

# Comparison of nonequilibrium processes in p+Ni and p+Au collisions at GeV energies

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The energy and angular dependence of double differential cross sections  $d^2\sigma/d\Omega dE$  were measured for  $p, d, t, {}^3,4,6\text{He}, {}^6,7,8\text{Li}, {}^7,9,10\text{Be}, {}^{10,11}\text{B}$ , and C produced in collisions of 1.2, 1.9, and 2.5 GeV protons with a Ni target. The shape of the spectra and angular distributions does almost not change whereas the absolute value of the cross sections increases by a factor  $\sim 1.7$  for all ejectiles in this beam energy range. It was found that energy and angular dependencies of the cross sections cannot be reproduced by the microscopic model of intranuclear cascade with coalescence of nucleons and the statistical model for evaporation of particles from excited, equilibrated residual nuclei. The inclusion of nonequilibrium processes, described by a phenomenological model of the emission from fast and hot moving sources, resulting from break-up of the target nucleus by impinging proton, leads to very good reproduction of data. Cross sections of these processes are quite large, exhausting approximately half of the total production cross sections. Due to good reproduction of energy and angular dependencies of  $d^2\sigma/d\Omega dE$  by model calculation it was possible to determine total production cross sections for all studied ejectiles. Results obtained in this work point to the analogous reaction mechanism for proton induced reactions on Ni target as that observed previously for Au target in the same beam energy range.

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## I. INTRODUCTION

The recent successful analysis [1, 2] of the inclusive spectra and angular distributions of double differential cross sections  $d^2\sigma/d\Omega dE$  for light charged particles (LCP's), i.e. particles with  $Z \leq 2$ , and intermediate mass fragments (IMF's), i.e. ejectiles heavier than  ${}^4\text{He}$ , produced in proton - Au collisions at proton beam energies 1.2, 1.9, and 2.5 GeV indicated, that the competition of two different processes is essential for understanding of the mechanism of proton - gold nucleus collisions. The traditional picture of the spallation reactions, namely the intranuclear cascade of nucleon - nucleon interactions followed by evaporation of particles from an equilibrated residuum of the cascade is not able to reproduce satisfactorily the experimental cross sections. This fact leads to the conclusion that a significant contribution of nonequilibrium processes to the reaction mechanism is present.

It was found that the difference between the data and theoretical cross sections from the above two-step model varies smoothly with the scattering angle and with the energy of the ejectile. It turned out, that this variation may be well reproduced assuming the isotropic emission

of nucleons and composite particles in the rest frame of two or three sources moving forward, i.e., along the beam direction. Such an effect has been interpreted in Refs. [1, 2] as indication of break-up of the target nucleus by fast proton from the beam. In that physical picture the proton drills a cylindrical hole in the nucleus knocking out the small group of nucleons placed on the straight way of the proton through the nucleus. This group moves quickly in forward direction behaving as a fireball, which on its part emits nucleons and LCPs whereas the "wounded" nucleus may decay into two excited prefragments which also serve as sources of LCPs and IMF's.

The present study was performed with the aim to investigate, whether the reaction mechanism observed and described in detail in Ref. [2] for Au target is also realized in collisions of protons with other target nuclei. The Ni target was used for this purpose because it has quite different properties than the Au target. The Ni nucleus is more than three times lighter, its N/Z ratio ( $\sim 1.1$ ) is approximately 1.4 times smaller from that of the Au nucleus (N/Z  $\sim 1.5$ ), and its binding energy ( $\sim 8.8$  MeV/nucleon) is significantly larger than that of the Au nucleus ( $\sim 7.9$  MeV/nucleon). The appearance of the same reaction mechanism for such different target nuclei might suggest that this phenomenon is of a general character, i.e., it occurs for all target nuclei in the studied

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energy range.

To facilitate the comparison of the results from the present study of the reactions in p+Ni system with results of previous investigations concerning p+Au system [2], the present paper is organized in similar way as reference [2]. Experimental data are discussed in the next section, the theoretical analysis is described in the third section starting from IMF data and followed by analysis of LCPs cross sections, discussion of results are presented in the fourth and summary with conclusions in the fifth section.

