STUDY OF INCLUSIVE CROSS SECTIONS OF ^{103}Rh(p,xp) AND $(p,x\alpha)$ REACTIONS AT THE PROTON ENERGY OF 22 MeV*

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(Received November 28, 2021; accepted November 29, 2021)

Double-differential protons and α-particles emission cross sections were measured for proton-induced reactions on ^{103}Rh nucleus at the incident energy of 22 MeV. The experiment was performed at the isochronous cyclotron of the Institute of Nuclear Physics (Kazakhstan). After integrating the double-differential cross sections over the angle, the integral cross sections of ^{103}Rh(p,xp) and $(p,x\alpha)$ reactions were obtained and compared with the TENDL-2019 evaluation. In general, the calculated spectra were in good agreement with the measured ones.

DOI:10.5506/APhysPolBSupp.14.821

1. Introduction

Verification of nuclear models, increasing their predictive power, is an urgent task in the design of perspective nuclear facilities, in particular, ADS electro-nuclear facilities for the transmutation of long-lived radioactive waste from the nuclear industry and energy production. At present, a number of computer codes based on various models have been developed, which make it possible to calculate all possible channels of nuclear reactions in the energy range from 1 keV to 200 MeV and associated observables. To optimize the parameters of the model, it is important to obtain new experimental data on the cross sections of nuclear reactions. Reviews on available experimental data in reactions with nucleons and heavier particles are presented in [1–3].

* Presented at III International Scientific Forum "Nuclear Science and Technologies", Almaty, Kazakhstan, September 20–24, 2021.

Double-differential reaction cross sections for outgoing protons and α-particles were measured on a ^{103}Rh nucleus at the incident proton energy of 22 MeV. Rhodium is a monoisotopic element, which makes it a good test nucleus for calculating the continuous energy spectra. At the same time, rhodium-based neutron detectors are used in nuclear reactors to measure neutron flux. It should be noted that particular interest represent the processes in which complex particles (deuterons, tritons, ^{3}He, and α-particles) are located in the input and/or output channels. Description of such interactions causes additional difficulties in comparison with nucleons since it is necessary to include additional reaction mechanisms, such as direct transfer and knock-out of nucleons, inelastic processes involving cluster degrees of freedom, and disintegration of the incident particle. The work performed is a continuation of research carried out at the Institute of Nuclear Physics (Kazakhstan) to determine double-differential and integral reaction cross sections initiated by protons on a number of structural elements of nuclear power systems, in particular, ADS for nuclear transmutation of long-lived radioactive waste and energy production [4, 5].

2. Experiment

The experimental data were measured using a 22 MeV proton beam obtained at the isochronous cyclotron U-150M. The registration system was adapted to measure inclusive spectra of protons and alpha-particles in the maximum range of energies of emitted particles formed as a result of 22 MeV protons interaction with ^{103}Rh target. The detection systems consisted of two telescopes that were used to detect the different particles. One telescope was composed of two Si detectors with thicknesses of 100 μm, and 2 mm for $(p, x\alpha)$ reaction. Another telescope was composed of Si detectors with thicknesses of 30 μm, and scintillator CsI(Tl) with thicknesses of 2.5 cm for (p, xp) reaction. The cross sections for nuclear reactions were obtained in the angular range of 30–135)°. The self-supporting foil of thickness of 3 mg/cm^2 with rhodium was used as a target. The thickness was determined by the energy loose of α-particles from radioactive sources while passing through the target.

Systematic errors in the measured cross sections are mainly defined by the errors in determination of the target thickness ($< 7\%$) and the solid angle of the spectrometer (1.3%). The energy of the accelerated particles beam was measured with the accuracy of 1.2%. The registration angle was installed with the accuracy of 0.5°. The statistical error depended on the type and energy of the detected particles and generally did not exceed 10%.

After integrating the double-differential cross sections over the angle, the integral cross sections of ^{103}Rh(p, xp) and $(p, x\alpha)$ reactions were obtained at an incident proton energy of 22 MeV, presented in Figs. 1 and 2.

