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Measurement of Neutron Activation Cross Sections on Mo isotopes in the Energy Range from 7 MeV to 15 MeV

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Abstract. An experimental study of the ^{92}Mo(n,p)^{92}Nb^{m}, ^{92}Mo(n,α)^{89}Zr, ^{95}Mo(n,p)^{95}Nb^{m}, ^{95}Mo(n,p)^{95}Nb, ^{96}Mo(n,p)^{96}Nb, ^{97}Mo(n,p)^{97}Nb, ^{98}Mo(n,p)^{98}Nb^{m}, ^{98}Mo(n,α)^{95}Zr, ^{100}Mo(n,α) ^{97}Zr, and ^{92}Mo(n,2n)^{99}Mo activation reaction cross sections were carried out in the 7-15 MeV energy range at the CV28 compact cyclotron at Physikalisch-Technische Bundesanstalt, Braunschweig. The PTB TOF spectrometer with a D(d,n) source is well suited for this difficult energy range were significant correction for non-monoenergetic neutrons have to be applied. Gamma-ray spectrometry was applied for the measurements of the activity of the reaction products.

1 Introduction

High accuracy neutron induced cross section data for molybdenum isotopes are important for different fields of science and applications. Molybdenum is considered as alloying element in different advanced nuclear energy system developments due to its excellent material properties at elevated temperatures. Improved quality and completeness of the data base are needed for reliable prediction of the materials behaviour under such conditions. Of particular importance for the integrity of the structural materials is the hydrogen and helium production originating from (n,p) and (n,α) processes proposed to be studied. Molybdenum consists of seven stable isotopes. Completeness of the experimental data for Mo isotopes will allow development of nuclear model parameterization in systematic way and validation of the model predictions.

2 Experimental procedure

Neutrons were produced by means of the D(d,n)^{3}He reaction, using a gas target of 3cm length and 1 cm diameter. The cyclotron was operated in a pulse mode with pulse width of about 1 ns. A pulse rate was 1 MHz during the neutron field characterization and 2 MHz during the sample irradiations. The neutron energy was measured using a NE213 detector at a distance of 12 m from the target and time-of-flight method. The samples consist of elemental molybdenum with 99.9% purity in disk-shaped form, 1mm thick and 10 mm in diameter. The samples were placed in front of a fission chamber at zero degree direction relative to the beam axis, at distance of 6 cm from the centre of the gas cell. The

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neutron fluence was monitored by both a low-mass ^{238}U (enriched to 99.98%) fission chamber and an aluminium foil mounted in front of the Mo sample. The mass of the ^{238}U deposit was 101.6 ± 0.6 µg.

For each energy point two irradiations with gas-in and gas-out were carried out and a normalized gas-out component was subtracted. The measured reaction rates were further corrected for the contribution of the breakup neutrons by folding the neutron flux distribution with the shape of the excitation function of $^{238}U(n,f)$, $^{27}Al(n,\alpha)^{24}Na$ or studied reaction. The measured neutron spectral distribution was compared with calculated one using Monte Carlo code SINENA, that include data of double-differential cross sections of the D(d,np) reaction. The detailed study of the D(d,np) double-differential cross sections at incident deuteron energies from 5.3 to 13.3 MeV and neutron emission angles between 0 and 15 degrees carried out at PTB in the past provided characterization of the neutron production from the deuteron breackup reaction on deuterium.

The radioactivity of the irradiated samples was measured by an HPGe detector of 300 cm^3 and a nominal efficiency of 70%. The detector calibration is described in [1]. The samples were placed at 15 mm distance from the entrance window of the detector. Additional measurement at 135 mm was carried out in order to determine the corrections for the coincidence summing effects. The measured values were compared with the calculated ones using a program code developed at PTB. The values of the calculated and measured summing corrections agree within a few per cent. In the sample with natural isotopic composition an interference occurs between the most intensive (778.224 keV) gamma line from the decay of ^{96}Nb and the 777.921 keV gamma rays from the decay of ^{99}Mo. That is why the 568.725 keV gamma line was used in the analysis of the $^{96}Mo(n,p)^{96}Nb$ reaction cross section.

All cross sections were determined relative to $^{238}U(n,f)$ and $^{27}Al(n,\alpha)^{24}Na$ standard cross sections obtained from ENDF/B-VII library [3]. Corrections were applied for the variation of the neutron fluence in time, measurement geometry, dead time effects and coincidence summing effects.

Table 1. Decay data for the studied reactions [2].

