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γ-ray production cross sections of inelastic neutron scattering on natural molybdenum

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Abstract. γ-ray production cross sections of inelastic neutron scattering have been measured for molybdenum using the (n,n'γ)-technique. The experiment was performed at the GELINA facility at the Institute for Reference Materials and Measurements (IRMM) with the Gamma Array for Inelastic Neutron Scattering (GAINS) setup. GAINS consisted of eight high purity germanium detectors at the time of this experiment. The sample was made of natural molybdenum, which includes seven isotopes ($A = 92, 94, 95, 96, 97, 98, 100$). The presence of so many isotopes in the sample leads to overlapping peaks in the spectra, which limits the amount of data that can be extracted from the analysis. Nevertheless, a total of 31 γ rays from the seven isotopes were analysed and γ-ray production cross sections were determined. Comparisons to other experimental results were made when such data was available. Also comparisons with model calculations were made with the Talys 1.6 code.

1 Introduction

The inelastic scattering cross sections for molybdenum are interesting in relation to transmutation related reactor concepts emphasising heterogeneous recycling of high level actinide nuclear waste. Power density limitations restrict the minor actinide loading of a fuel rod. In addition, natural uranium or ^{238}U should not be used to dilute the minor actinides in order to avoid further build-up of plutonium and minor actinides. As an alternative molybdenum (or zirconium) are considered as potential inert fuel components. In this case there will be large amounts of molybdenum (or zirconium) present in the reactor core or the reactor blanket. Therefore inelastic scattering of neutrons will be important in modifying reaction rates due to the changes to the neutron energy spectrum [1, 2].

2 Experimental setup

The experiment was performed at the Institute for Reference Materials and Measurements (IRMM). The neutron beam was produced using the Geel Electron Linear Accelerator (GELINA) pulsed white neutron source and the Gamma Array for Inelastic Neutron Scattering (GAINS) setup [3] was used for γ-ray detection. GAINS is located at the GELINA flight path 3, 198.8 m from the neutron source, which produced neutron bursts at a 800-Hz rate. The configuration of GAINS at the time of the experiment consisted of 8 large volume HPGe detectors manufactured by Canberra. The detectors were mounted in angles of 110° and 150° with respect to the beam direction, four detectors at both angles. The neutron flux was measured with a ^{235}U fission chamber located 146.8 cm upstream from the GAINS sample position [4, 5]. Data acquisition for the HPGe detectors utilized Acquiris DC440 digitizers, which had a 12 bit amplitude resolution and a sampling rate of 440 million samples/s. A description of the data acquisition system is given in Ref. [6]. The sample was a natural molybdenum disk supplied by Alfa Aesar. The physical properties of the sample are summarized in Table 1 and the isotopic composition of natural molybdenum is given in Table 2. For this experiment the total data taking time was 26 days.

Table 1. Properties of the molybdenum sample.

Mass (g)	114.32(1)
Diameter (mm)	80.404(2)
Thickness (mm)	2.0(1)
Density (g/cm^3)	11.3(6)

Table 2. Isotopic composition of natural molybdenum (%).

^{92}Mo	14.77(31)
^{94}Mo	9.23(10)
^{95}Mo	15.90(9)
^{96}Mo	16.68(1)
^{97}Mo	9.56(5)
^{98}Mo	24.19(26)
^{100}Mo	9.67(20)

3 Data analysis

The procedure to extract γ-production, level population and inelastic scattering cross sections from GAINS data

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is described in Refs. [3–5]. Experimentally the determination of the γ-ray production cross sections starts from the measured differential γ-production cross sections. At neutron energy E for detector i positioned at an angle θ_i this is given by

$$\frac{d\sigma_i}{d\Omega}(\theta_i, E) = \frac{1}{4\pi}\frac{Y_i(E)}{Y_{\mathrm{FC}}(E)}\frac{\epsilon_{\mathrm{FC}}\sigma_{\mathrm{U}}(E)}{\epsilon_i}\frac{t_{\mathrm{U}}}{t_{\mathrm{S}}}\frac{A_{\mathrm{S}}}{A_{\mathrm{U}}}\frac{1}{c_{\mathrm{MS}}(E)}, \quad (1)$$

where Y_i is the γ-ray yield, Y_{FC} the fission chamber yield, ϵ_{FC} the fission chamber efficiency, ϵ_i the γ-ray detection efficiency, $\sigma_{\mathrm{U}}(E)$ the ^{235}U neutron-induced fission cross section from [7], t_{U}, t_{S}, A_{U}, A_{S} the mass areal densities and mass numbers of ^{235}U and the sample. Finally $c_{\mathrm{MS}}(E)$ is the correction factor for neutron multiple scattering.