## II. EXPERIMENTAL DATA

The experiment was performed with the selfsupporting Ni target of the thickness about of  $150 \mu\text{g}/\text{cm}^2$ , irradiated by internal proton beam of COSY (COoler SYNchrotron) of the Jülich Research Center. The experimental setup and procedure of data taking were in details described in Refs. [1] and [3]. The beam was operated in so called supercycle mode to assure identical experimental conditions for all three studied proton energies - 1.2, 1.9 and 2.5 GeV, i.e., the same setup, electronics, the target thickness and its position. In this mode several cycles were alternated for each requested beam energy, consisting of protons injection from JULIC cyclotron to COSY ring, their acceleration with the beam circulating in the ring below the target, and irradiating the target by slow movement of the beam in the upward direction. The using of supercycle mode minimizes systematic effects which might distort the studied energy dependence of the cross sections.

Double differential cross sections  $d^2\sigma/d\Omega dE$  were measured at seven scattering angles;  $16^\circ$ ,  $20^\circ$ ,  $35^\circ$ ,  $50^\circ$ ,  $65^\circ$ ,  $80^\circ$ , and  $100^\circ$  as a function of energy of ejectiles for the following isotopes  ${}^1,2,3\text{H}$ ,  ${}^{3,4,6}\text{He}$ ,  ${}^{6,7,8}\text{Li}$ ,  ${}^{7,9,10}\text{Be}$ , and  ${}^{10,11}\text{B}$ . The carbon ejectiles were only charge identified.

The absolute normalization of the cross sections was achieved by comparing the total production cross sections of  ${}^7\text{Be}$  particles, obtained by angle and energy integration of measured differential cross sections, with values of  ${}^7\text{Be}$  total production cross sections published in the compilation of Bubak *et al.* [4]. It turned out that present values of total production cross sections at proton beam energy 1.2 GeV are in perfect agreement with those obtained by Herbach *et al.* [5]. The same quality agreement was observed for total production cross sections of the present work at 2.5 GeV and Li, Be, and B cross sections measured by Raisbeck *et al.* [6] on Ni target with 3.0 GeV proton beam.

Typical spectra of isotopically identified ejectiles obtained in the present experiment are shown in Fig. 1. All spectra are smooth and do not change their shapes with increasing beam energy, however, the magnitude of the cross sections increases slightly with the energy.

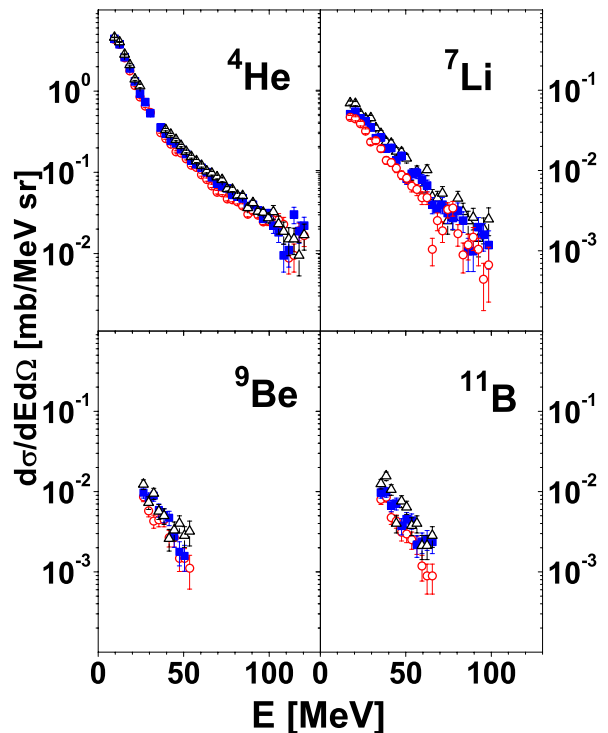


FIG. 1: Typical spectra of  ${}^4\text{He}$ ,  ${}^7\text{Li}$ ,  ${}^9\text{Be}$ , and  ${}^{11}\text{B}$  ejectiles (upper left, upper right, lower left, and lower right parts of the figure, respectively) measured at  $35^\circ$  for three energies of the proton beam; 1.2, 1.9, and 2.5 GeV, impinging on to the Ni target. Open circles represent the lowest energy, full squares - the intermediate energy, and the open triangles show the data for the highest energy.

