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INVESTIGATION OF (p, xp) AND $(p, x\alpha)$ REACTIONS OF 30-MeV PROTONS WITH THE ^{103}Rh NUCLEUS*

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Double-differential and integral cross sections of the (p, xp) and $(p, x\alpha)$ reactions on the ^{103}Rh nucleus were measured at $E_p = 30$ MeV using a proton beam delivered by the U-150M cyclotron of the Institute of Nuclear Physics (Almaty, Kazakhstan). A self-sustaining ^{103}Rh foil of 3 μm thickness was used as a target. The obtained experimental results were compared with the TENDL-2019 nuclear data library, which provides the output of the TALYS nuclear model code. We assert that the TENDL-2019 evaluations provide a valid description of the obtained experimental data.

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1. Introduction

The key problem in the physical scenario of the operation of various nuclear facilities is the lack of information on the cross sections of nuclear reactions with charged particles and neutrons in a wide range of excitation energies and masses. It is physically and economically impossible to measure all the necessary cross sections. Consequently, the development of nuclear

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models that have sufficient predictive power plays an important role. On the basis of such models, computer codes have been developed that can be used to calculate all possible channels of nuclear reactions in the energy range from 1 keV to 200 MeV, and related observables. To optimize the model parameters and debug the codes, 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 Refs. [1–3].

The work is a continuation of research carried out at the Institute of Nuclear Physics (Kazakhstan) to determine double-differential and integral reaction cross sections induced by 30-MeV protons in a number of structural elements of nuclear power systems, in particular Accelerator-Driven Systems (ADS) for nuclear transmutation of long-lived radioactive waste from the nuclear industry and energy production [4–6]. New additional data are needed on nuclear reactions such as (p,xp), *etc.*, taking place in the target site, which, along with the deceleration of the primary proton beam due to ionization losses, lead to the formation of a spectrum of low-energy protons.

For this reason, double-differential cross sections for proton and α-particle emission in proton-induced reactions on ^{103}Rh at the incident energy of 3 MeV were measured. The rhodium was chosen for the investigation as a good test nucleus for continuous spectra calculations due to monoisotopicity. At the same time, rhodium neutron detectors are used in nuclear reactors to measure neutron flux [7]. The energy spectra of secondary particles from proton-induced reactions on a ^{103}Rh target were measured earlier only at an incident particle energy of 18 and 25 MeV (neutrons) [8], 18 MeV (protons) [9] and 30, 43 and 56 MeV (α particles) [10].

2. Experiment

The experimental data were obtained using a 30-MeV proton beam extracted from the U-150M isochronous cyclotron of the Institute of Nuclear Physics. The system was capable of measurements in a wide range of energies of secondary particles. Measurements of the cross sections of nuclear reactions were carried out using a scattering chamber of 60 cm diameter, equipped with a rotary charged-particle spectrometer, target drive systems, a collimation system and a Faraday cup to measure the number of particles passing through the target.

The standard ΔE–E technique for registration and identification of products of nuclear reactions was used. For the (p,xp) reaction, the thickness of the silicon ΔE detector was 100 μm, and the thickness of the total absorption crystal CsI(Tl) used as a stop detector was 25 mm. For the $(p,x\alpha)$ reaction, the telescope consisted of a 30 μm thick silicon ΔE detector and a 2 mm thick silicon E detector.

A self-sustaining 98% enriched ^{103}Rh foil was used as a target. Its thickness was determined to be 3 μm from a measurement of α-particle energy loss in the target. A ^{226}Ra radioactive source was used for this measurement, emitting α particles of 4.782, 5.305, 5.490, 6.002 and 7.687 MeV energy.

The uncertainties of the measured cross sections include the uncertainty in the determination of the target thickness (5%), the current integrator calibration (1%) and the solid angle of the spectrometer (1.3%). The energy of the proton beam was measured with a precision of 1.2%. The detection angle was determined with a precision of 0.5°. These sources of combined uncertainty amounted to less than 10%. The statistical uncertainty of the number of detected particles, which depended on their type and energy, was $1 \div 8\%$ for protons and $1 \div 15\%$ for α particles. Integral cross sections for the ^{103}Rh(p,xp) and ^{103}Rh$(p,x\alpha)$ reactions of 30-MeV proton energy, obtained from the double differential cross sections and averaged in the energy range of 0.5 MeV, are shown in Fig. 1.

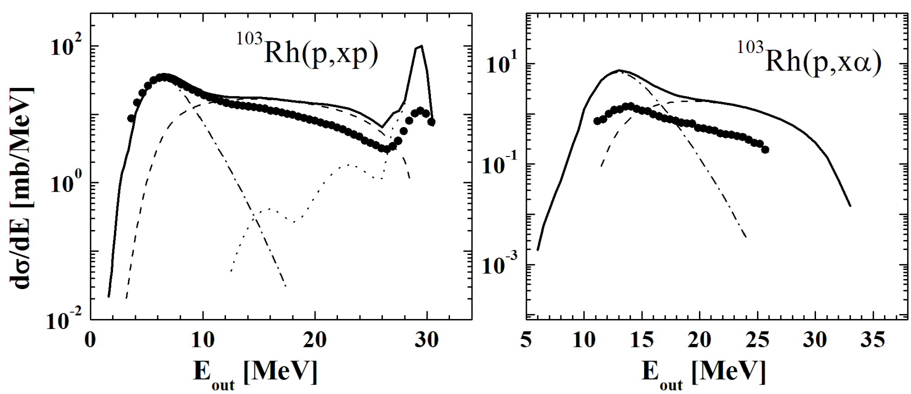

Fig. 1. Comparison of the experimental integral cross sections for the ^{103}Rh(p,xp) and ^{103}Rh$(p,x\alpha)$ reactions with the calculations. The symbols show the experimental results; the solid lines show the total calculated cross sections; the dotted lines show the calculated direct components; the dashed lines show the calculated preequilibrium components; and dash-dotted lines show the calculated evaporation components.