Reaction	Isotopic abundance (%)	$T_{1/2}$	E_γ (keV)	Intensity
$^{92}Mo(n,p)^{92}Nb^m$	14.84	10.15 d	934.44	0.9907
$^{92}Mo(n,\alpha)^{89}Zr$	14.84	78.41 h	909.15	0.9904
$^{95}Mo(n,p)^{95}Nb^m$	15.92	3.61 d	235.69	0.248
$^{95}Mo(n,p)^{95}Nb$	15.92	34.991 d	765.803	0.99808
$^{96}Mo(n,p)^{96}Nb$	16.68	23.35 h	568.781	0.58
$^{97}Mo(n,p)^{97}Nb$	9.55	72.1 min	657.94	0.9823
$^{98}Mo(n,p)^{98}Nb^m$	24.13	51.3 min	787.363	0.934
$^{98}Mo(n,\alpha)^{95}Zr$	24.13	64.032 d	756.725	0.5438
$^{100}Mo(n,\alpha)^{97}Zr$	9.63	16.744 h	743.36	0.9306
$^{100}Mo(n,2n)^{99}Mo$	9.63	65.94 h	739.5	0.1213

2 Results

The results of our measurements are shown in the Figs. 1 and 2 together with the data from other authors, retrieved from the EXFOR database [4] and the Evaluated Nuclear Data Files [5,6].

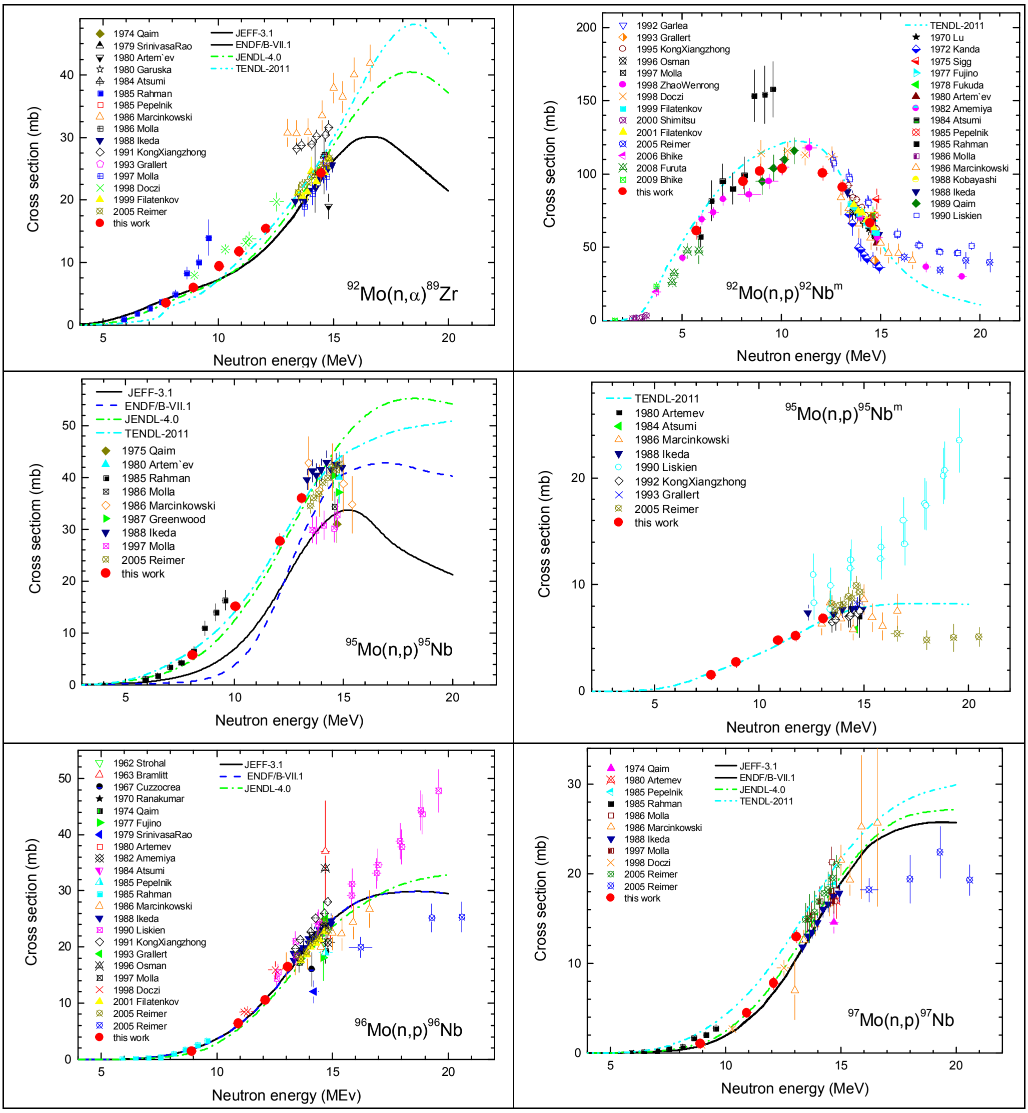

Figure 1. Experimental results for the indicated reactions compared with results from other authors and Evaluated Nuclear Data Files.