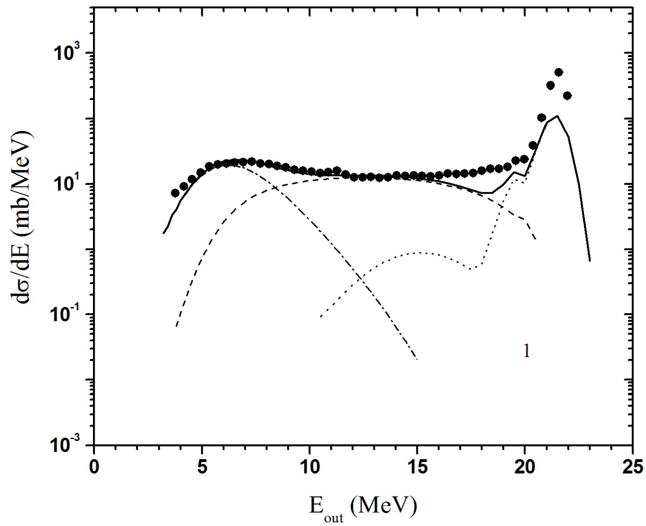

Fig. 1. Comparison of experimental integral cross sections of ^{103}Rh(p,xp) reaction at $E_P = 22$ MeV with calculations. The symbols show the experimental results; the solid lines show the total calculated cross sections; the dotted lines show the calculated direct components; the dashed lines show the calculated preequilibrium components; and dash-dotted lines show the calculated evaporation components.

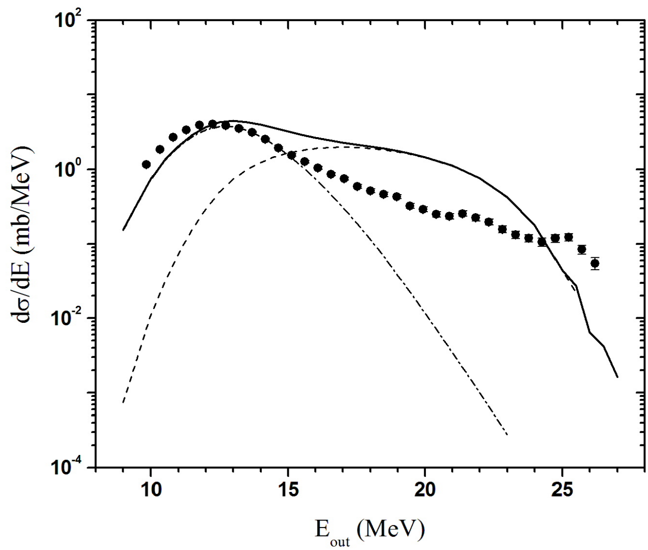

Fig. 2. Comparison of experimental integral cross sections of ^{103}Rh(p,$x\alpha$) reaction at $E_P = 22$ MeV with calculations. All explanations are as for Fig. 1.

3. Results and discussion

The experimental results of the (p, xp) and $(p, x\alpha)$ reactions on the ^{103}Rh nucleus at $E_P = 22$ MeV were compared with the TENDL-2019 nuclear data library [6], which provides the output of the TALYS nuclear model code. Calculations were carried out in the framework of the exciton model of nuclear decay, which is essentially a statistical approach describing the transition of an excited nucleus to an equilibrium state [7]. In the two-component exciton model, proton and neutron degrees of freedom are considered separately [8] and it is assumed that the nucleus was characterized by parameters p_π, h_π, p_ν, and h_ν, where p and h denote particle and hole, and π and ν — proton and neutron degrees of freedom, respectively. $(Z_a,0,N_a,0) = (1,0,0,0)$ particle–hole configuration was taken as the initial one. It is assumed that the difference between the number of particles and holes during the transition to the equilibrium state remains constant for the core compounds $p_\pi - h_\pi = Z_a$, $p_\nu - h_\nu = N_a$ and $p - h = A_a$, where A_a is the mass number of the incident particle. This condition is not always true, especially when approaching the equilibrium state, but is quite adequate for pre-equilibrium calculations.

In addition to the calculations in the framework of the exciton model, calculations were performed in the framework of other mechanisms of nuclear reactions. For nuclear reactions involving complex ejectiles, direct-like reactions were included in TALYS according to the Kalbach phenomenological parametrization [2]. For the equilibrium cross-section calculation, the Hauser–Feshbach model with a width fluctuation correction was used in the TALYS code.

From a comparison of the experimental and theoretically calculated integral spectra, it follows that the main contribution to the hard part of the integral cross section for the (p, xp) and $(p, x\alpha)$ reactions is defined by the pre-equilibrium mechanism, to the soft part, by decay from the compound nucleus. The contribution of the one-step direct mechanisms is insignificant, except for the (p, xp) reaction, where this mechanism is responsible for formation of a bump corresponding to elastic and inelastic processes.

4. Conclusion

New experimental data for the inclusive ^{103}Rh(p, xp) and $(p, x\alpha)$ reactions at $E_P = 22$ MeV were presented. From a comparison between the experimental cross sections and the TENDL-2019 evaluation, the contribution of different reaction mechanisms to forming of energy spectra of emitted particles were established.

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The obtained experimental results supplement the database of nuclear data on the cross sections of the reactions and can be used in the design of safe and waste-free hybrid nuclear power plants.

This work was supported by the Scientific Research Program No. BR091 58499 of the Ministry of Energy of the Republic of Kazakhstan.

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