CROSS-SECTION OF THE $^{100}Mo(\gamma,pn)^{98m}Nb$ REACTION AT BREMSSTRAHLUNG END-POINT ENERGIES UP TO 92.5 MeV

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The photoproduction of the ^{98m}Nb nucleus on natural molybdenum was studied using bremsstrahlung irradiation with end-point energies $E_{\gamma max}$ in the range from 37.5 to 92.5 MeV. The experiment was performed at the electron beam of the LUE-40 linac RDC "Accelerator" of NSC KIPT. Measurements were performed using the activation method and off-line γ-ray spectrometric technique. For the $^{100}Mo(\gamma,pn)^{98m}Nb$ reaction, the experimental flux-averaged cross-sections $\langle\sigma(E_{\gamma max})\rangle_m$ were determined and compared with theoretical predictions. The theoretical values $\langle\sigma(E_{\gamma max})\rangle_m$ for the studied reaction were calculated using the cross-sections σ(*E*) from the TALYS1.96 code for different gamma strength functions *GSF* and level density models *LD*.

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INTRODUCTION

The development of modern theoretical models to describe the mechanisms of photonuclear reactions (direct, compound-nucleus, pre-equilibrium, quasi-deuteron, etc.) is actively ongoing. Modern computational codes, such as TALYS [1], require regular validation using reliable experimental data. For reactions with one or two neutrons, the calculated results obtained with different theoretical models are generally similar. However, the differences between the various theoretical models become more pronounced for reactions with three or more neutron emissions, as well as for reactions involving charged particles or small clusters in the reaction output channel. Therefore, experimental data for multiparticle reactions over a wide range of atomic masses and photon energies are extremely important, as they provide a testing ground for theoretical models.

Photonuclear reactions on molybdenum isotopes have been investigated in a number of works, for example [2–7]. Most studies have focused on photoneutron reactions on molybdenum isotopes at giant dipole resonance energies. These investigations have provided experimental data and revealed systematic patterns that help describe the mechanism of collective nuclear excitation. The effect of isospin splitting of the giant dipole resonance can be explored in photonuclear reactions accompanied by proton emission. However, experimental data on reactions in which a charged particle or a small cluster appears in the output channel are practically absent in the literature due to the very small cross-sections of such processes.

In this work, the production of the ^{98m}Nb in photonuclear reactions on ^{nat}Mo was studied at the bremsstrahlung end-point energy range of $E_{\gamma max}$ = 37.5…92.5 MeV. The obtained experimental results are compared with theoretical estimates based on the cross-sections σ(*E*) from the TALYS1.96 code for nine gamma strength functions *GSF* and six level density models *LD*.

This work continues the research on photonuclear reactions on natural molybdenum with the production of ^{90}Nb and ^{90}Mo [8], ^{95}Nb [9,10], and ^{93m}Mo [11], previously carried out at the linear electron accelerator LUE-40 of NSC KIPT.

EXPERIMENTAL PROCEDURE

The experimental complex for the study of the ^{98m}Nb production in the photonuclear reactions on ^{nat}Mo is presented as a block diagram in Fig. 1. Detailed information about the experimental method used is given, for example, in works [12, 13].

The experiment was performed using the electron linear accelerator LUE-40 of the Research and Development Centre "Accelerator" of the National Science Centre "Kharkiv Institute of Physics and Technology" National Academy of Sciences of Ukraine. The linac LUE-40 provides an electron beam with an average current $I_e \approx 4$ μA and full width at half maximum (FWHM) of energy spectrum $\Delta E_e/E_e \approx 1$ %. The range of initial energies of electrons is E_e = 30…100 MeV [14, 15].

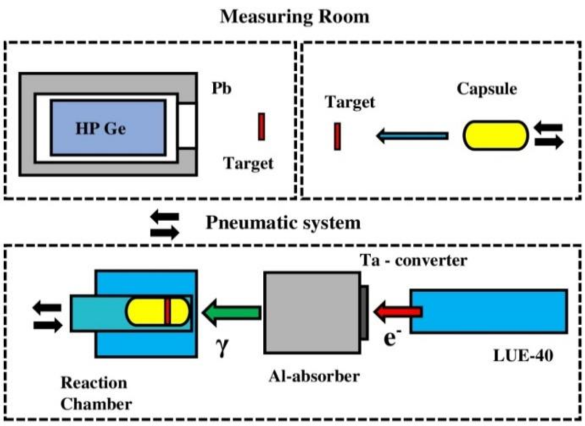

Fig. 1. Schematic block diagram of the experiment. The upper part shows the measuring room, where the irradiated target is extracted from the capsule and is placed in front of the HPGe detector for induced γ-activity measurements. The lower part shows the linac LUE-40, the Ta-converter, the Al-absorber, and the exposure reaction chamber

