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Neutron capture and total cross-section measurements on ^{94,95,96}Mo at n_TOF and GELINA

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Abstract. Capture and total cross section measurements for ^{94,95,96}Mo have been performed at the neutron time-of-flight facilities, n_TOF at CERN and GELINA at JRC-Geel. The measurements were performed using isotopically enriched samples with an enrichment above 95% for each of the ^{94,95,96}Mo isotopes. The capture measurements were performed at n_TOF using C_6D_6 detectors and a new sTED detector. The transmission measurements were performed at a 10 m station of GELINA using a ^{6}Li glass neutron detector. Preliminary results of these measurements are presented.

1 Introduction

Cross sections for neutron interactions with molybdenum are important for a broad range of scientific and technological applications ranging from nuclear astrophysics to nuclear power plants.

Molybdenum is found as a pollutant in pre-solar silicon carbide grains and has a crucial role in stellar nucleosynthesis in Asymptotic Giant Branch (AGB) stars [1].

In a nuclear reactor, molybdenum is a component of stainless steel and is also produced as a fission product. It plays a role in criticality safety studies based on a burn-up credit approach [2]. In addition, the use of molybdenum for the production of Accident Tolerant Fuel (ATF) is under study [3]. Finally, molybdenum is considered a promising candidate for new generation research reactors based on UMo alloys with Low Enriched Uranium (LEU) [4].

Nevertheless, cross sections recommended in the main evaluated nuclear data libraries have relatively large uncertainties. In this work capture measurements performed at n_TOF [5] and transmission measurements at GELINA [6] using isotopically enriched samples are described.

2 Production of the starting resonance parameter file

Several experimental data sets for neutron interaction with Mo isotopes are reported in the literature. Using the capture and transmission data available in literature new resonance parameter files were compiled. These files were adjusted to results of transmission measurements performed at the 50 m flight-path station of GELINA using natural molybdenum samples. This adjustment, using the R-matrix code REFIT [7], resulted in a new set of parameters for the stable Mo isotopes up to 5 keV. A detailed description of the procedure can be found in [8].

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3 Samples

For each of the ^{94,95,96}Mo isotopes 2 g of enriched metallic powder were purchased. The declared isotopical enrichment for each batch is higher than 95%. The isotopic composition in wt% is reported in Table 1.

Table 1: *Isotopic composition of the three enriched Mo powders.*

^{92}Mo	^{94}Mo	^{95}Mo	^{96}Mo	^{97}Mo	^{98}Mo	^{100}Mo
0.63%	98.97%	0.36%	0.01%	0.01%	0.01%	0.01%
0.31%	0.69%	95.40%	2.24%	0.51%	0.65%	0.20%
0.28%	0.24%	1.01%	95.90%	1.00%	1.32%	0.25%

Two types of samples were produced: powder samples contained in an aluminum container and pressed powder samples sealed in a plastic bag. The former were used for the first capture measurements at the EAR2 station of n_TOF in 2021. For these measurements the powder was inserted in an aluminum container with an internal diameter of 2 cm. A total of 1.73 g, 0.93 g, and 1.61 g of powder was used for ^{94}Mo, ^{95}Mo, and ^{96}Mo respectively. The capsules were mounted on a Mylar disk and hold in place using a thin layer of Kapton foil.

The self-sustained pressed powder samples with a 2 cm diameter were produced at JRC-Geel. The areal density and weight of these samples are reported in Table 2.

These samples were used for capture cross section measurements at n_TOF and transmission measurements at GELINA.

