INCLUSIVE SPECTRA OF REACTIONS ^{56}Fe(p,xp), (p,xα) MEASURED AT E_P=29.9 MeV

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Working out the pre-equilibrium decay mechanism in nuclear reactions, which reflects the dynamics of the excited system formation and its evolution to the equilibrium state, remains an actual problem of the nuclear reaction theory. The problem is largely connected with obtaining the new experimental data on double-differential cross-sections in (p,xp), (p,xd) etc. reactions at different proton energies. These reactions play an important role in the applied researches on safe secure and wasteless nuclear power system creation (accelerator + sub critical reactor). In this respect, there is a problem of determining the spatial and power distribution of the secondary particles, generated not only during the transition of primary proton beam of target assembly and neutron flow, but also more composite (^{2,3}H, ^{3,4}He) particles, which can be represent themselves as initiators of the reactions by emitting neutrons.

The inclusive spectra of protons and α-particles emitted from proton induced reactions on ^{56}Fe isotopes at E_p=29.9±0.2 MeV in angular ranges of 30-135^0 with the step of 15^0 were measured on isochronous cyclotron U-150M of Institute of Nuclear Physics Republic of Kazakhstan. Typically, intensities varied between 40 and 180 nA with a beam energy resolution of 0.3%. The self-supporting isotopic enriched (95%) 2.7 mg/cm^2 thick ^{56}Fe foil was used in these experiments.

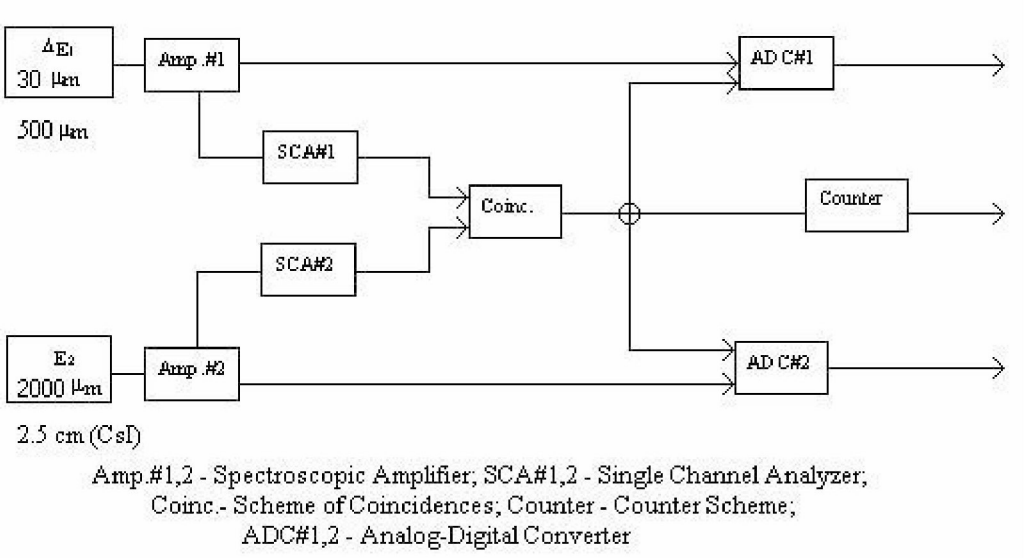


Fig.1. The design of the registration system

The two-detector telescope system (□E-E) registration of α-particles was used. The thickness of silicon detectors was □E–30 microns and E-2000 microns, respectively. Solid angle subtended by a telescope of detectors was equal to Ω=2.72*10^{-5} sr ±1%.

For registration and identification of protons the same two-detector telescope (ΔE-E) system was used. It consisted of silicon surface-barrier ORTEC detector (500 micron) and a total absorption CsI (Tl) (25 mm) scintillation detector. The solid angle subtended by a telescope of detectors was equal to Ω=2.59*10^{-5}sr. Because of using such thick surface-barrier detector the power spectrum of protons was measured within a short interval starting from E_p≈11 MeV up to ≈27 MeV.

