

PHOTOPRODUCTION OF ^{98m}Nb ON NATURAL MOLYBDENUM AT BREMSSTRAHLUNG END-POINT ENERGIES UP TO 95 MeV

**I.S. Timchenko^{1,2}, O.S. Deiev², S.M. Olejnik², S.M. Potin²,
V.A. Kushnir², V.V. Mytrochenko², A. Herzán¹**

¹ *Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*

² *NSC “Kharkiv Institute of Physics and Technology”, Kharkiv, Ukraine*

The development of modern theoretical models to describe the mechanisms of photonuclear reactions (direct, compound-nucleus, pre-equilibrium, quasi-deuteron, etc.) is currently underway. 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.

Photonuclear reactions on molybdenum isotopes have been investigated in several studies. Most of these works have focused on photoneutron reactions on Mo isotopes at giant dipole resonance energies [2,3]. 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 our work, we experimentally studied the photoproduction of the ^{98m}Nb nucleus in natural Mo targets at bremsstrahlung end-point energies of $E_{\gamma\text{max}} = 37.5\text{--}92.5$ MeV.

The experiment was conducted using the electron beam of the electron linear accelerator LUE-40 RDC "Accelerator" at the National Scientific Center “Kharkiv Institute of Physics and Technology” (NSC KIPT) [4]. The measurements were performed using the activation method and offline γ -ray spectrometry. Detailed information on the experimental method used can be found, e.g., in [5].

In the experiment, the ^{98}Nb nucleus was only produced in reactions with the ^{100}Mo isotope. Both the ground state and metastable states of ^{98}Nb are populated in the photonuclear reaction. 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. The ^{98g}Nb nucleus decays into the ^{98}Mo nucleus via β^- decay (100%) with a half-life $T_{1/2}$ of 2.86 ± 0.06 s. Since the cooling time in the experiment was more than 30 minutes, we were able to measure cross-sections only for the production of the ^{98}Nb nucleus in its isomeric state.

^{98}Mo stable	^{99}Mo 65.924(6) h β^- 100 %	^{100}Mo 7.01×10^{18} y $2\beta^-$ 100 %
^{97}Nb g: 72.1(7) min β^- 100 % m: 58.7(18) s IT 100 %	^{98}Nb g: 2.86(6) s β^- 100 % m: 51.1(4) min β^- 99.9 %	^{98}Nb g: 15.0(2) s β^- 100 % m: 2.5(2) min β^- 98(2) % IT < 3.8%
^{96}Zr 2×10^{19} y	^{97}Zr 16.749(8) h β^- 100 %	^{98}Zr g: 30.7(4) s β^- 100 % m: 1.9(2) μs IT 100 %

Fig. 1. Nuclear spectroscopic data are from [6]. The ^{98}Nb and ^{98}Zr nuclei formed on ^{100}Mo via $(\gamma, pn) + (\gamma, d)$ and $(\gamma, 2p)$ reactions are highlighted in red.

In the same reaction, the ^{98}Zr nucleus can also be produced in its ground and metastable states. The half-life of the isomeric state is $T_{1/2} = 1.9 \pm 0.2$ μs , and it decays to the ground state via an internal transition (100 %). The ^{98}Zr ground state decays only to the ground state of the ^{98}Nb nucleus via β^- decay (100 %, $T_{1/2} = 30.7 \pm 0.4$ s), and thus it does not contribute to the population of the ^{98m}Nb . Nuclear spectroscopic data were adopted from [6] (see Fig. 1).

The production of the ^{98m}Nb nucleus on ^{100}Mo is possible in two ways: $^{100}\text{Mo}(\gamma, pn)^{98m}\text{Nb}$ and $^{100}\text{Mo}(\gamma, d)^{98m}\text{Nb}$, with the energy threshold values of $E_{\text{thr}} = 18.10$ MeV and 15.89 MeV, respectively. The threshold for the production of the ^{98m}Nb nucleus in the metastable state is 84 keV higher than in the ground state. Theoretical cross-sections $\sigma(E)$ for reactions $^{100}\text{Mo}(\gamma, x)^{98m}\text{Nb}$, $^{100}\text{Mo}(\gamma, pn)^{98m}\text{Nb}$, $^{100}\text{Mo}(\gamma, d)^{98m}\text{Nb}$ were calculated with the TALYS1.96 code. As shown in Fig. 2, the cross section for the $^{100}\text{Mo}(\gamma, d)^{98m}\text{Nb}$ reaction is very small. This reaction contributes less than 1% to