On the axis of the electron beam, there are a converter, an absorber, and a reaction chamber. The converter, made of tantalum metal, is a 20 × 20 mm plate with thickness *l* = 1.05 mm, and is attached to an aluminum absorber, shaped as a cylinder, with dimensions

∅ 100 × 150 mm. The thickness of the aluminum absorber was calculated to remove residual electrons with energies up to 100 MeV from the bremsstrahlung beam.

For the experiment, targets were made of natural molybdenum, which were thin discs with a diameter of 8 mm and a thickness of ~0.11 mm, corresponding to a mass of ~57…60 mg. Natural molybdenum consists of seven stable isotopes, but the photoproduction of ^{98m}Nb occurs only at the ^{100}Mo isotope. For our calculations, we used the isotope abundance of ^{100}Mo as 9.63%.

The target was placed in an aluminum capsule and delivered by a pneumatic transport system to the reaction chamber for irradiation and back to the measurement room to record the induced γ-activity of reaction products in the target substance.

The induced γ-activity of the targets was detected using a Canberra GC-2018 semiconductor HPGe detector. Its efficiency was 20% relative to the NaI(Tl) scintillator with dimensions 3 inches in diameter and 3 inches in thickness at energy E_γ = 1332 keV. The FWHM resolution is 1.8 keV for energy E_γ = 1332 keV, and 0.8 keV for E_γ = 122 keV. The dead time for γ-quanta detection varied between 0.1 and 5%. The absolute detection efficiency $\varepsilon(E_\gamma)$ for γ-quanta of different energies was obtained using a standard set of γ-rays sources: ^{22}Na, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{241}Am, ^{133}Ba. The analytical curve in the form $\ln\varepsilon(E_\gamma) = \Sigma a_i(\ln E_\gamma)^i$, proposed in [16], was used to determine the value of $\varepsilon(E_\gamma)$ for various energies of γ-quanta.

The electron bremsstrahlung spectra were calculated using the open-source software code GEANT4.9.2, with the PhysList G4LowEnergy [17]. The real geometry of the experiment was used in calculations as well as the space and energy distributions of the electron beam were taken into account.

The bremsstrahlung flux was monitored by the yield of the ^{100}Mo(γ,n)^{99}Mo reaction (the half-life $T_{1/2}$ of the ^{99}Mo nucleus is 65.94 ± 0.01 h) by comparing the experimentally obtained flux-averaged cross-section values $\langle\sigma(E_{\gamma max})\rangle$ with the computation data $\langle\sigma(E_{\gamma max})\rangle_{th}$. To determine the experimental $\langle\sigma(E_{\gamma max})\rangle$ values it has used the yield for the γ-transition of energy E_γ = 739.50 keV and intensity I_γ = 12.13 ± 0.12 %. The flux-averaged cross-section $\langle\sigma(E_{\gamma max})\rangle_{th}$ values were computed using the cross-sections σ(*E*) from the TALYS1.96 code with default parameters. Details of the monitoring procedure can be found, for example, in works [13, 18–21].

The γ-radiation spectrum of a ^{nat}Mo target irradiated by a bremsstrahlung γ-quanta flux with high end-point energy is a complex pattern. There are emission γ-lines of nuclei-product of the ^{nat}Mo(γ,*ypxn*) reactions located on a background substrate, which is formed as a result of Compton scattering of photons. As an example, in Fig. 2 γ-radiation spectrum of a ^{nat}Mo target with a mass of 57.862 mg after irradiation with $E_{\gamma max}$ = 92.50 MeV is shown.

I0n the photonuclear reaction on ^{100}Mo, the nucleus ^{98}Nb can be formed in both the ground and metastable states. However, within a half-life $T_{1/2}$ equals to (2.86±0.06) s, the ^{98g}Nb nucleus transforms into the ^{98}Mo nucleus via β^- decay (100%). Decay of the isomeric state can occur through two channels: internal transition *IT* to ground state (0.1%) and β^- decay (99.9±0.1%). The half-life $T_{1/2}$ of the ^{98m}Nb nucleus is (51.1±0.4) min. Since the cooling time in the experiment was more half an hour, we were able to measure the cross-sections only for the formation of the ^{98m}Nb nucleus in the isomeric state.

