined as those cross sections in which are taken into account emergent “b” particles coming not only from the channel “b+B” but from other channels also involving the “b” particles. If in the cross sections are considered emergent “b” particles only from “b+B” channel than the cross section is defined as exclusive. Extensive information about Talys and its possibility is given in the reference [6].

In the cross sections calculations, the compound, direct and pre-equilibrium nuclear reaction mechanisms were taken into account for incident neutrons energy starting from the proton threshold up to 20 MeV. Compound processes are described by Hauser–Feshbach formalism [7], direct processes by Distorted Wave Born Approximation (DWBA) [8] and pre-equilibrium by two-component exciton model [9]. Discrete and continuum states of the residual nuclei were considered together with corresponding nuclear densities based on Fermi gas model [6].

In the incident and emergent channels, the interaction is described by all type of Woods–Saxon potentials like volume, surface, spin-orbit with real and imaginary part. For a very large number of nuclei, in Talys, there are the nuclear potential parameters extracted from experimental data (local parameters). In the situation when for some nuclei the potential parameters do not exist it is possible to obtain them using the global parameters according to the approach described in [6,10].

Another physical values of interest, which can be measured by activation method, are the isomer ratios. Usually, in the experiment, the isomer ratio is defined like [11]:

$$R = \frac{Y_m}{Y_g} = \frac{\int_{Ethr}^{E\max} N_0 \phi(E) \sigma_m(E) dE}{\int_{Ethr}^{E\max} N_0 \phi(E) \sigma_g(E) dE}, \quad (1)$$

where $Y_{m,g}$ are yields of isotope in isomer (m) and ground (g) states; N_0 is number (concentration) of nuclei in the target; ϕ is the flux of incident beam; $\sigma_{m,g}$ are the cross sections production of m and g states respectively; E_{thr} is the threshold energy of emergent particle emission; E_{max} is the maximum energy of incident beam.

For the evaluation of isomer ratio, by activation method, the following relation for observed activity is used [12]:

$$A_{obs} = \frac{N\sigma\varphi a\varepsilon}{\lambda}[1 - Exp(-\lambda t)]Exp(-\lambda T)[1 - Exp(-\lambda \Delta T)]. \quad (2)$$

N is the number of atoms of the isotope of the element; σ is cross section; a is γ-ray abundance; φ is neutron flux; ε is detector efficiency; λ is decay constant; t, T, ΔT are the irradiation time, cooling time and counting times respectively.

RESULTS AND DISCUSSIONS

In the Figure 1, the inclusive cross sections for ^{94}Mo(n,p) process with the separation on different nuclear reaction mechanisms and residual nucleus states, are represented.

