Equilibration of Composite System Formed by Intermediate Energy Nucleons

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Abstract

The development of the multi-particle preequilibrium model (MCP) is presented. The movement of the composite system formed by the nucleons of 100 MeV- 3 GeV energy to the equilibrium is discussed. The physical criterium of the equilibration time choice is proposed. The comparison of calculated neutron multiplicities in 208Pb + p reaction with experimental data has served as the basis for the testing of the proposed method. It is appeared, that calculated neutron multiplicities are in good coincidence with experimental data without parameter fitting.

Introduction

In the traditional approaches of the preequilibrium decay calculations the choice of the equilibrium moment t_{eq} does not influence the nucleon number (always one) and this moment means the calculation stop down when the populations of all the particle-hole configurations achieve almost stable values (fig.1). It can be seen from fig. 1, that already at 6th step on time (axis Y) the populations of the various configurations become constant. Both an absence of a sharp border between the system characteristics before and after balance and a large sensitivity of the particle multiplicities to the chosen time t_{eq} do not allow to use this approach in multiparticle emission case.

The value of t_{eq} is the upper limit of the integral in calculation of the nucleon spectra:

$$S(\varepsilon) = \sum_{n} \int^{t_0} P(n,t) \cdot W(n,\varepsilon) dt \qquad (1),$$

where the under integral expression being product of state population by nucleon emission rate, is quickly falling down function of a time. Thus, the uncertainties of the time of balance do not influence the shape and value of the spectra. On the other hand, the preequilibrium nucleons are escaping from the composite system which is moving to equilibration. The number of these nucleons (multiplicity) depends on the time of the process finish crucially.

There are two ways of the problem decision: i) to fix the maximal number of preequilibrium nucleons and to use this value as a fitting parameter; ii) to find same physical evidences of a system equilibration and to use this criterium in calculations without fitting. We used the first approach in our calculations [1, 2], but here we propose the second one to predict the multiplicities of nucleons produced in the high energy reactions.

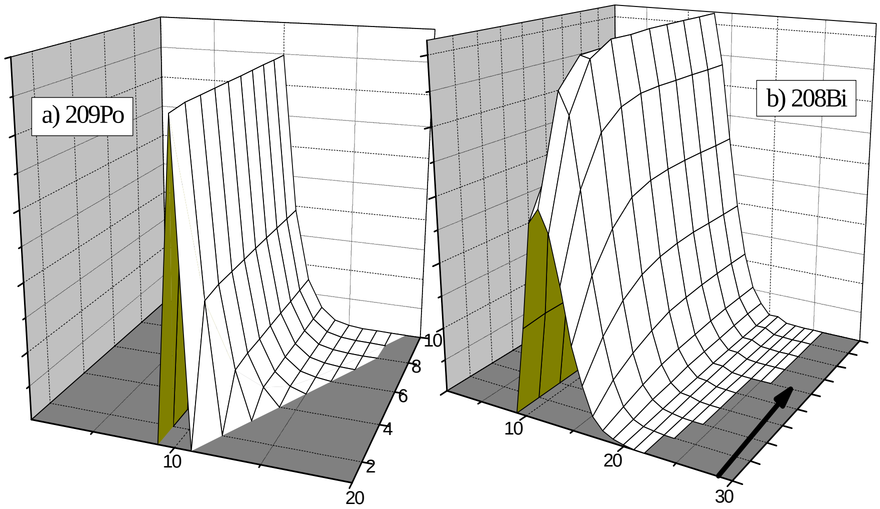

Fig. 1 Particle-hole state populations of 209Bi+p(1500 MeV) reaction. X axe is the number of configuration; Y axe is an equilibration time.

Equilibration time

The evidences of the fact that the composite system is in a statistical balance, are, certainly, the spectra of its radiations. If the radiation has a statistical property (spectral shape), the source of this radiation is equilibrium one. For the analysis and the definition of the balance moment the neutron spectra are the best source of information (fig. 2a), since the spectra of protons have not soft part because of a column barrier (fig. 2b). The methods of calculation of gamma-spectra in preequilibrium model are not reasonable theoretically based.