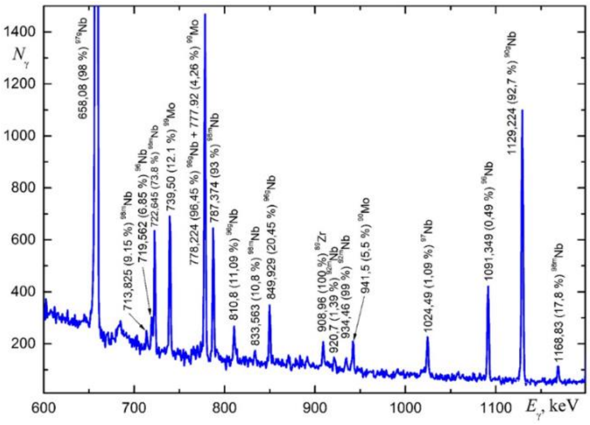

Fig. 2. Fragments of γ-ray spectrum in the energy range 600 ≤ E_γ ≤ 1200 keV from the ^{nat}Mo target of mass 57.86 mg after irradiation of the bremsstrahlung γ-flux at $E_{\gamma max}$ = 92.50 MeV. Irradiation and measurement times were both 3600 s. The γ-line with energy of E_γ = 787.36 keV and an intensity I_γ = (93.07± 0.16)% was used in the investigation

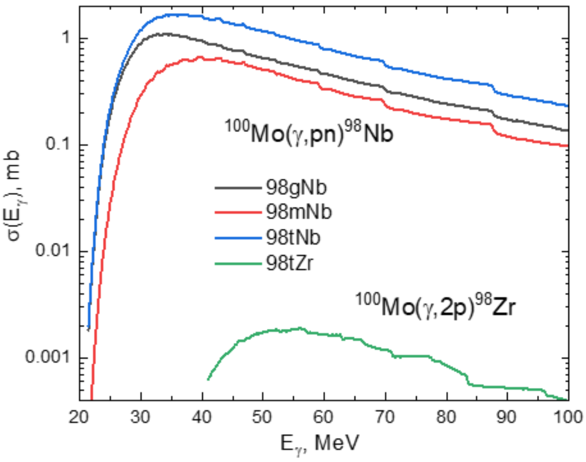

Fig. 3. Theoretical cross-section σ(E) for the formation of the ^{98}Nb and ^{98}Zr nuclei on ^{100}Mo. Calculations are from the TALYS1.96 code (LD2, GSF7)

A photonuclear reaction with the formation of the ^{98}Zr nucleus can also occur on the ^{100}Mo isotope. The nucleus ^{98}Zr can be formed in both the ground and metastable states. The isomeric state of ^{98m}Zr decays into the ground state of ^{98g}Zr with a half-life of $T_{1/2}$ = (1.9±0.2) μs via internal transition *IT* (100%). The ground state of ^{98g}Zr decays with $T_{1/2}$ = (30.7±0.4) s (β^- decay 100%) only to the ground state of the ^{98}Nb nucleus, and does not contribute to the metastable state.

However, we estimated the contribution of the ^{100}Mo(γ,2p)^{98}Zr $-\beta^-\rightarrow$ ^{98g}Nb channel to the total photoproduction yield of the ^{98}Nb nucleus. The calculations with the TALYS1.96 code showed that the upper estimate of this contribution is less than 0.2% (Fig. 3).

To study the ^{100}Mo(γ,pn)^{98m}Nb reaction, the yield for the γ-transition with energy E_γ = 787.36 keV and intensity I_γ = (93.07±0.16)% was used. Nuclear spectroscopic data of the nuclei-products of reactions were taken from the database [22].

CALCULATION OF CROSS-SECTIONS σ(*E*) AND FLUX-AVERAGED CROSS-SECTIONS ⟨σ($E_{\gamma max}$)⟩

In the experiment on a natural Mo target, the ^{98m}Nb nucleus formed only on the ^{100}Mo isotope. The threshold for the formation of the ^{98m}Nb nucleus in the metastable state is 84 keV higher than that for the ground state. The production of the ^{98m}Nb nucleus is possible through two channels, the thresholds for which are given below:

^{100}Mo(γ,pn)^{98m}Nb – E_{thr} = 18.10 MeV,

^{100}Mo(γ,d)^{98m}Nb – E_{thr} = 15.89 MeV.

The cross-sections σ(*E*) of studied reactions for monochromatic photons were calculated using the TALYS1.96 code for the six different level density models *LD* and nine gamma strength functions *GSF*.