3. Analysis

The experimental results for the (p,xp) and $(p,x\alpha)$ reactions on the ^{103}Rh nucleus at $E_p = 30$ MeV were compared with TENDL-2019 nuclear data library [11], which provides the output of the TALYS nuclear model code. In this code, a theoretical analysis was performed in the frame of a modified version of the two-component exciton model [12]. In this model, proton and neutron degrees of freedom are considered separately and it is assumed that the nucleus is 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. Particles and holes are determined by their position relative to the Fermi level, defined as half the distance between the last filled and the first vacant partial states when the nucleus is in the ground state. $(Z_a, 0, N_a, 0) = (1, 0, 0, 0)$ 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 (stripping, pick-up, break-up and knock-out mechanisms) 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.

Figure 1 shows a comparison of the calculated and experimental integral cross sections of the (p, xp) and $(p, x\alpha)$ reactions on the ^{103}Rh nucleus. It has been established that the main contribution to the integral reaction cross section of the (p, xp) reaction in the energy range from 10 MeV to the bump corresponding to elastic and inelastic scattering is coming from the pre-equilibrium mechanism. In the low-energy part of the spectrum, in addition to the pre-equilibrium mechanism, the contribution of compound processes is significant. The contribution of direct processes is negligible.

The formation of high-energy α particles was due to direct-like reactions (stripping and knock-out mechanisms). The contribution of emissions from the equilibrium state increased with the decrease of α-particle energy, and it dominated the cross section for low energies. The contribution of the pre-equilibrium components was negligible.

In addition, the TENDL-2019 predictions were compared with experimental data from the (p, xp) reactions on ^{56}Fe [5], ^{90}Zr [4], ^{197}Au [13], and ^{209}Bi [6] and $(p,x\alpha)$ reaction on ^{56}Fe [5], ^{197}Au [14], and ^{209}Bi [14] at the incident proton energy of 30 MeV (Fig. 2). Again, a good agreement is obtained. One can observe that for (p, xp) reactions, the emission of secondary low-energy protons becomes more suppressed for heavier target nuclei.

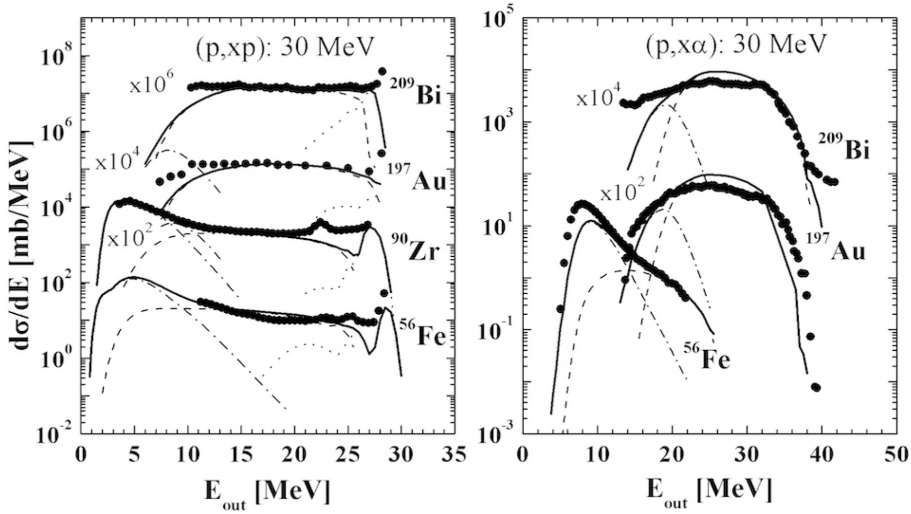

Fig. 2. Comparison of the experimental integral cross sections with the calculations. The symbols show the experimental results; the solid lines show the total calculated cross sections; the dotted lines show the calculated direct components; the dashed lines show the calculated preequilibrium components; and dash-dotted lines show the calculated evaporation components.

4. Conclusions

Experimental energy spectra of secondary protons and α particles from the reactions of 30-MeV protons with the ^{103}Rh nucleus were obtained in a wide range of energies (from 4 to 30 MeV) and angles (30–135°, with a step of 15°). From a comparison between the experimental cross sections and the TENDL-2019 nuclear data library, one can deduce that the main contribution to the (p, xp) reaction cross section is due to the pre-equilibrium mechanism. Considering the mechanisms contributing to the inclusive $(p, x\alpha)$ reaction cross sections, the emission of α particles can mostly be attributed to direct-like reactions, with the exception of the low-energy range, where the emission of particles from the equilibrium state becomes significant.

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