## III. THEORETICAL ANALYSIS

The analysis of the present experimental data was performed according to the same procedure as that applied previously to the data from proton induced reactions on the Au target in the work of Budzanowski *et al.* [2]. First, the cross sections were evaluated from the intranuclear cascade with inclusion of possibility to coalesce the outgoing nucleons into LCPs, and with possibility to evaporate the particles from the excited, equilibrated residua of intranuclear cascade. Such two-step model of the reaction mechanism is most frequently used in the literature for the description of spallation reactions at high proton energies. The INCL4.3 computer program of Boudard *et al.* [7] has been used for calculations of intranuclear cascade and GEM2 program of S. Furihata [8, 9] has been applied to evaluate evaporation cross sections. Since the data were generally underestimated by two-step model a phenomenological analysis was performed in the following. This analysis was based on the assumption that additional processes exist besides the mechanisms described above. They were pa-

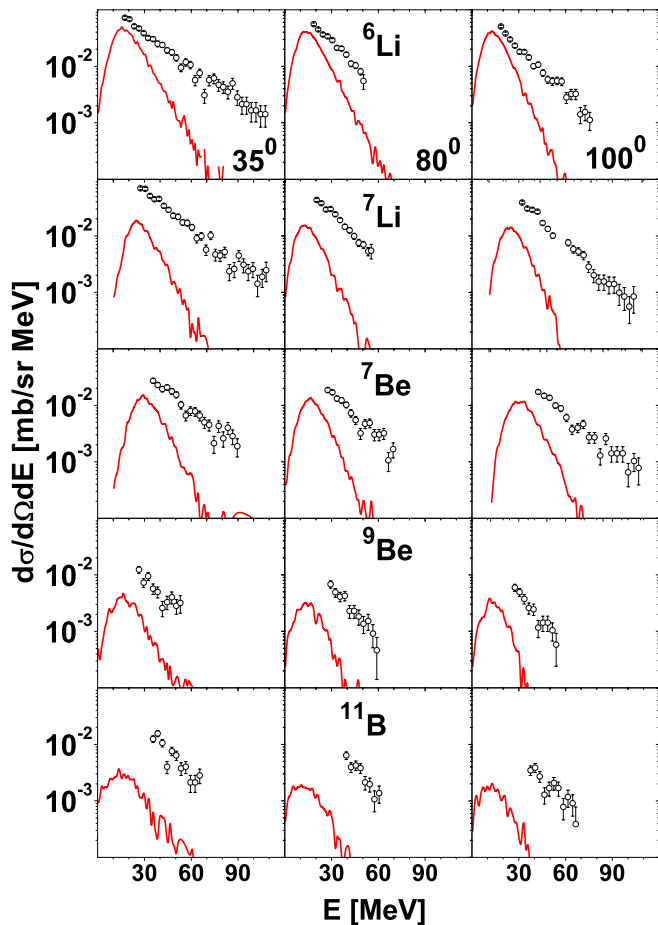


FIG. 2: Typical spectra of selected lithium, beryllium, and boron isotopes from p+Ni collisions measured at 35°, 80°, and 100° (left, middle, and right columns, respectively) for 2.5 GeV proton beam impinging on to the Ni target. The detected particles are listed in the central panel of each row of pictures. Open circles represent the experimental data, and solid lines correspond to intranuclear cascade followed by evaporation of particles, respectively.

parameterized by incoherent sum of isotropic emission of particles from highly excited sources moving in forward direction, i.e., along to the beam. Each of the sources has a Maxwellian distribution of the energy  $E$  available for the two body decay resulting in emission of the detected particles;  $d^2\sigma/dE d\Omega \sim \sqrt{E} \exp(-E/T)$ . The velocity of the source -  $\beta$  (in units of speed of light), its temperature -  $T$  (in MeV), and the contribution to the total production cross section -  $\sigma$  are treated as free parameters. The presence of the Coulomb barrier, which hinders emission of low energy particles, was taken into account multiplying the Maxwellian energy distribution by a smooth function  $P(E)$  corresponding to the transmission probability through the barrier. Two parameters were introduced to characterize the properties of the Coulomb barrier:  $k$ -parameter, i.e., height of the