The spectrometer energy calibration was carried out on kinematics of levels of residual nuclei in the reaction $^{12}C(p,x)$ and with use of recoil protons emitted from polyethylene target. The base calibration expresses the relation between the channel number in line spectra with the lost energy in detector. We can find it by subtraction of the particle energy loss in target and detectors from kinetic energy. The energy of the particle before it hits the telescope of detectors is determined by using this base calibration and restoring losses in detector. After that, we define the energy of the emitted particle by adding losses in target. The base calibration ΔExE is approximated by a straight line and does not depend on any kind of fragments. The total energy resolution of the spectrometer occurred to be 400 keV.

The experimental integral cross sections of reactions are shown in figures 2 and 3. We have compared our results with cross sections of reactions $^{54}Fe(p,x\alpha)$, (p,xp) at E_p=29 and 39 MeV obtained by Bertrand and Peelle [1]. There is no any isotopic difference in cross sections. The energy range of integral spectrum for reaction $^{56}Fe(p,xp)$ starts from 11 MeV and we think that the soft part of it would have the same shape as for reaction on ^{54}Fe.

Experimental partial cross-sections of reactions $^{56}Fe(p,x\alpha)$, (p,xp) are given in table 1.

Table 1. Experimental partial cross sections (mb) of reactions (p,xα), (p,xp)

^{56}Fe	OER(MeV)	σ(mb)
(p,xα)	5-25	132.2±1.2
(p,xp)	11-27	219.41±1.4

[a]OER denotes outgoing energy range

Based on exciton model of pre-equilibrium decay [2] the spectra of multi-step direct (MSD) and compound (MSC) processes for (p,xp), (p,xα) reaction on ^{56}Fe were calculated (fig.2-3). This code uses the Griffin exciton model [3] for pre-equilibrium nuclear reactions to describe the emission of particles with mass numbers of 1 to 4 from an equilibrating composite nucleus. A distinction is made between open and closed configurations in this system and between the multi-step direct and multi-step compound components of the pre-equilibrium cross sections [4]. Additional MSD components are calculated semi-empirically to account for direct nucleon transfer reactions and direct knock-out processes involving cluster degrees of freedom. Evaporation from the equilibrated composite nucleus is included in the total MSC cross section. Output of energy differential and double differential cross sections is provided for the first particle emitted from the composite system. For that, there are additional subroutines in this program, which use the total MSD (including direct) and total MSC (including evaporation) cross sections to calculate the angular distributions for the emitted particles. This is done phenomenologically [5].

The configuration (1p0h) was chosen to be initial. Single particle level density was calculated as g=A/13. The Huizenga optical potential parameters [6] for α-particle channel and the Becchetti-Greenlees parameters [7] for proton channel were used to generate reaction transmission coefficients.

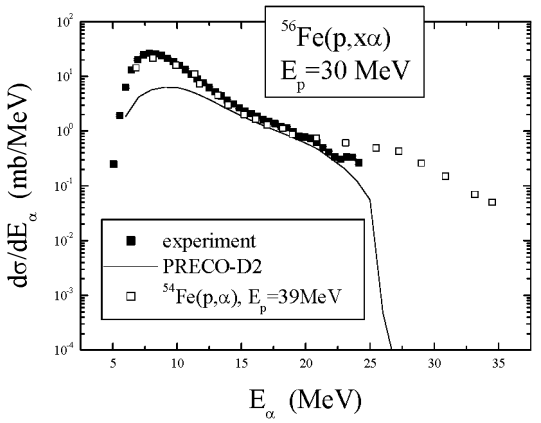


Fig.2. Integral cross sections of reaction ^{56}Fe(p,xα) at E_p=30 MeV

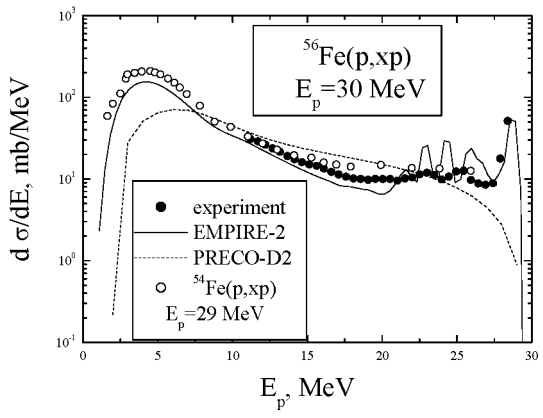


Fig.3. Integral cross sections of reaction ^{56}Fe(p,xp) at E_p=30 MeV

From comparison of experimental and calculated integral spectra (fig.4) it follows that main contribution in experimental cross section is due to MSD reaction mechanism. It is also shown that evaporated part of cross-section is underestimated in framework of used version of exciton model. This can be explained by the fact that used master equation approach gives only pre-equilibrium part of MSC process, so the emission from complex equilibrium configuration of composite system are not considered.