Theoretical cross-sections σ(*E*) for reactions ^{100}Mo(γ,*x*)^{98m}Nb, ^{100}Mo(γ,pn)^{98m}Nb, ^{100}Mo(γ,d)^{98m}Nb are shown in Fig. 4. As seen in the figure, the cross-section for the ^{100}Mo(γ,d)^{98m}Nb reaction is very small. Theoretical calculations based on the TALYS1.96 code showed that the contribution of this reaction to the total yield of ^{98m}Nb is less than 1%. Therefore, in our work, we assumed that the ^{98m}Nb nucleus production will occur only through the ^{100}Mo(γ,pn)^{98m}Nb reaction.

The cross-sections σ(*E*) were averaged over the bremsstrahlung flux $W(E, E_{\gamma max})$ in the energy range from the threshold of the corresponding reaction E_{thr} to the maximum energy of the bremsstrahlung spectrum $E_{\gamma max}$. As a result, flux-averaged cross-section values were obtained:

$$\left\langle \sigma\left(E_{\gamma\max}\right)\right\rangle = \frac{\int_{E_{th}}^{E_{\gamma\max}} \sigma(E) W\left(E, E_{\gamma\max}\right) dE}{\int_{E_{th}}^{E_{\gamma\max}} W\left(E, E_{\gamma\max}\right) dE}. \quad (1)$$

For the calculations of the flux-averaged cross-section for the ^{100}Mo(γ,pn)^{98m}Nb reaction were performed using the threshold value E_{thr} = 18.1 MeV.

EXPERIMENTAL RESULTS

The cross-sections for the formation of the ^{98m}Nb nucleus in the metastable state in the reaction on ^{nat}Mo can be determined from direct measurements of the number of counts of γ-quanta Δ*A* in the full absorption peak at an energy of 787.36 keV. To calculate the experimental values ⟨σ($E_{\gamma max}$)⟩ the following expression was used:

$$\left\langle \sigma\left(E_{\gamma\max}\right)\right\rangle = \frac{\lambda \Delta A}{\varepsilon N_x I_\gamma \Phi\left(E_{\gamma\max}\right)\left(1-e^{-\lambda t_{irr}}\right) e^{-\lambda t_{cool}} \left(1-e^{-\lambda t_{meas}}\right)}, \quad (2)$$

where $\Phi\left(E_{\gamma\max}\right) = \int_{E_{thr}}^{E_{\gamma\max}} W\left(E, E_{\gamma\max}\right) dE$ – the sum of bremsstrahlung flux quanta in the energy range from the reaction threshold E_{thr} = 18.1 MeV to $E_{\gamma max}$, N_x is the number of studied atoms (just ^{100}Mo), I_γ – the intensity of the analyzed γ-quanta, ε – the absolute detection efficiency for the analyzed γ-quanta energy, λ is the decay constant

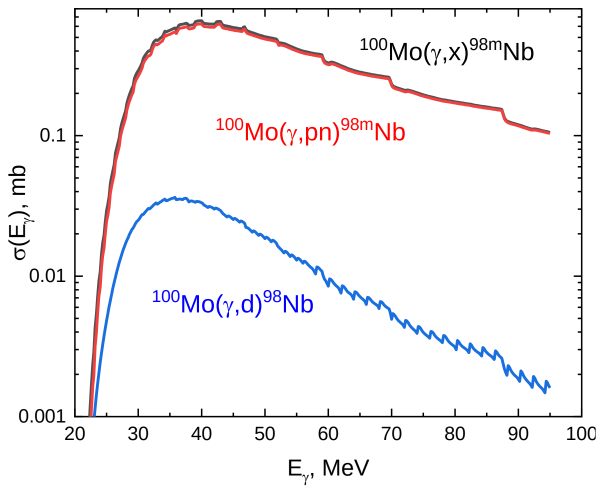

Fig. 4. Theoretical cross-section σ(E) for reactions ^{100}Mo(γ,x)^{98m}Nb, ^{100}Mo(γ,pn)^{98m}Nb, ^{100}Mo(γ,d)^{98m}Nb. Calculations are from the TALYS1.96 code (LD2, GSF7)