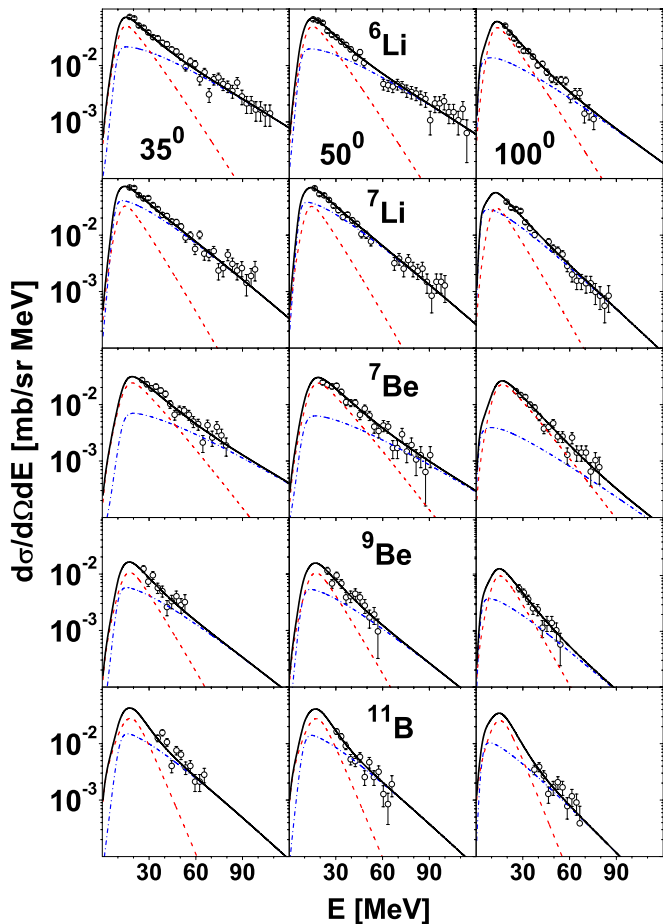


FIG. 3: Typical spectra of lithium, beryllium, and boron ejectiles from p+Ni collisions measured at 35°, 50°, and 100° (left, middle, and right columns, respectively) for 2.5 GeV proton beam impinging on to the Ni target. The detected particles are listed in the central panel of each row of pictures. Open circles represent the experimental data, dashed, dot - dashed, and solid lines correspond to slow emitting source, fast emitting source and the sum of both contributions, respectively.

Coulomb barrier in units of the height of the barrier  $B$  of two charged, touching spheres of radius  $1.44 A^{1/3}$ ;  $B = Z_1 Z_2 e^2 / 1.44 (A_1^{1/3} + A_2^{1/3})$  MeV, and the ratio  $B/d$ , where  $d$  is a diffuseness of the transmission function through the barrier:  $P(E) = (1 + \exp((E - kB)/d))^{-1}$ . Details of this procedure, as well as interpretation of parameters of the model can be found in Appendix of Ref. [1].

### A. Intermediate mass fragments

The shape of the spectra of IMFs is almost independent of the beam energy. Thus, only the cross sections measured at 2.5 GeV beam energy have been used for illustration of the quality of data description. On the

contrary, the shape of the spectra changes in regular way with variation of the detection angle, namely the spectra become more steep when the scattering angle increases. This is especially well visible when the data are compared at angles differing strongly as, e.g.,  $35^\circ$  and  $100^\circ$ . Experimental spectra measured at three selected angles –  $35^\circ$ ,  $80^\circ$ , and  $100^\circ$  – are shown on Fig. 2 for most abundant isotopes of lithium, beryllium and boron as open circles together with the evaporation model predictions (solid lines). Fluctuations of the theoretical spectra are due to the Monte Carlo method of model calculations, i.e. due to limited statistics of generated events. As can be seen, the theoretical spectra are more steep than the experimental ones and the absolute values of theoretical cross sections are several times smaller than the data. The former effect is most pronounced for  ${}^6,{}^7\text{Li}$  and  ${}^7\text{Be}$  cross sections whereas the latter is present for all detected IMFs. Furthermore, the evaporation model does not reproduce the tendency of shape variation with the angle.

All these facts indicate that an important contribution of another reaction mechanism must be added to evaporation cross sections to assure good reproduction of the data. This contribution is comparable in magnitude with the evaporation cross section for Li and becomes even more dominant for Be and B isotopes. Thus, the IMF's data have been analyzed in the frame of a phenomenological model of two moving sources as it was done for p+Au reactions [1]. In this way the IMF's production on Ni target could be compared with that for the Au target.