It can be seen from a fig. 2, that everyone subsequent nucleon has a more and more soft spectrum which is coming nearer to equilibrium one. For example, it is possible approximately to consider a spectrum of the 9-th neutron as a statistical shape, but the spectra shape changing occurs not only that the system comes nearer to balance, but also because of its excitation energy decreasing after the nucleon emission. Therefore we shall consider spectra of neutrons from various particle - hole configurations without dependence on the emission order. The spectra calculated with MCP model of neutrons from various particle – hole states are shown in a fig. 3 in the comparison with appropriate evaporation spectra. Last ones are received as the results of the parameter adjustment of the evaporation formula to the results of the MCP model. One can concludes that the configuration # 20 (21p20h) emits especially nonequilibrium neutrons, in spite of the fact that this state is rather complex already. Only spectrum of radiation of the 25-th configuration comes nearer to an evaporational spectrum.

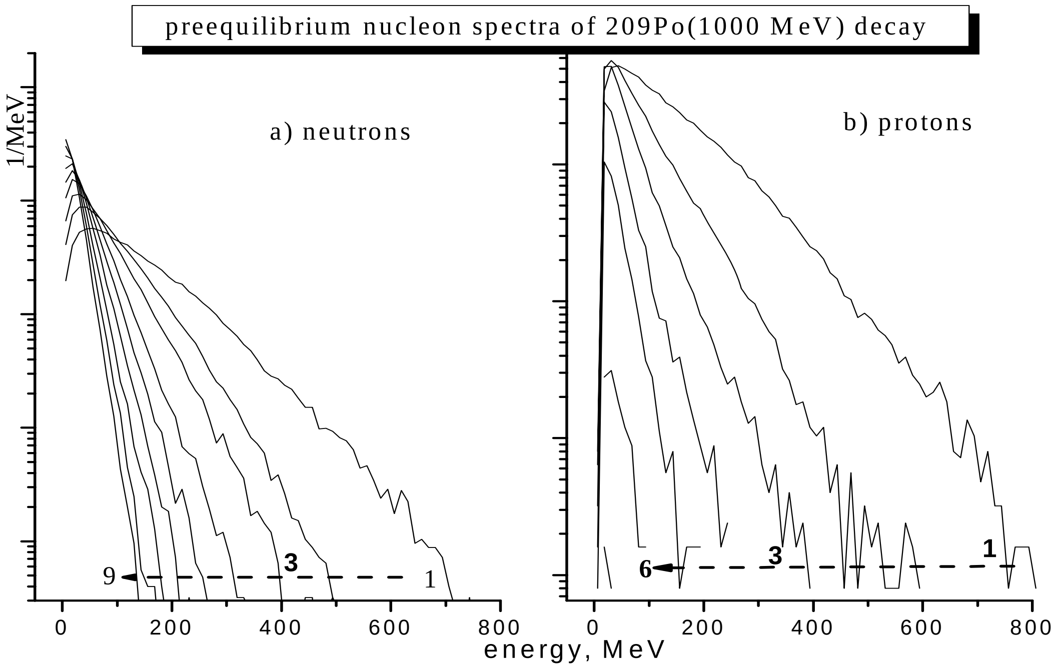

Fig. 2. Calculated spectra of preequilibrium neutrons and protons. The numbers mark the order of emission.