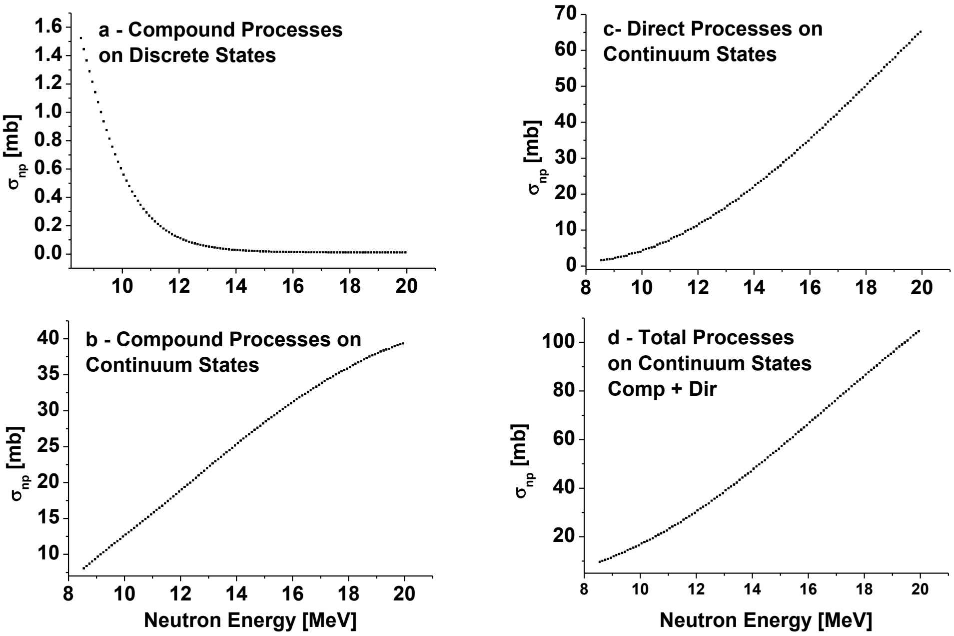

Figure 1. Inclusive cross section in ^{94}Mo(n,p) reaction.

Compound processes on discrete states are with order of magnitude lower than compound processes on continuum states (Figure 1.a and 1.b). Direct processes on discrete states can be neglected and therefore they are not shown in Figure 1. If at low energy, in the threshold region can be considered that the compound processes are dominant, with the increasing of incident energy direct mechanism gives more contribution to the cross section in comparison with compound mechanisms (Figure 1.b and 1.c). In the Figure 1.d, the total inclusive cross section is represented. Both processes (direct and compound) are generated by pre-equilibrium mechanism as is resulting from Talys evaluations.

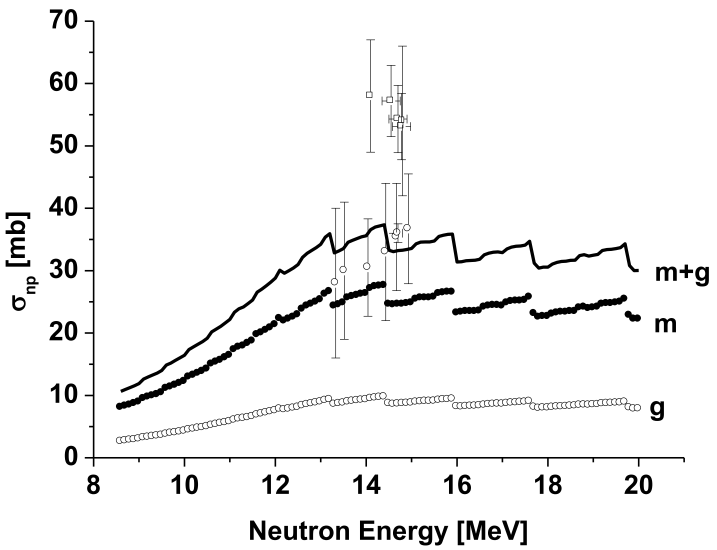

Figure 2. Exclusive cross section in ^{94}Mo(n,p)^{94m,g}Nb reaction. g. – ground; m – isomer; m+g – total; points – two sets of experimental data

The incident neutrons energy dependence of cross section production of ^{94}Nb, from proton threshold, up to 20 MeV, in ^{94}Mo(n,p)^{94m,g}Nb is represented in the Figure 2. The isomer and ground states cross sections production are represented by the curve m) and g) respectively from Figure 2. The total production of ^{94}Nb is given by m+g) in Figure 2. Talys allows to evaluate the exclusive cross section on other levels of residual nucleus but their values are much lower than the contribution of ground and first isomer states and they are neglected.

The total cross section production of ^{94}Nb isotope, obtained with Talys, is compared with experimental data from literature [13]. From Figure 2 it is noticed that there are two sets of experimental data in the 12–16 MeV region, where the cross section has higher value. It is easy to describe one of the experimental set but as a first step is better to use the default Talys input and to consider a satisfactory agreement between theory and experiment.