The parameters of two moving sources were searched for by fitting the two moving sources cross sections to experimental data, which consisted of energy spectra measured at seven angles:  $16^\circ$ ,  $20^\circ$ ,  $35^\circ$ ,  $50^\circ$ ,  $65^\circ$ ,  $80^\circ$ , and  $100^\circ$ . To decrease the number of parameters it was assumed that the velocity of the slow source emitting IMF's is equal to the velocity of the heavy residuum from intranuclear cascade, i.e.,  $\beta_1=0.005$ . The mean values of this velocity was found in calculations of intranuclear cascade to be equal to  $0.0051c$ ,  $0.0049c$ , and  $0.0047c$  for 1.2, 1.9, and 2.5 GeV beam energy, respectively. It was checked that the modification of this parameter by 30% causes changes of other parameters smaller than their errors estimated by fitting computer program. In evaluation of  $k$ -parameter it was assumed that  $B$  - value is defined as the Coulomb barrier between the emitted particles and the target nucleus. The results of the fit are not very sensitive to the value of the  $k$ -parameter because the experimental low energy limit of the spectra is above the position of the Coulomb barrier for most of IMFs. Thus fixed values of  $k_1 = 0.75$  and  $k_2 = 0.3$  were used. The  $B/d$  ratio was arbitrarily assumed to be equal to 5.5.

Values of the best fit parameters are listed in Table I. The errors of the parameters are also given when the program searching for the best fit could estimate them. However, sometimes program was not able to estimate the errors, especially when strong ambiguities of parameters were present. In such a case the values of the parameters are quoted without estimation of errors. Sometimes

it was useful to fix the values of parameters to avoid numerical problems leading to ambiguities. Such values are quoted in the table in parentheses.

A very good description of the spectra of all IMF's has been obtained as can be judged from the inspection of Fig. 3 and values of the  $\chi^2$  given in the Table I, which usually vary between 1 and 2.

It is obvious from comparison of Figs. 2 and 3 that the spectra of particles emitted from the slow source are very similar to the evaporation spectra of particles from the residuum of intranuclear cascade, however, it is not the case for the spectra of the fast source. They have much smaller slope and are dependent on the scattering angle. It is evident that their presence is necessary to reproduce the high energy part of experimental spectra.

The cross sections of both emitting sources increase with beam energy. This is illustrated on Fig.4 where ratios of the production cross sections for beam energy 1.2 and 1.9 GeV to the cross sections for 2.5 GeV are presented. It turned out that the increase of the cross sections with the beam energy is the same, in the limits of errors, for contributions emerging from both emitting sources. The cross sections increase approximately by factor 1.7 when beam energy increases from 1.2 GeV to 2.5 GeV (cf. numbers depicted in Fig. 4). Since the energy dependence is very similar for both emitting sources, the relative contributions of the sources remain constant in the studied energy range and, moreover, both are equal in the limits of errors: The averaged over IMFs ratio of  $\sigma_2/(\sigma_1 + \sigma_2)$  is equal to 0.50(14), 0.46(11), and 0.48(16) for beam energy 1.2, 1.9, and 2.5 GeV, respectively. Thus, this ratio averaged over three energies is equal to 0.48(7).

The parameters of the sources, which influence the shape of the spectra (velocity  $\beta$  and temperature  $T$ ) should not change with the beam energy because the shape of experimental spectra is independent of the beam energy (cf. Fig. 1). However, there is a distinct difference for each energy between values of the parameters characterizing the slow source and the fast source. The velocity of the fast source  $\beta_2$ , averaged over IMFs is equal to 0.027(3), 0.027(2), and 0.023(2) for beam energy 1.2, 1.9, and 2.5 GeV, respectively. These values are about five times larger than fixed velocity of the slow source ( $\beta_1 = 0.005$ ). The temperature parameter  $T_2$  of the fast source is about two times larger than the temperature parameter of the slow source  $T_1$ . Its values (averaged over IMFs) are equal to 16.8(1.2), 17.4(6), and 17.8(8) MeV for the fast source and 7.6(3), 8.4(6), and 8.1(5) MeV for the slow source at three studied beam energies 1.2, 1.9, and 2.5 GeV, respectively.