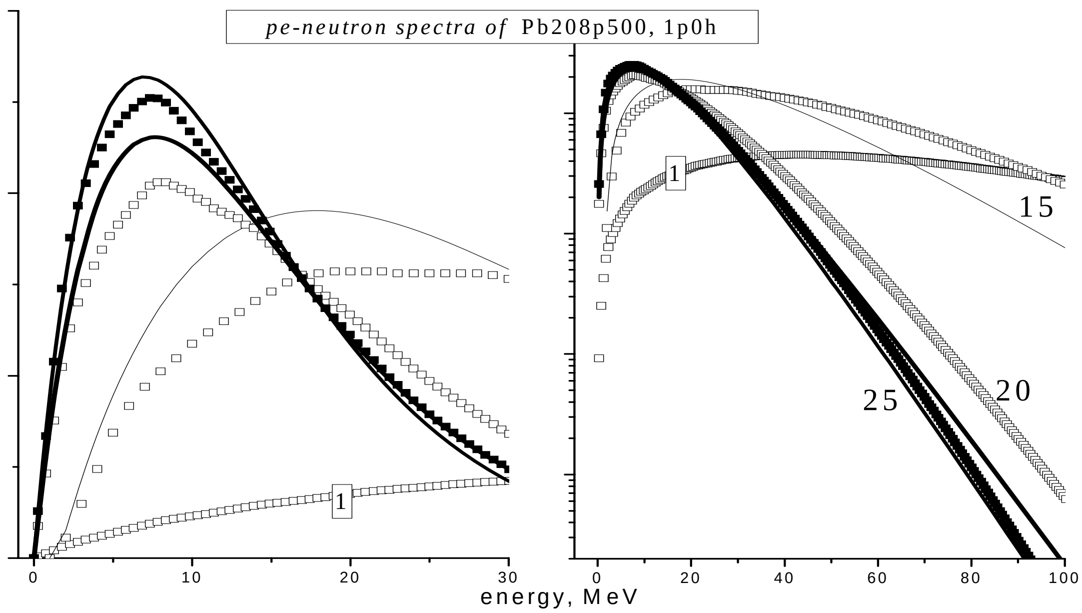

Fig. 3. Calculated spectra of neutrons from various particle-hole configuration (symbols) and the spectra calculated with evaporation model (lines). Numbers designate states.

The χ^2 parameter is the characteristics of the coincidence of the preequilibrium and evaporational spectrum shapes. The values of this parameter are given in a fig. 4 for the analysis of radiations of various composite systems formed in reactions of protons with the energies up to 1500 MeV with 209Bi target.

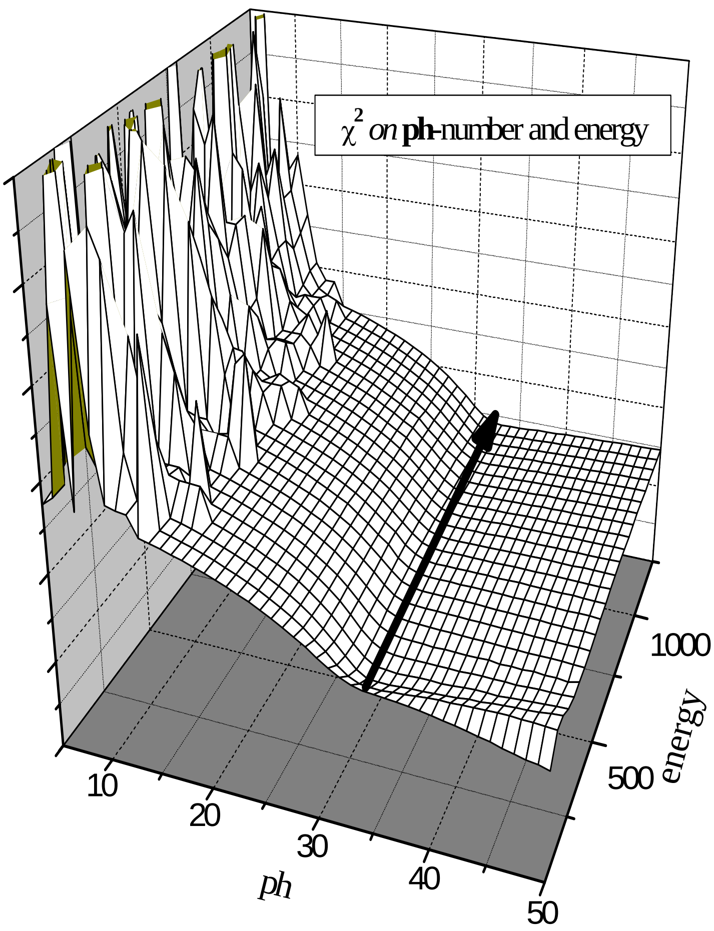

Fig. 4. Deviations of calculated by MCP model spectra of neutrons from an evaporation shape as a dependence on numbers of ph-configuration and energy of protons in 208Pb+p reaction. The red arrow marks $N_{ph}^{max} = 30$ configuration.

The initial configurations (ph < 5) of the exited systems emit the especially nonequilibrium neutrons – the huge values of χ^2 parameter demonstrate it. Moreover, the averaged energies received according to the evaporation formula exceed the real excitation energy of breaking up systems. In a process of a system complication (growing up the particle and hole numbers) the χ^2 parameter value decreases - it means the system goes to an equilibrium. So, for the configurations with ph > 15 the $\chi^2(ph,E)$ distributions become smooth and, finally, they reach a constant value corresponded to the minimally possible value (the configurations more complex than 30th one). Curious fact is that the number of the greatest nonequilibrium configuration $N_{ph}^{\max} = 30$ does not depend on proton projectile energy.