New reaction cross section data were obtained for the first time for the ^{95}Mo(n,p)^{95}Nb between 10 and 13 MeV, ^{95}Mo(n,p)^{95}Nb^{m} between 8 and 12 MeV, ^{98}Mo(n,p)^{98}Nb^{m} between 11 and 13 MeV and ^{100}Mo(n,α)^{97}Zr at 11 and 12 MeV. There are only two data sets below 13 MeV for some of the studied reactions, namely 1995 Rahman up to 10MeV and 1998 Doczi between 9 and 13 MeV. Our results for the ^{92}Mo(n, α)^{89}Zr, ^{96}Mo(n,p)^{96}Nb and ^{97}Mo(n,p)^{97}Nb reaction cross sections agree with the data of 1995 Rahman around 8 MeV, however those data are systematically higher above 8 MeV. There are fair agreement with the data of 1998 Dozci for the ^{92}Mo(n, α)^{89}Zr, ^{96}Mo(n,p)^{96}Nb and ^{97}Mo(n,p)^{97}Nb reaction cross sections. Regarding the data for the ^{92}Mo(n,p)^{92}Nb^{m} reaction cross section reported by different authors although the results agree at some of the data points there are differences in the trends of the excitation function suggested by different measurements.

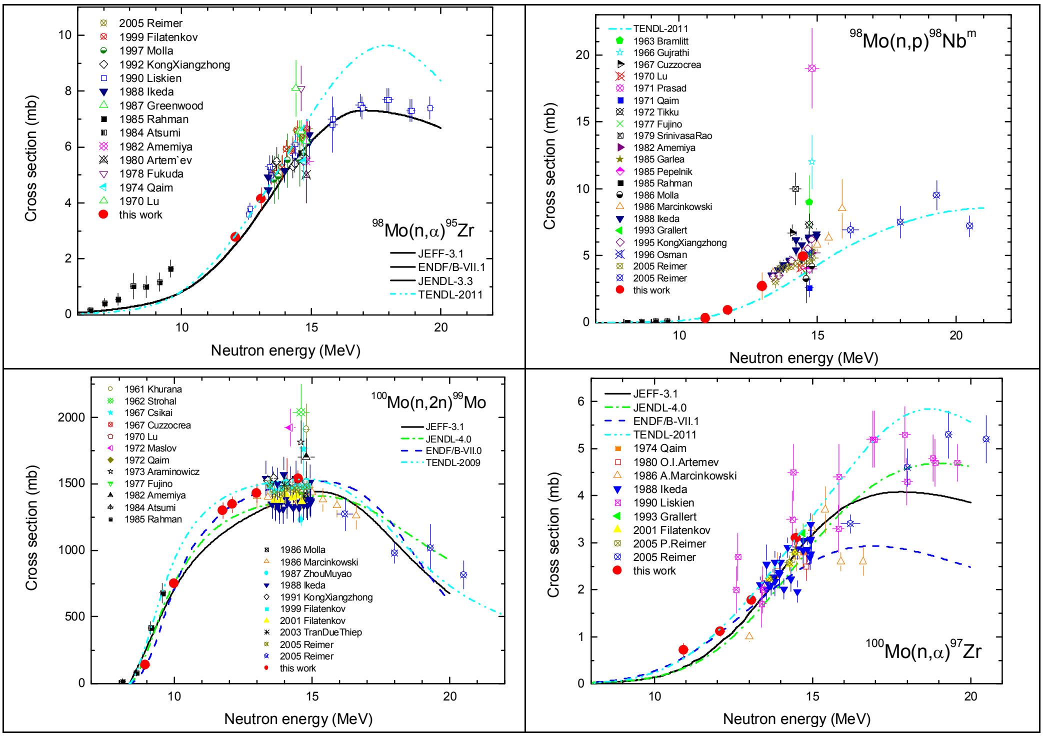

Figure 2. Experimental results for the indicated reactions compared with results from other authors and Evaluated Nuclear Data Files.

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