## B. Light charged particles

All experimental spectra of LCPs from p+Ni collisions contain large high energy component (cf. Figs 1, 5, and 6), which cannot be reproduced by evaporation of parti-

TABLE I: Parameters of two moving sources fitted to p+Ni data for isotopically identified IMF's and for  ${}^4\text{He}$ :  $\beta_i$ ,  $T_i$ , and  $\sigma_i$  correspond to source velocity, its apparent temperature, and total production cross section, respectively. The sum  $\sigma \equiv \sigma_1 + \sigma_2$  is also listed. The left part of the Table (parameters with indices "1") corresponds to the slow moving source, and the right part contains values of parameters for the fast moving source. The upper row for each ejectile corresponds to beam energy 1.2 GeV, the row in the middle to 1.9 GeV, and the lowest one to the energy 2.5 GeV.

Ejectile	Slow source		Fast source			$\sigma$ mb	$\chi^2$
	$T_1/\text{MeV}$	$\sigma_1/\text{mb}$	$\beta_2$	$T_2/\text{MeV}$	$\sigma_2/\text{mb}$		
${}^4\text{He}$	7.0(2)	244(6)	0.040(3)	18.1(5)	76(6)	320(9)	7.3
	7.3(2)	269(6)	0.036(2)	19.4(5)	94(6)	363(9)	4.7
	7.9(2)	283(8)	0.035(2)	20.1(5)	101(7)	384(11)	4.4
${}^6\text{Li}$	9.1(4)	8.3(4)	0.035(3)	18.6(5)	4.1(5)	12.4(7)	1.5
	10.4(4)	11.5(6)	0.037(3)	19.8(5)	4.5(6)	16.0(9)	1.4
	9.4(5)	11.6(8)	0.026(3)	20.5(6)	8.0(9)	19.6(1.2)	1.3
${}^7\text{Li}$	8.1(7)	4.9(7)	0.022(2)	14.7(4)	6.6(9)	11.5(1.2)	1.3
	9.6(7)	8.0(1.0)	0.025(3)	15.9(5)	7.0(1.2)	15.0(1.6)	1.3
	9.6(1.0)	5.2(1.3)	0.018(2)	16.0(5)	12.3(1.8)	17.5(2.2)	1.4
${}^8\text{Li}$	[8.0]	[0.2]	0.040(8)	14.4(2.0)	1.2(5)	1.4(5)	1.4
	9.4(3.8)	0.6(5)	0.032(6)	17.2(1.1)	3.7(1.0)	4.3(1.1)	1.0
	8.0(1.8)	1.3(4)	0.029(5)	18.0(1.0)	6.4(1.5)	7.7(1.6)	1.0
${}^7\text{Be}$	8.7(1.3)	2.8(5)	0.025(3)	16.8(7)	3.6(7)	6.4(9)	1.4
	9.5(9)	4.9(6)	0.025(3)	19.2(9)	3.9(8)	8.8(1.0)	1.0
	11.3(7)	6.9(6)	0.032(5)	21.4(1.3)	2.6(7)	9.5(9)	1.0
${}^9\text{Be}$	[8.6]	1.1(2)	[0.023]	12.1(8)	1.3(2)	2.4(3)	1.1
	8.1(1.6)	2.0(5)	0.024(7)	14.2(1.2)	1.6(7)	3.6(9)	0.8
	8.3(2.0)	2.4(7)	0.019(7)	16.9(2.4)	1.8(1.1)	4.2(1.3)	1.0
${}^{10}\text{Be}$	6.1(1.9)	1.0(4)	0.030(16)	27.8(9.0)	0.4(2)	1.4(5)	1.8
	7.9(1.7)	1.0(4)	[0.023]	17.6(3.1)	0.7(2)	1.7(5)	1.8
	6.1(1.9)	1.7(6)	0.024(11)	23.0(9)	0.8(4)	2.5(7)	1.3
${}^{10}\text{B}$	[6.0]	1.6(1.2)	0.018(4)	15.5(3.1)	1.7(6)	3.3(1.4)	1.7
	[6.0]	3.3(1.2)	[0.023]	16.4(1.5)	2.4(4)	5.7(1.3)	1.8
	[6.0]	3.2(1.4)	[0.023]	17.7(1.8)	2.7(4)	5.9(1.5)	1.9
${}^{11}\text{B}$	[6.0]	3.1(9)	[0.023]	13.4(1.2)	1.8(3)	4.9(1.0)	1.3
	[6.0]	5.2(1.2)	[0.023]	17.8(2.2)	2.3(3)	7.5(1.3)	1.5
	[6.0]	5.9(3.6)	0.016(4)	14.8(3.2)	4.1(1.8)	10(4)	1.7