Thus, the states up to which the preequilibrium emission has to be calculated are fixed, The ph-configuration with higher complexity will be consider as "equilibrium state" or as the states of the compound nucleus. The statistical model of nuclear reaction will be used for the calculations of the decay characteristics of these compound states.

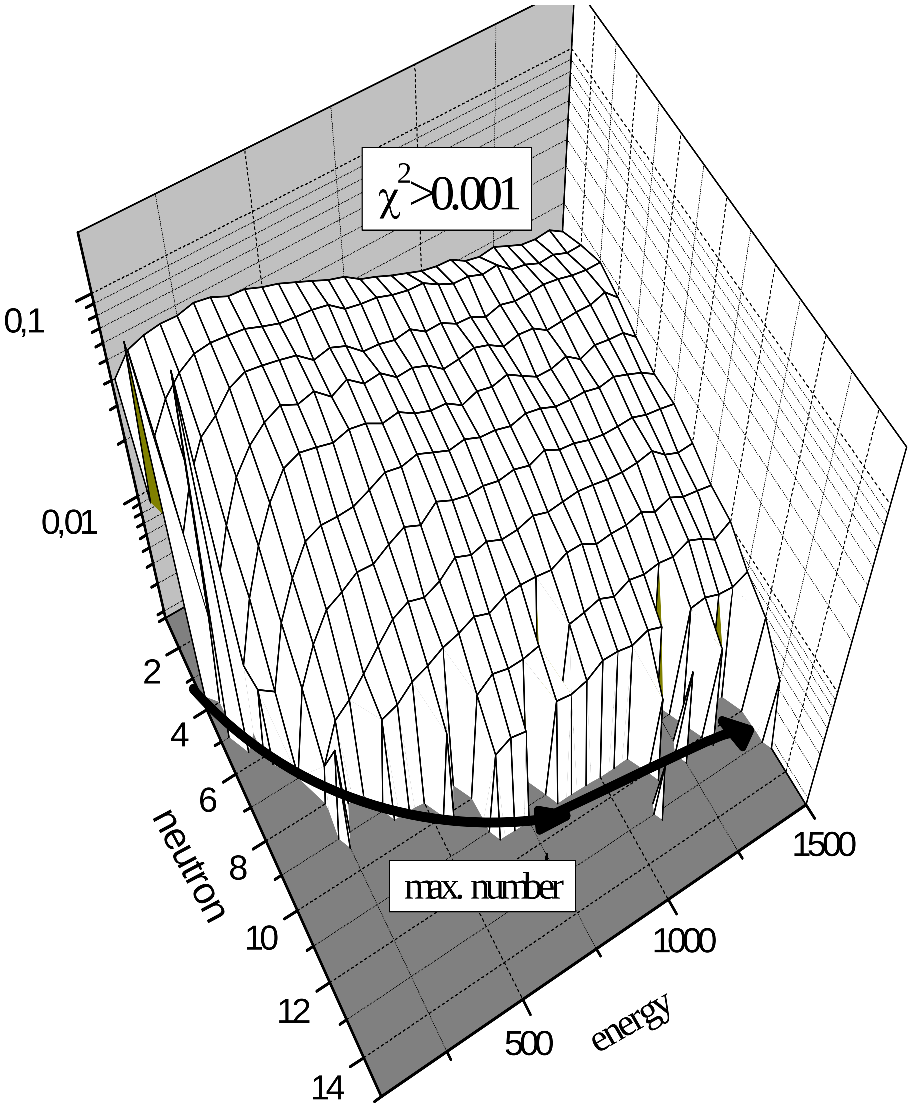

Fig. 5. Deviations of the neutron spectrum shape from equilibrium one depending on neutron serial numbers and on proton energy. The line shows the maximal number of nonequilibrum neutrons.

The preequilibrium neutron number depends on the configuration numbers obviously, but by a complex manner. The dependence of the deviation values of a spectrum shape on the neutron serial numbers and on the projectile proton energy is shown in fig. 5. The amount of the neutrons with nonequilibrium spectra increases as the energy of protons increases.

Neutron multiplicity

The secondary particle multiplicity (the averaged number of particle per one projectile) has important role in the transport calculation – shielding, activations, etc. The experimental data on the neutron multiplicities are the best base of the theoretical model testing for the intermediate energy region, simultaneously. We used the experimental neutron multiplicities as a function of proton energy to prove our approach of equilibration is valid. The comparison of the data is presented in fig. 6.