For the isomer ratios calculations (1), evaluated cross sections and some model for incident neutrons source are necessary. Further characteristic of the ground and isomer states, like spin, parity and time of life are: $(J^{\Pi})_g= 6^+$, τ_g= 20300 y, and $(J^{\Pi})_m= 3^+$, τ_m= 6.23 min, with a low energy gamma transition ΔE_γ= 40.902 keV [14]. Below are given the isomer ratios R, for incident neutron flux: a) ϕ= 1 and b) $\phi\sim (E_n)^{-0.9}$

$$R_a = 2.852 \pm 0.1 \quad \text{and} \quad R_b = 2.860 \pm 0.130 \tag{3}$$

Isomer ratios can be measured in an activation type of experiment. Considering a target of Mo with dimensions 1×1×1 cm^3, irradiated by a neutron flux of type b) ($\phi\sim (E_n)^{-0.9}$), with irradiation time, t= 3 min, cooling time T= 3 min, counting time ΔT= 6 min then, the observed activities (2) for different energies are in Table 1.

Table 1. Observed activities

^{94}Mo(n,p)^{94m}Nb			^{94}Mo(n,p)^{94g}Nb	
E_n[MeV]	σ_m[mb]	A_{obs}[dez]	σ_g[mb]	A_{obs}[dez]
14.1	27.1	$8.75\cdot10^6$	9.48	$6.4\cdot10^{-3}$
20	22.2	$7.17\cdot10^5$	7.83	$4.3\cdot10^{-3}$

Isomer state of ^{94m}Nb requires a short live type of measurement but not enough to evidence the ground state. Nevertheless, a short time measurement can provide new data of isomer state, ^{94m}Nb. Pure target of ^{94}Mo is very difficult to produce then is necessary also to investigate other reactions in which the residual nucleus ^{94}Nb is obtained or in those processes where protons in the emergent channel coming from other isotopes of Mo are obtained.

The parameters of optical nuclear potential, in the incident and emergent channels, which have the most influence on the cross sections, are the volume Woods–Saxon (WS) potential with real and imaginary part and the real part of spin–orbit interaction. The results are in the Table 2.

Table 2. Parameters of Woods–Saxon optical potential

Channel	WS volume						Spin-orbit		
	Real part			Imaginary part			Real part		
	V [MeV]	r_v [fm]	a_v [fm^{-1}]	W [MeV]	r_w [fm]	a_w [fm^{-1}]	V_{so} [MeV]	r_{so} [fm]	a_{vso} [fm^{-1}]
n+^{94}Mo	50.99	1.220	0.658	0.16	1.220	0.658	5.99	1.050	0.58
p+^{94}Nb	61.94	1.215	0.664	0.13	1.215	0.664	6.03	1.043	0.59

Because cross sections are not so influenced by Woods–Saxon surface potential (real and imaginary) and imaginary part of spin-orbit interaction their values are not shown here. The expressions of all Woods–Saxon optical potential can be found in [6].

CONCLUSIONS

The ^{94}Mo(n,p)^{94}Nb reaction with fast neutrons from protons threshold up to 20 MeV, was analyzed. Target and residual nuclei are of great interest in many applications. The inclusive and exclusive cross sections were obtained with default input of Talys. The contribution of each nuclear reaction mechanism related to discrete and continuum states were extracted together with parameters of Woods–Saxon optical potential. Because in this process the isomer state ^{94m}Nb is obtained the isomer ratios, using different model of incident neutrons flux, were determined. The cross sections and isomer ratios can be measured in an activation experiment and therefore observed activities were evaluated. In a short time measurement, in principle it is possible to extract new nuclear data on ^{94m}Nb isotope. Taking into account that a pure ^{94}Mo target is very difficult to obtain, in the future it is necessary to evaluate the influence of other Mo isotopes on the ^{94}Mo(n,p)^{94}Nb process.

The theoretical results on the (n,p) reactions with fast neutrons on ^{94}Mo nucleus can be effectuated at the FLNP JINR Dubna basic facilities and the present work can be considered a starting point for future proposals.

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