

Continuous spectra of light charged particles from interaction of 30 MeV energy protons with cooper

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Abstract. This paper presents the experimental double-differential and integral cross sections of reactions (p,xp), and (p,x α) on ^{nat}Cu nucleus. The experiment with the protons, accelerated to energy of 30.0 MeV was performed at the isochronous cyclotron of Institute of Nuclear Physics (Kazakhstan). We investigated the adequacy of the theoretical models in explaining the measured experimental data and contributions of direct, preequilibrium and compound processes in the formation of the cross sections were determined. We assert that the traditional frameworks are valid for the description of the experimental data.

1 Introduction

In the middle of the last century, the idea of creating a nuclear power system was put forward, implemented to date as the Accelerator Driven System (ADS), consisting of a proton accelerator (deuterons), a neutron-producing target and a subcritical reactor (blanket) with a thermal neutron flux [1, 2]. In addition to the energy production, the system allows the transmutation of long-lived radioactive waste from the nuclear industry [3]. According to the physical scenario of the ADS operation, high-energy protons during the passage of the target assembly generate not only a neutron flux, but also a spectrum of more complex nuclides of hydrogen and helium that act as initiating reaction agents with the emission of secondary neutrons. The range of nucleon composition and excitation energies in the ADS system is much more complicated than in traditional reactors.

There is need in new experimental data on nuclear reactions with hydrogen and helium nuclides occurring in the spallation target, fuel assemblies, and structural materials [3, 4]. Reviews on available experimental data of reactions with nucleons are presented in [5]. Several experiments on double-differential cross sections measurements have been performed at energy about 30 MeV [6–11]. More over at this energy many channels of reactions are open, and the total cross section of the reactions for nuclei of such mass region reaches its maximum [12].

For this reason, the double-differential cross sections of light particles (protons and α -particles) emitted from proton induced reactions on ^{nat}Cu at the incident energy of

30.0 MeV were measured. The copper was chosen as object of investigation as widely used constructional material in different nuclear plants [13]. The energy spectra of secondary particles protons and α were measured earlier on ⁶³Cu target only at proton energy of 14 MeV [14]. The experimental data were analysed in frame of spin-dependent statistical theory and good agreement for (p,x α) and poor one for (p,xp) were obtained.

2 Experiment

The experimental data were obtained on the proton beam of isochronous cyclotron U-150M at the Institute of Nuclear Physics of Kazakhstan. A system of multiprogramming analysis was adapted for the measurement of the inclusive spectra of protons and alpha-particles in the maximum energy range of the secondary particles. The measurements of cross sections of nuclear reaction products were carried out using a scattering chamber, equipped with a rotary spectrometer of charged particles, target systems, collimation system and the Faraday cylinder to measure the number of particles passing through the target. The measurements have been done within the angle range of 30–135° for the inclusive reactions (p,xp) and within the angle range of 30–120° for (p,x α).

The standard ΔE -E technique for registration and identification of products of nuclear reactions was used. The detector telescope had a silicon ΔE detector a thickness of 30 microns and silicon E detector with a thickness of 2000 microns for the reaction (p,x α). For the reaction (p,xp), the thickness of the silicon ΔE detector was 100 microns, and the thickness of the stop detector of total absorption-crystal CsI(Tl) was 25 mm. The solid angles of the tele-

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Table 1. Experimental partial cross sections of reactions (p,xp) and (p,x α) on the nucleus ^{nat}Cu at $E_p=30.0$ MeV

Reaction	$^{nat}Cu(p,xp)$	$^{nat}Cu(p,x\alpha)$
Partial cross section, mb	877.7 ± 8.5	52.4 ± 0.5
Energy range, MeV	$4 \div 30$	$8 \div 32$

scopes were made equal to 5.34×10^{-5} and 4.62×10^{-5} sr, respectively.

The self-supporting foil of thickness of 3.5 mg/cm^2 with natural cooper was used as target. The thickness was determined by the energy loose of α -particles from radioactive sources while passing through the target.

The kinetic energy of the particle of corresponding channel number X was determined from the known state of the residual nucleus (target ^{12}C , CH_2) in order to calibrate the E-detector.

Systematic errors of measured cross sections were mainly due to the uncertainty in the thickness of the target determination ($<5\%$), the current integrator calibration (1%) and the solid angle of the spectrometer (1.3%). The energy of the beam of accelerated particles was measured with an accuracy of 1.2%. The angle of the registration was recorded with an accuracy of 0.5° . The total systematic error did not exceed 10%.