Table 2: *Characteristics of the enriched pressed powder pellets. The areal density is determined with an uncertainty of 0.1%*

Sample	Areal density (at/b)	Weight (g)
^{94}Mo	3.9595 (40)$\times10^{-3}$	1.9526 (2)
^{95}Mo	3.9539 (40)$\times10^{-3}$	1.9745 (2)
^{96}Mo	3.8056 (40)$\times10^{-3}$	1.9175 (2)

4 Measurements

Capture cross section measurements at the EAR2 station of n_TOF were performed in October 2021 and the second half of 2022. The experimental area is located at 18 m from the neutron source. For the first campaign the samples inserted in an aluminum container were used. Additional measurements with gold, dummy sample, lead, and empty sample holder were performed for normalization and determination of the background. A measurement with a ^{nat}Mo sample was carried out to verify the composition of the samples and the isotopic assignment of resonances. The detection setup consisted of four C_6D_6 detectors and one small volume C_6D_6 detector, referred to as an sTED detector [9]. The neutron fluence rate at EAR2 was monitored using a SiMON monitor, consisting of a ^{6}Li enriched Mylar foil viewed by four silicon detectors [10].

For the second campaign at EAR2 in 2022 the pressed pellet samples were used. The detection setup consisted of 8 sTED and 2 C_6D_6 scintillators and a newly developed deuterated-stilbene detector. Additional measurements with a gold, lead, and an empty plastic bag were performed for normalization and determination of the background.

The pressed powder pellets were also measured at the EAR1 station in 2022. This station is located at 184 m from the spallation target. The measurements were performed using an array of 4 C_6D_6 detectors. Measurements with a gold, lead and an empty plastic bag were performed. In this campaign, also a ^{nat}Mo pressed powder sample was measured. The neutron beam was monitored using a similar SiMON detector as used in EAR2.

Transmission measurements were performed at the 10 m station of GELINA at the beginning of 2022. The neutron beam is measured with a Li-glass scintillator enriched in ^{6}Li. The measurements were carried out using the enriched pressed powder pellets and two pressed powder samples made from ^{nat}Mo. The accelerator was operated at 400 Hz and the moderated neutron beam was used. Measurements with a Co black resonance filter were complemented with measurements using a Bi black resonance filter. The latter were carried out to observe the ^{96}Mo resonance at 130 eV. Additional measurements with a Na and W black resonance filter in the beam were performed to determine the time-of-flight dependence of the background in the whole region.

5 Preliminary results

Preliminary results of the capture measurements at n_TOF are shown in Fig.1 and Fig.2. Fig.1 shows the response of the C_6D_6 detectors as a function of neutron energy resulting from the first campaign at EAR2. The response taken with the ^{95}Mo sample is compared with the one taken with the lead sample and without sample. This comparison illustrates the good signal to background ratio in particular in the thermal energy region. Fig.2 shows the response in the energy region between 10 eV and 10 keV obtained by the 4 C_6D_6 detectors using the ^{96}Mo sample at EAR1. The response resulting from the measurements with the ^{96}Mo sample is compared with the one from the measurements with the empty sample holder and a plastic bag.

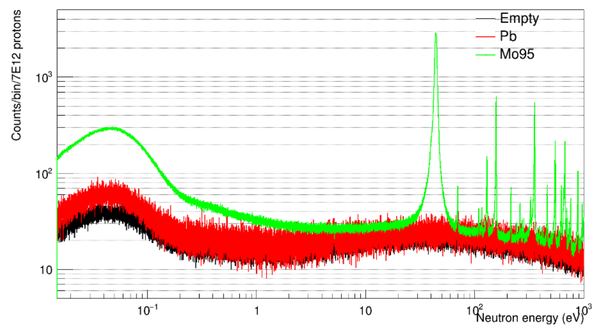

Figure 1: *Response of the capture measurements at EAR2 with the ^{95}Mo sample (green), empty sample (black) and a lead sample (red). All histograms are normalized by the total number of protons produced (divided by 7×10^{12}).*

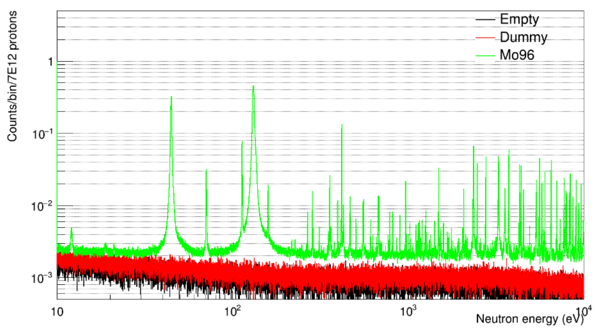

Figure 2: *Response of the capture measurements at EAR1 with the ^{96}Mo sample (green), the empty sample (black) and a dummy made of plastic (red). All histograms are normalized by the total number of protons produced (divided by 7×10^{12}).*