cles from the equilibrated remnant of the intranuclear cascade. Thus, the nonequilibrium emission of LCPs must play an important role. The coalescence of nucleons escaping from the target nucleus together with nucleons taking part in the intranuclear cascade may lead to such an emission. Indeed, Boudard et al. [7] and Letourneau et al. [10] have shown that the microscopic calculation of coalescence occurring when the intranuclear cascade proceeds is able to reproduce a large part of the observed effect. However, it was found that the improvement of the description of LCPs spectra deteriorates simultaneously the proton spectra because increasing of the production of composite particles occurs on the account of decreasing emission of the nucleons. This contradiction led the present authors to search for another nonequilibrium process, which could be responsible for the observed enhancement of the high energy part of the LCP spectra. It was proposed [2], that the emission from a fireball, i.e., a fast and hot group of nucleons consisting of target nucleons lying on the straight way of the bombarding proton through the target nucleus [11], can account for the missing nonequilibrium component of the LCP cross sections. A sum of the coalescence of nucleons and the

emission of LCPs from the fireball was found to be crucial for the very good description of the data for proton induced reactions on Au target at three beam energies: 1.2, 1.9, and 2.5 GeV [2]. Furthermore, the emission of the fireball, which introduces a strong rearrangement of the target nucleus can lead to a break-up of the remnant of the target and thus to an appearing of two moving sources also emitting intermediate mass fragments and LCps. Therefore, this hypothesis explains simultaneously the presence of the nonequilibrium emission for IMFs which was discussed above.

Since the fireball contains only several nucleons its contribution is present only for LCPs. On the contrary, the fast and slow excited prefragments of the target may emit IMFs as well as LCPs. In the present analysis their contribution to spectra of LCPs has been, however, neglected because it was estimated (by extrapolation of parameters found for IMFs to lighter ejectiles) to be much smaller than contributions of other reaction mechanisms. Magnitude of cross sections for emission of LCPs from two sources - products of break-up - were estimated to be  $\sim 10\%$  of the total cross sections, i.e., to be of order of errors of the fitting procedure.