Determination of the absolute γ-ray detection efficiency of the GAINS spectrometer relies on Monte-Carlo simulations described in Ref. [8]. First the absolute γ-ray detection efficiency is determined experimentally with a ^{152}Eu point source. An MCNP5 [9] simulation is then done and the model of the setup is adjusted until a satisfactory agreement between the experimental and simulated efficiencies is reached. This geometry is then used in a simulation where the point source is replaced with an area source corresponding to the sample.

4 Results

As natural molybdenum consists of seven isotopes, the number of different γ-ray transitions caused by the inelastic scattering of neutrons is large. This is illustrated in Figure 1, where a portion of the γ-ray energy spectrum from the reaction $^{\mathrm{nat}}$Mo(n,n'γ)$^{\mathrm{nat}}$Mo is shown. Close-lying or overlapping peaks cause difficulties with background subtraction. They also limit the neutron energy range where the γ-ray production cross sections for a single transition can be determined.

Some cases where it was possible to determine γ-ray production cross sections relatively cleanly are shown in Figures 2 and 3 for ^{92}Mo and ^{96}Mo, respectively. Comparisons were also made with some available experimental data and calculations made with the Talys 1.6 code [10]. The calculations were done using the Talys default model. There is a good agreement with the experimental results, except for the $2^+_1 \rightarrow 0^+_{\mathrm{g.s.}}$ transition in ^{92}Mo and the $2^+_{1,2} \rightarrow 0^+_{\mathrm{g.s.}}$ transitions in ^{96}Mo. In the case of the $2^+_1 \rightarrow 0^+_{\mathrm{g.s.}}$ transition in ^{92}Mo a significant discrepancy was found between our results and those of Garrett *et al.*, reported in Ref. [11]. In that work the cross sections were normalized with a calculation using the Gnash code [12] for this particular 1510 keV transition in ^{92}Mo. The normalization point was at neutron energy of 8 MeV.

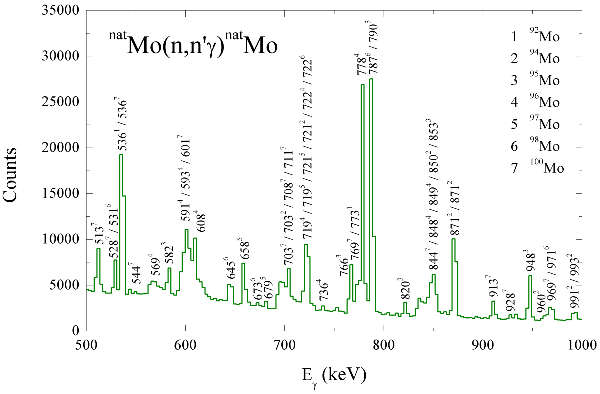

Figure 1. A portion of the γ-ray energy spectrum from the reaction $^{\mathrm{nat}}$Mo(n,n'γ)$^{\mathrm{nat}}$Mo. Several γ-ray transition energies present in the seven isotopes constituting natural molybdenum are indicated in the figure to illustrate the problem with overlapping peaks.