Preliminary results of the transmission measurements at GELINA using the enriched pellets are shown in Fig.3, 4, and 5. These figures compare the experimental and theoretical transmissions as function of incident neutron energy. The latter are derived with REFIT using the resonance parameter file of Ref.[8] and the one recommended in JENDL-3. These figures illustrate the improvement that was made by combining the results of a detailed, critical literature study with an adjustment to transmission data using a ^{nat}Mo sample. Note that JENDL-3 is the basis of the resonance parameters recommended in the latest versions of the main libraries (ENDF/B, JEFF and JENDL).

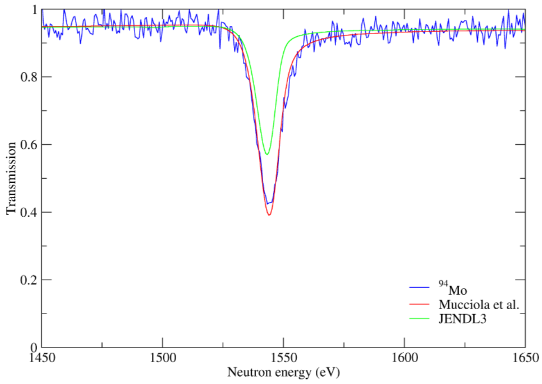

Figure 3: *Transmission though ^{94}Mo enriched sample. The experimental transmission is compared with the calculated one using the parameters in JENDL-3 and Ref.[8]*

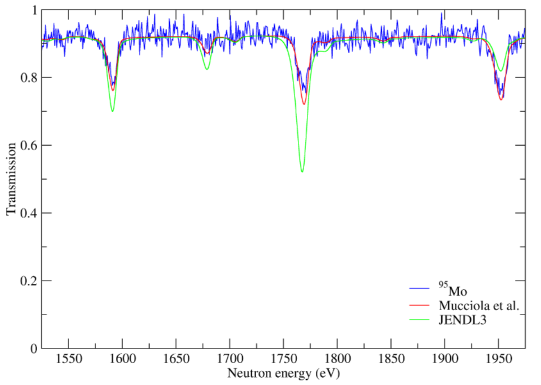

Figure 4: *Transmission though ^{95}Mo enriched sample. The experimental transmission is compared with the calculated one using the parameters in JENDL-3 and Ref.[8]*

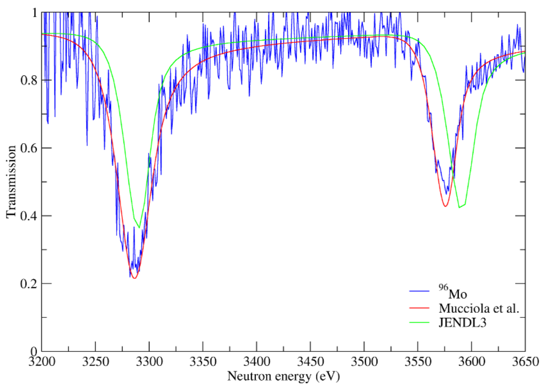

Figure 5: *Transmission though ^{96}Mo enriched sample. The experimental transmission is compared with the calculated one using the parameters in JENDL-3 and Ref.[8]*

6 Conclusions

The measurement conditions of transmission measurements at GELINA and capture cross section measurements at n_TOF to improve the resonance parameters for neutron interactions with ^{94,95,96}Mo were described. The preliminary results of the transmission measurements were used to validate the resonance parameter files for these isotopes obtained in Ref.[8]. Recommendations for new resonance parameters will be given after a simultaneous resonance analysis of the results of the experiments described in this work.

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