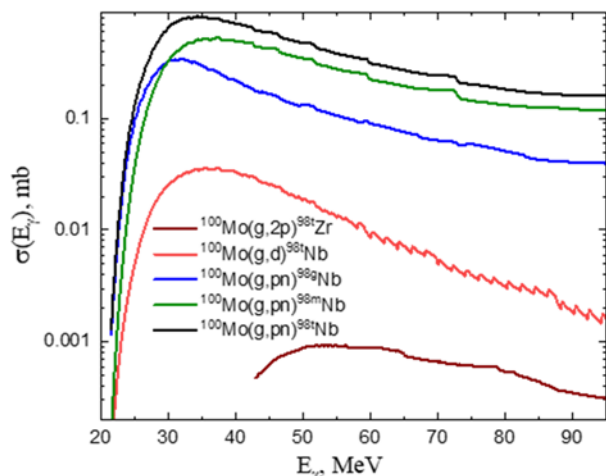


Fig. 2. Theoretical cross-section $\sigma(E)$ for the formation of the ^{98}Nb and ^{98}Zr nuclei on ^{100}Mo (the TALYS1.96 code with default parameters)

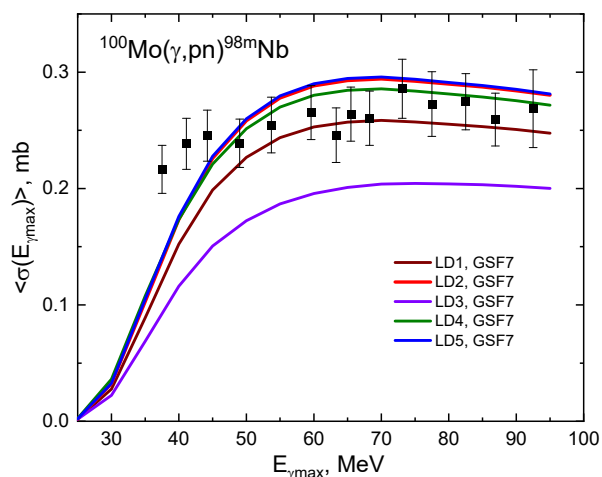


Fig. 3. The flux-averaged cross-section $\langle\sigma(E_{\gamma\text{max}})\rangle_m$ for the formation of the $^{98\text{m}}\text{Nb}$ nucleus on ^{100}Mo . Black points – our experimental data, curves – calculations with TALYS1.96 for different options LD and GSF.

through the MSCA4Ukraine project, which is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Research Executive Agency or the MSCA4Ukraine Consortium. Neither the European Union nor the European Research Executive Agency, nor the MSCA4Ukraine Consortium as a whole nor any individual member institutions of the MSCA4Ukraine Consortium can be held responsible for them. This work was also supported by the Slovak Research and Development Agency under Contract No. APVV-24-0516, and the Slovak grant agency VEGA (Contract No. 2/0175/24).

1. A. Koning and D. Rochman. Nucl. Data Sheets 113 (2012) 2841.
2. H. Beil, et al. Nucl. Phys. A27 (1974) 427-449.
3. P. Carlos, et al. Nucl. Phys. A219 (1974) 61-78.
4. M.I. Aizatskyi, et al. Probl. At. Sci. Technol. 3 (2014) 60.
5. A.N. Vodin, et al. Nucl. Phys. A1014 (2021) 122248.
6. Live Chart of Nuclides, <https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html>.

the total yield of $^{98\text{m}}\text{Nb}$. Therefore, in our work, we assumed that the $^{98\text{m}}\text{Nb}$ nucleus production will occur only through the $^{100}\text{Mo}(\gamma, \text{pn})^{98\text{m}}\text{Nb}$ reaction, and in our calculations, the $E_{\text{thr}} = 18.10$ MeV was used. Also, we provide an estimate of the contribution of the $^{100}\text{Mo}(\gamma, 2\text{p})^{98}\text{Zr} - \beta^- \rightarrow ^{98\text{g}}\text{Nb}$ channel to the total yield of the ^{98}Nb nucleus. This contribution is less than 0.2% (see Fig. 2).

The experimental flux-averaged cross-sections $\langle\sigma(E_{\gamma\text{max}})\rangle_m$ for the production of $^{98\text{m}}\text{Nb}$ in the $^{100}\text{Mo}(\gamma, \text{pn})^{98\text{m}}\text{Nb}$ reaction can be determined from direct measurements of the number of counts of γ rays, ΔA , in the full absorption peak at an energy of 787.36 keV with intensity $I_\gamma = 93.07 \pm 0.16$ %. The obtained $\langle\sigma(E_{\gamma\text{max}})\rangle_m$ of the studied reaction at bremsstrahlung end-point energies from 37.5 to 92.5 MeV are presented in Fig. 3.

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 %. Description of the errors can be found in [5].

The flux-averaged cross-sections $\langle\sigma(E_{\gamma\text{max}})\rangle_{\text{th}}$ were calculated using the cross-sections $\sigma(E)$ 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 obtained experimental results are compared with theoretical estimates, and it is shown that the parameters LD4 and GSF7 are closest to the experimental data.

This work has received funding through the Grant of the National Academy of Sciences of Ukraine under Contract No. 0121U108705 and No. 0126U001494. I.S. Timchenko has received funding