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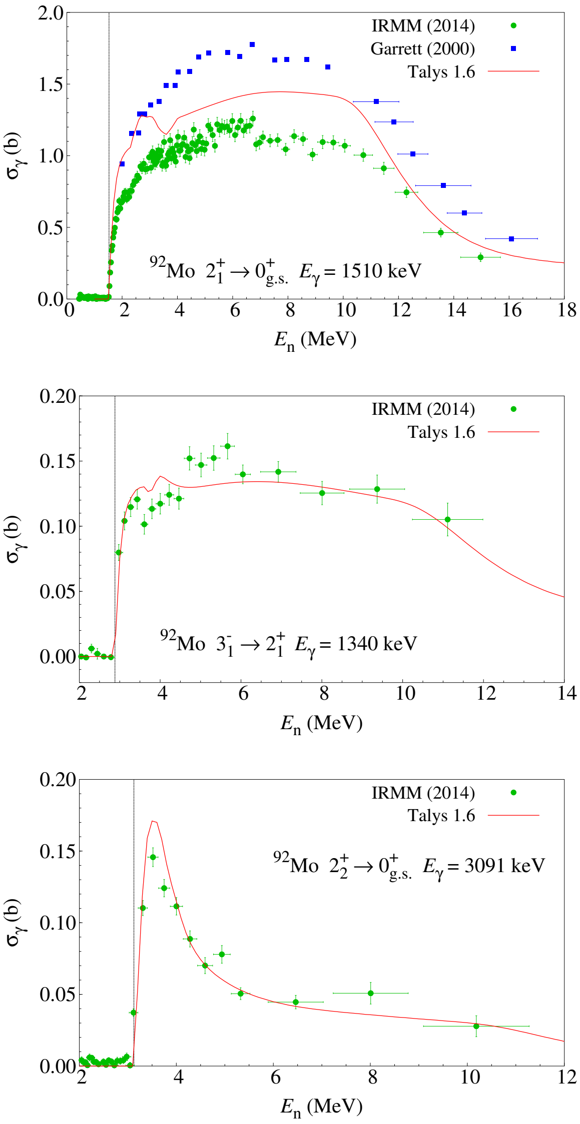

Figure 2. γ-ray production cross sections for three transitions in ^{92}Mo. Comparisons are made with experimental data where available and also with Talys 1.6 calculation.

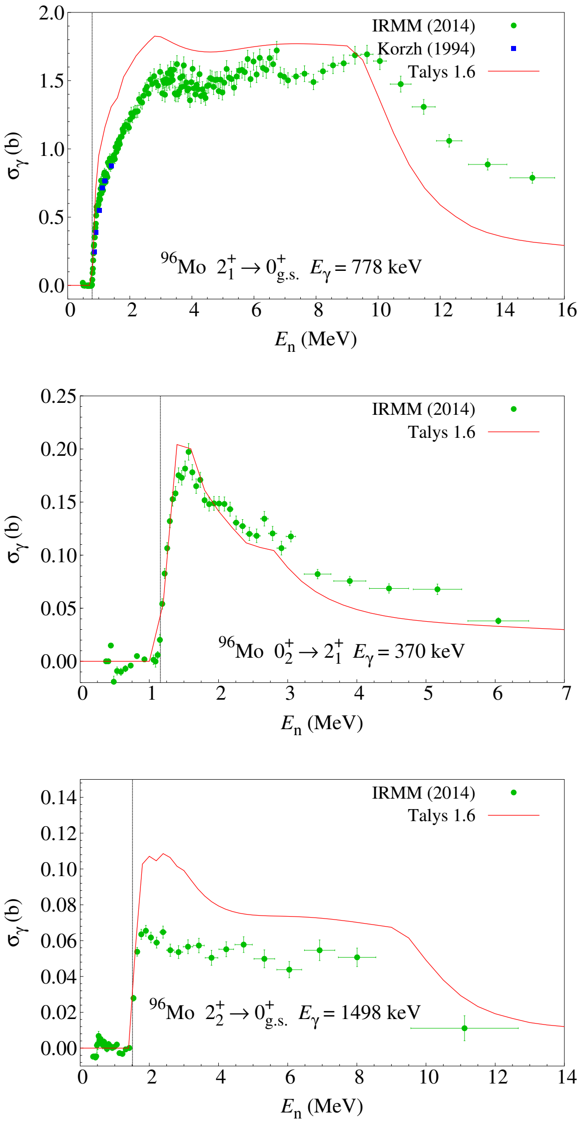

Figure 3. γ-ray production cross sections for three transitions in ^{96}Mo. Comparisons are made with experimental data where available and also with Talys 1.6 calculation.