The statistical error, the value of which depended on the type and energy of the detected particles, was $1 \div 8\%$ for protons and $1 \div 15\%$ for α -particles.

Integrated over an angle cross sections of reactions ^{nat}Cu (p,xp) and (p,x α), determined from the double-differential cross sections and averaged over the energy range of 0.5 MeV are shown in Figures 1 and 2. Table 1 contains the numerical values of the experimental partial cross sections of these reactions.

3 Results

An analysis of the experimental results of reactions (p,xp) and (p,x α) on the nucleus ^{nat}Cu at $E_p = 30.0$ MeV was done within the exciton model of decay of nuclei, which was a statistical approach describing the transition of the excited nucleus to equilibrium state. This model is widely used in the interpretation of many experimental results. One of the advantages of the model was that the kinetic equations basically, could describe the process of relaxation of the excited nuclear systems, from the simplest quasiparticle configurations to establishment of statistical equilibrium. It is essentially a statistical model, where the excited states of a compound system are characterized by the number of excited particles (above the Fermi level) and holes (below the Fermi level). The model describes the energy spectra both nucleons and complex particles in exit channel simultaneously.

In the two component exciton model, proton and neutron degrees of freedom are considered separately [15] 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. They are related

with the parameters of a single-component model in the following relations $p=p_\pi+p_\nu$ and $h=h_\pi+h_\nu$. They can also be combined to obtain the total number of excitons $n=p+h=p_\pi+h_\pi+p_\nu+h_\nu=n_\pi+n_\nu$.

It was assumed that the compound nucleus is formed with the particle-hole configuration that allows only for the incident nucleon as particle degrees of freedom and did not include hole degrees of freedom. Such configuration is denoted as $(p_\pi, h_\pi, p_\nu, h_\nu)=(Z_a, 0, N_a, 0)$, where a refers to bombarding particle.

The difference between the number of particles and holes in the transition to the equilibrium state remained constant for the compound nucleus $p_\pi-h_\pi=Z_a$, $p_\nu-h_\nu=N_a$ and $p-h=A_a$, where A_a was mass number of the incident particle. This condition was not always true, especially when approaching a state of equilibrium, but it was adequate for the pre-equilibrium calculations. The theoretical analysis of the experimental results was made within the code PRECO-2006 [16], which had been optimized for this case. We chose the $(Z_a, 0, N_a, 0)=(1, 0, 0, 0)$ particle-hole configuration as our starting point. The normalization factor was taken equal to 15 MeV. The optical potential parameters of Huizenga [17] have been used for α -particles, and those of Becchetti and Greenlees [18] for protons. The excitation energy of compound nucleus and binding energy of the protons in the primary and secondary emission were calculated. In addition to the calculations within exciton model, the calculations in the framework of other mechanisms of nuclear reactions: direct processes (nuclon transfer, nucleon knock out, inelastic scattering) and equilibrium emission with the formalism of the Weisskopf compound nucleus decay were carried out.

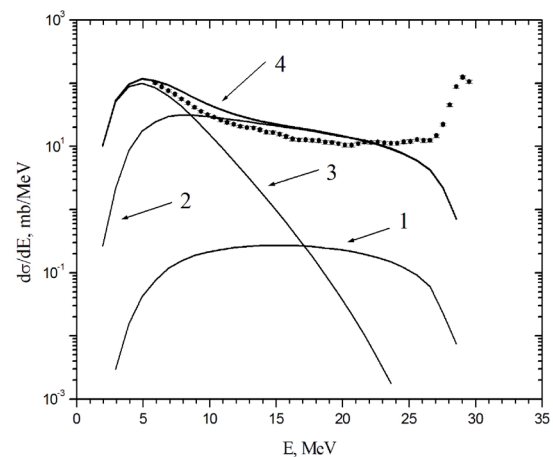


Figure 1. The comparison of experimental integral cross sections of reactions ^{nat}Cu (p,xp) with the exciton model calculations (PRECO-2006). Symbols are experimental data, lines are theoretical calculations: 1 - one-step processes, 2 - pre-equilibrium component, 3 - emission of particles from the equilibrium state, 4 - total integral cross section.