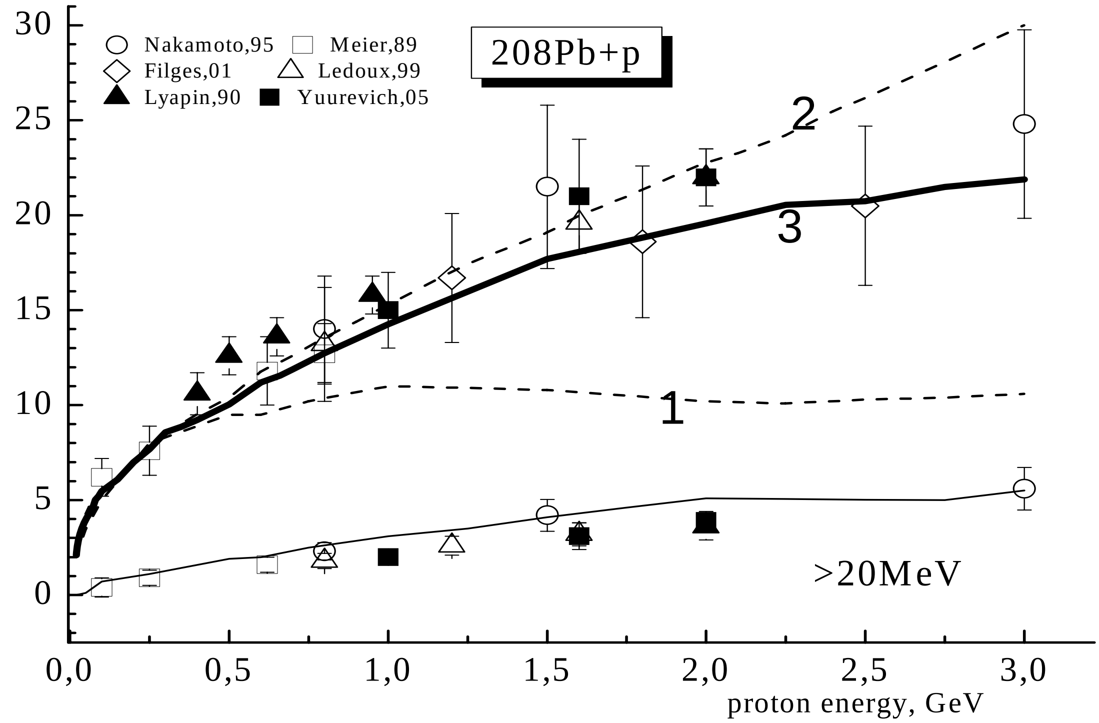

Fig. 6. The neutron multiplicities of 208Pb + p reaction. The symbols are the experimental data. The dashed lines are the results of calculations with the fixed M_n = 5, M_p = 2 (curve#1) and with M_n = 25, M_p = 10 (curve # 2). The results of calculations with fixed maximal preequilibrium configuration are shown by solid curve # 3.

The helpful feature of experimental data of fig.6 is the dividing of the data on soft and hard parts by 20 MeV border. This feature permits to understand the influence of the different model on the calculation results. Two tapes of the calculation results are presented in fig.6. the first one is the results with fixed maximal numbers of preequilibrium neutrons M_n and protons M_p, the second data type is the results of calculations with fixed final preequilibrium configuration as it was described above. It is obvious the numbers of nucleons permitted for emission $M_n = 5$, $M_p = 2$ are not enough to describe the experimental data. The parameter values for fitting are $M_n = 25$, $M_p = 10$ (curve #2). The results of calculations with fixed maximal preequilibrium configuration (i.e. without parameter playing) are shown by solid curve # 3.

Conclusion

To avoid the parameter fitting in calculation of the secondary particle multiplicity of the intermediate and high energy reactions with multiparticle preequilibrium model we fixed the highest particle-hole configuration (#30) of the composite system which emits preequilibrium nucleons yet. The more complicated configurations were declared as the states of the compound nucleus. The results of the neutron multiplicity calculations coincide with the experimental data for the wide projectile energy region of 208Pb + p reaction.

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References

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2. Grudzevich O., Yavshits S. Proc. of Int. Conference on Nuclear Data for Science and Technology, 2007. Nice, France. v.2, p.1213.