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Evaluation of ^{4}He production cross-section for tantalum, tungsten and gold irradiated with neutrons and protons at the energies up to 1 GeV

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Abstract

Popular nuclear models and approaches used for the description of the α-particle emission in the nucleon induced reactions at the intermediate energies were analyzed. The α-particle emission spectra, the non-equilibrium α-particle yields and the total α-production cross-sections were calculated with the help of the GNASH code, the modified ALICE code, the DISCA code and the different codes from the MCNPX package. The results of the calculation were compared with available experimental data, systematics values and data from ENDF/B-VI and JENDL-HE. Data from FENDL/A-2, JENDL-3.3, CENDL-2 and JEFF-3/A were also used for the comparison with calculations and measured data for neutron induced reactions below 20 MeV. The discrepancies between the calculations and the experimental data have been analyzed. The α-particle production cross-section has been evaluated for ^{181}Ta, ^{nat}W and ^{197}Au at the energies of the incident neutrons and protons from several MeV to 1 GeV.

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1. Introduction

The study of helium production in nuclear reactions is an important part of the research of radiation damage of materials. Recently the determination of reliable helium production cross-sections for tantalum and tungsten has got a special interest for the TRIGA/TRADE project [1]. Tantalum and tungsten are proposed as materials of the target, which undergone the intense influence of the primary proton beam and secondary neutrons produced in nuclear reactions.

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The available experimental data for helium production in tantalum and tungsten irradiated with nucleons are not enough for detail testing of the methods of the calculation and the determination of the nuclear model parameters relevant to the helium isotope emission at the energies of the primary particles up to 1 GeV. A considerable amount of the experimental data for ^{4}He production including the total yields and α-particle emission spectra is available for ^{197}Au. These data are used in the present work for testing of theoretical models.

The goal of this work is the study and the evaluation of the ^{4}He-production cross-section for ^{181}Ta, W and ^{197}Au irradiated with neutrons and protons at low and intermediate energies.

The evaluation of the cross-sections was done at the energies from several MeV up to 1 GeV. The evaluation included the analysis of available experimental data and the contents of evaluated data libraries (ENDF/B-VI, JENDL-HE, JENDL-3.3, CENDL-2, FENDL/A-2, JEFF-3/A), the calculations with the help of the modern theoretical approaches, codes and systematics. The brief description and the analysis of the models used for the cross-section calculation are given in Section 2. Section 3 presents the comparison of the results of calculations with experimental data. The evaluation of the ^{4}He-production cross-section for ^{181}Ta, W and ^{197}Au is discussed in Section 4.

2. Brief description of models and codes used for helium production cross-section calculation

This section describes briefly nuclear models, approaches and codes used in the present work for the calculation of the total and differential ^{4}He-production cross-sections for nucleon induced reactions.

2.1. Pre-compound model combined with evaporation model

2.1.1. The GNASH code

The GNASH code implements the pre-equilibrium exciton model and the statistical Hauser–Feshbach model [2]. The basic description of the code and the models used is given in [3].

The pre-equilibrium nucleon emission is described by the following expression resulting from an analytical solution of master equations of the exciton model:

$$\frac{d\sigma}{d\varepsilon_x} = \sigma_{non}(E_p)\frac{(2S_x+1)\mu_x\varepsilon_x\sigma_x^{inv}(\varepsilon_x)}{\pi^2\hbar^3} \times \sum_{n=n_0} R_x(n)\frac{\omega(p-1,h,U)}{\omega(p,h,E)}\frac{1}{\lambda_n^+ + \lambda_n^- + \gamma_n}D(n), \quad (1)$$

where σ_{non} is the cross-section of non-elastic interaction of the primary particle with a nucleus at the kinetic energy E_p; S_x and μ_x are spin and reduced mass of the outgoing nucleon of x-type; ε_x is the kinetic energy of the nucleon; σ_x^{inv} is the inverse reaction cross-section for x-particle; $\omega(p, h, E)$ is the density of exciton states with "p" particles and "h" holes ($p + h = n$) at the excitation energy E calculated according to Williams [4]; U is the final excitation energy, $U = E - Q_x - \varepsilon_x$ and Q_x is the separation energy for nucleon; λ_n^+ and λ_n^- are transition rates from the n-exciton state to the states with $n + 2$ and $n - 2$ excitons, correspondingly; γ_n is the nucleon emission rate; $R_x(n)$ is the factor describing the difference between the number of neutrons and protons in the n-exciton state; $D(n)$ is the factor, which takes into account the "depletion" of the n-exciton state due to the nucleon emission; n_0 is the initial exciton number. The transition rates λ_n^+ and λ_n^- are calculated as follows:

$$\lambda_n^{\pm} = (2\pi/\hbar)\langle|M|^2\rangle\omega^{\pm}(n,E), \quad (2)$$

where $\langle|M|^2\rangle$ is the averaged squared matrix element for two-body interaction parameterized as the set of functions of E/n in [5]; $\omega^{\pm}$ is the density of states available for transitions from "n" to "$n + 2$" and "$n - 2$" exciton states calculated according to [3,6].

The multiple pre-equilibrium emission (two precompound nucleons escape) is described according to [7]. The improvement of the approach [7] is discussed in [8].

The pre-equilibrium α-particle emission spectrum for nucleon induced reaction is calculated as a sum of components corresponding to the mechanism of pick-up and knock-out