The comparison of theoretical and experimental integrated cross sections of the reactions (p,xp) and (p,x α) on

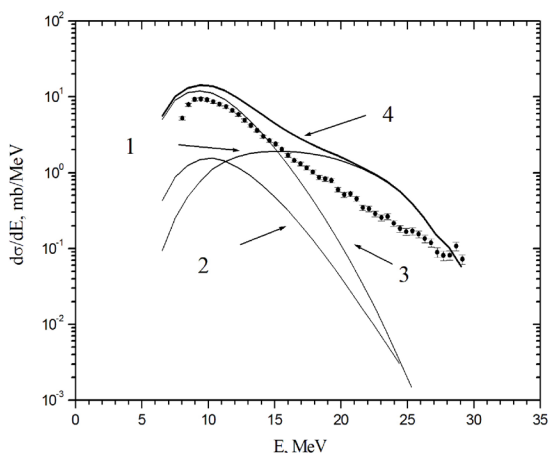


Figure 2. The comparison of experimental integral cross sections of reactions $^{nat}Cu(p,\alpha)$ with the exciton model calculations (PRECO-2006). Symbols are experimental data, lines are theoretical calculations: 1 - one-step processes, 2 - pre-equilibrium component, 3 - emission of particles from the equilibrium state, 4 - total integral cross section.

the nucleus ^{nat}Cu are presented in Figure 1 and 2. It was found that the main contribution to the integral cross sections of reactions (p,xp) in the energy range from 10 MeV to bump corresponding to the elastic and inelastic scattering, provided by pre-equilibrium mechanism (line 2 in Figure 1). In the low-energy part of the spectrum, in addition to the pre-equilibrium, the contribution of the compound processes was significant (line 3 in Figure 1). The contribution of single-step direct mechanisms in the (p,xp) was negligible.

When considering the contribution of the mechanisms forming inclusive cross sections of reactions (p,xα), it was observed that the formation of high-energy α-particles was due to direct single-step processes (line 1 in Figure 2). The contribution of emissions from the equilibrium state increased with the decrease of α-particle energy, and it was determinant in the cross section formation of the low-energy range. The contribution of the components of the pre-equilibrium was negligible.

In addition to the exciton model, calculation based on quantum-mechanical theory of the preequilibrium decay have been carried out in frame of EMPIRE-II code [19]. The analysis of the experimental cross sections of the $^{nat}Cu(p,xp)$ reaction is carried out within the Hauser-Feshbach theory by considering the multiparticle emission of both single-charged (protons, deuterons) and two-charged (α-particles) fragments. In this code, the contributions of statistical direct and compound processes are described by multistep direct [20] and multistep compound [21] models.

The results of the calculations are shown in Figure 3. These results indicate that the form of integral spectra of reaction (p,xp) for emission protons energy from 5 MeV up to the kinematical limit is determined by the multi-

step direct processes. The contribution of the multi-step compound mechanism is negligible. The emission of protons from 2.5 up to 10 MeV are determined by the Hauser-Feshbach theory.

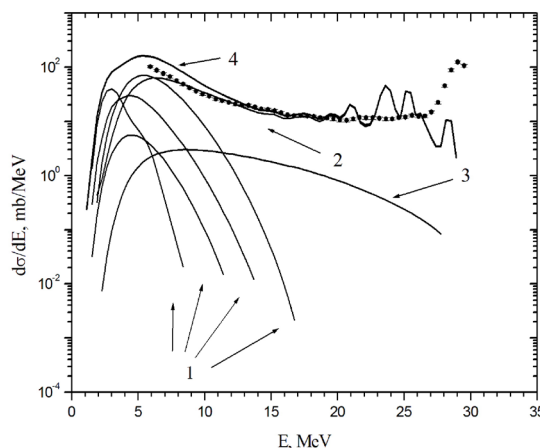


Figure 3. The comparison of experimental integral cross sections of reactions $^{nat}Cu(p,xp)$ with the quantum mechanics model calculations (EMPIRE-II). Symbols are experimental data, lines are theoretical calculations: 1 - Hauser-Feshbach emission, 2 - multi-step direct component, 3 - multi-step compound component, 4 - total integral cross section.

4 Conclusions

We have presented new experimental data at $E_p=30.0$ MeV within the angle range of 30–135° for the inclusive reactions (p,xp) and within the angle range of 30–120° for (p,xα) on nucleus ^{nat}Cu , which has not been investigated in detail so far. We have shown the extension of the pre-equilibrium reactions to this energy region and have interpreted the results of the experiments. We have also discussed the adequacy of the theoretical models in explaining the measured experimental data. In our theoretical analysis, we determine the contributions of direct, pre-equilibrium and compound processes in the formation of measured cross sections. The obtained experimental results complete the base of nuclear reaction cross section data and can be used in the designing of safe and wasteless hybrid nuclear power plants.

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