In addition we carried out the analysis of experimental cross-sections data of reaction ^{56}Fe(p,xp) in accordance with the Hauser-Fechbach theory, while taking into account the multi-particle emission of both single-charged (protons, neutrons) and double-charged fragments (deuterons, α-particles), and also pursuant to the stringent quantum-mechanical theory (program EMPIRE [8]). Thus, the contributions of statistical direct and compound processes for the reaction (p,xp) were calculated. In all cases, the parameter of level density was determined by Gilbert-Cameron parameterization [9].

The calculation results are shown in fig. 5. It is shown that the contribution of multi-particle compound of the mechanism determines the emission of protons from 2,5 MeV up to 10 MeV, and the contribution of multi-step direct process extends from 5 MeV up to the kinematics threshold. The shape of (p,xp) reaction integral spectra is determined by the multi-step direct processes. At the same time, the shape of spectra within the indicated theory that can be connected to the contribution of single-step direct mechanisms, which are not taken into account within this approach, is not to be described for reaction (p,xd).

The quantum-mechanical theory allows one to play back the shape of spectra and that of the absolute cross-section for reaction (p,xp).

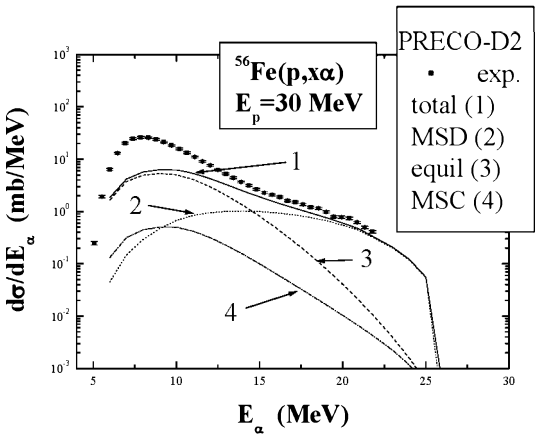


Fig.4. Analysis of integral cross sections of reaction ^{56}Fe(p,xα) at E_p=30 MeV in exciton model (Kalbach)

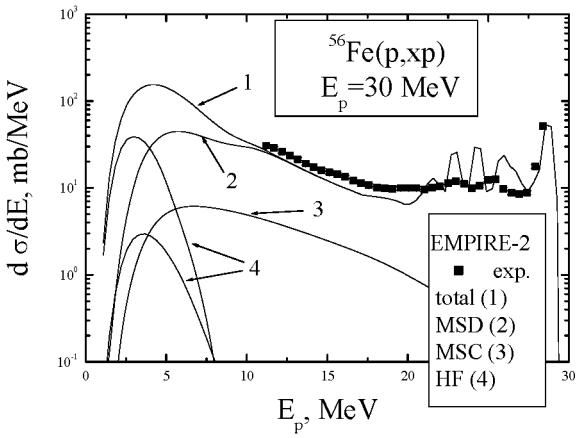


Fig.5. Analysis of integral cross sections of reaction ^{56}Fe(p,xp) at E_p=30 MeV in strict quantum-mechanics theory

From the analysis of the results of the double differential inclusive cross-sections of reactions ^{56}Fe(p,xp), (p,xα) at E_p=29,9±0,15 MeV within the phenomenological exciton model of pre-equilibrium decay and microscopic theory of MSD and MSC processes, it is well established that the contribution of the multi-particle compound emission into cross-sections of reactions is determined by protons with energies from 2,5 up to 10 MeV, and from 5 MeV up to the kinematics limit in direct processes. The introduction of α-particles pre-formation calculations is necessary for the adequate description of the experimental cross-sections of the reaction (p,xα). It can be noted that the using of phenomenological and semi-microscopic approaches allows adequate description of the experimental cross-sections of reactions (p,xp) and (p,xα).

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