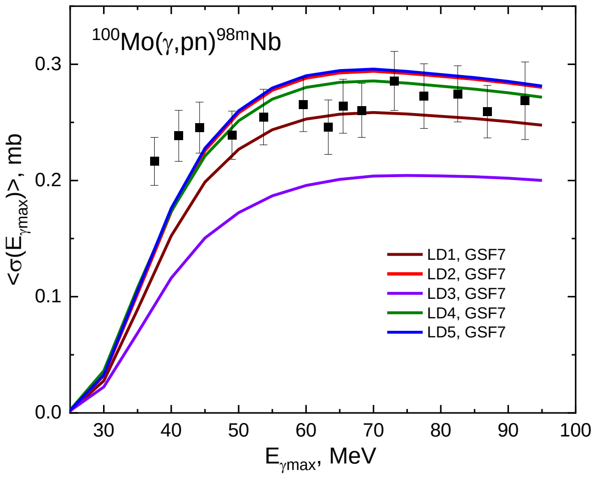

Fig. 5. The flux-averaged cross-section ⟨σ($E_{\gamma max}$)⟩$_m$ for the formation of the ^{98m}Nb nucleus on ^{100}Mo. Black points – experimental data, curves – calculations for different options LD and GSF

(ln2/$T_{1/2}$), t_{irr}, t_{cool} and t_{meas} are the irradiation time, cooling time and measurement time, respectively.

The contribution of background lines (E_γ = 785.37 and 785.96 keV) to the total activity of the ^{98m}Nb nucleus by the 787.36 keV transition was insignificant. For the cross-section value at 37.5 MeV, this contribution is less than 0.5% and decreases with increasing energy.

The uncertainty of measured flux-averaged cross-sections was determined as the square root of the quadratic sum of statistical and systematic errors. The statistical error in the observed γ-activity is mainly due to counting statistics in the full absorption peak of the corresponding γ-ray, which varies between 1.6 and 4.4%. A detailed description of the errors can be found in the work [12].

The experimental values of the flux-averaged cross-section ⟨σ($E_{\gamma max}$)⟩$_m$ of the ^{nat}Mo(γ,pn)^{98m}Nb reaction were determined at bremsstrahlung end-point energies ranging from 37.5 to 92.5 MeV and are presented in Fig. 5.

Fig. 5 also shows the theoretical values of the flux-averaged cross-sections. A discrepancy is observed between the theoretical cross sections obtained with some

TALYS1.96 parameter sets and the experimental data. The results obtained with the parameters LD4 and GSF7 are closest to the experimental data.

CONCLUSIONS

In the present work, the experiment was performed using the beam of the LUE-40 linear electron accelerator of RDC "Accelerator" of NSC KIPT, and the γ-activation and off-line γ-ray techniques. The bremsstrahlung flux-averaged cross-section $\langle\sigma(E_{\gamma max})\rangle_m$ for the ^{98m}Nb photoproduction in photonuclear reactions on ^{100}Mo targets was determined. The bremsstrahlung end-point energy range was $E_{\gamma max}$ = 37.5…92.5 MeV.

The flux-averaged cross-sections $\langle\sigma(E_{\gamma max})\rangle_{th}$ were calculated using the cross-sections σ(*E*) for the studied reactions from the TALYS1.96 code with different gamma strength functions *GSF* 1-9 and level density models *LD* 1-6. The calculated results with the parameters *LD*4 and *GSF*7 are the closest to the experimental data.

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22. Live Chart of Nuclides
https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

ПОПЕРЕЧНИЙ ПЕРЕРІЗ РЕАКЦІЇ $^{100}Mo(\gamma,pn)^{98m}Nb$ ПРИ ЕНЕРГІЯХ ГАЛЬМІВНОГО ВИПРОМІНЮВАННЯ ДО 92,5 МеВ

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Фотоутворення ізотопу ^{98m}Nb на природному молібдені досліджували методом гальмівного опромінення в діапазоні максимальної енергії гамма-квантів $E_{\gamma max}$ від 37,5 до 92,5 МеВ. Експеримент виконано на електронному пучку лінійного прискорювача ЛУЕ-40 НДК «Прискорювач» ННЦ ХФТІ. Вимірювання проводили за допомогою методу наведеної γ-активності та офлайн γ-спектроскопії. Для реакції $^{100}Mo(\gamma,pn)^{98m}Nb$ визначено експериментальні усереднені за потоком перерізи $\langle\sigma(E_{\gamma max})\rangle_m$, які можна порівняти з теоретичними розрахунками. Теоретичні значення $\langle\sigma(E_{\gamma max})\rangle$ для досліджуваної реакції розраховано з використанням перерізів $\sigma(E)$, отриманих у коді TALYS 1.96 для різних варіантів силової гамма-функції *GSF* та моделей щільності рівнів *LD*.