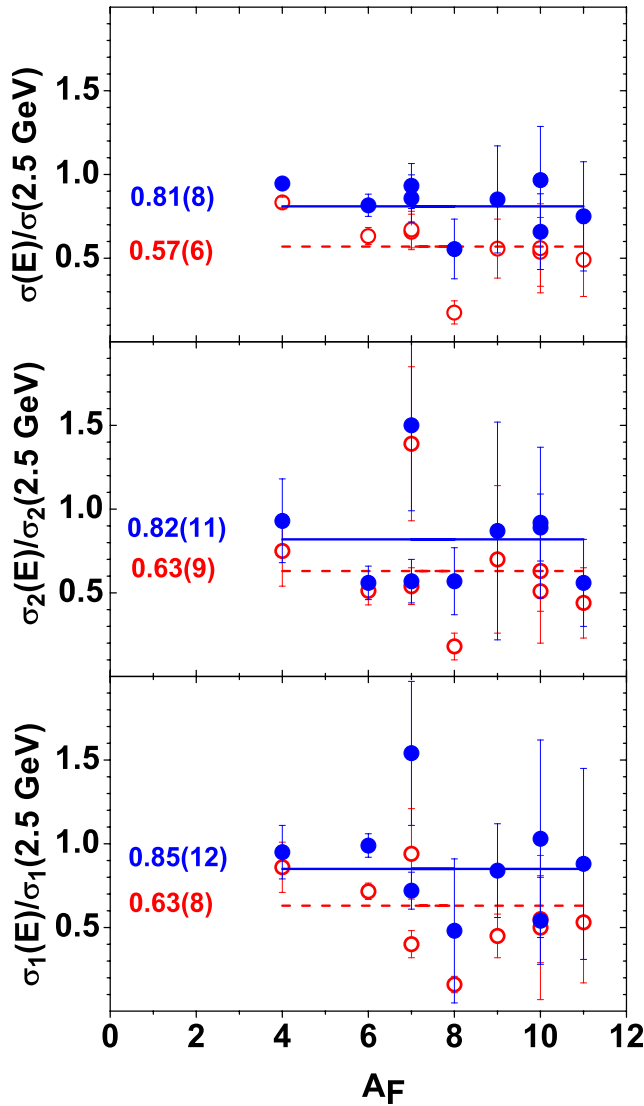


FIG. 4: Ratio of production cross section determined at 1.2 (open circles) and 1.9 GeV (full dots) to the cross sections found at 2.5 GeV beam energy. The lower panel presents cross sections for slow sources, panel in the middle for fast sources, and upper panel for sum of both contributions. The horizontal lines depict values of the ratios averaged over IMFs; the solid lines for the 1.9 GeV, and the dashed lines for 1.2 GeV.

In the present study the same procedure of the description of LCP spectra as that in ref. [2] has been applied. The INCL4.3 computer program [7] has been used for the description of the intranuclear cascade of nucleon-nucleon collisions with inclusion of coalescence of nucleons, whereas the GEM2 computer program [8, 9] served for evaluation of evaporation of particles from heavy target residuum remaining after the intranuclear cascade. The default parameter values, proposed by the authors of both programs, have been used, respectively.

Since there is no explicit room for the presence of the

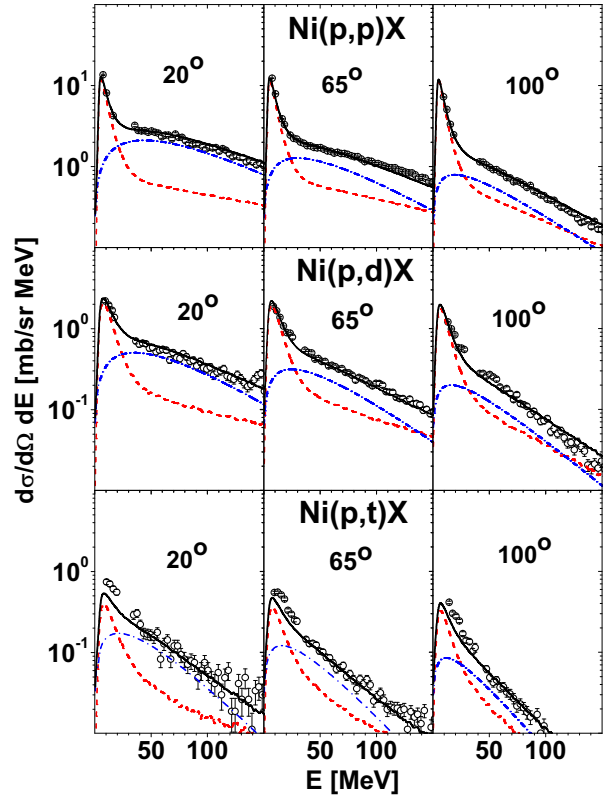


FIG. 5: Typical spectra of protons, deuterons, and tritons (upper, middle, and lower rows of the figure, respectively) measured at  $20^\circ$ ,  $65^\circ$ , and  $100^\circ$  (left, middle, and right columns of the figure, respectively) for 2.5 GeV proton beam impinging on to the Ni target. Open circles represent the experimental data, dashed, dot - dashed, and solid lines correspond to the two-step model, the emission from the fireball and the sum of both contributions, respectively.

fireball in the microscopic calculations performed according to the intranuclear cascade model, the inclusion of fireball emission should be accompanied by decreasing the contribution from direct processes simulated by intranuclear cascade and coalescence of escaping nucleons. Thus, the spectra of protons evaluated from intranuclear cascade with inclusion of coalescence and with contribution of evaporation of particles were multiplied by a factor  $F$ , common for all scattering angles, treated as a free parameter and then added to the contribution from the fireball emission calculated according to the formula of single moving source emitting isotropically the LCP's [12]. The same, fixed value of the scaling factor has been used for further analysis of data for other LCPs. The parameters of the single moving source - the fireball, i.e. its temperature parameter -  $T_3$ , velocity of the source -  $\beta_3$ , total production cross section associated with this mechanism -  $\sigma_3$  were treated also as free parameters.

Parameters  $k_3$  (the height of the Coulomb barriers in units of  $B$  - Coulomb barrier between the ejectile and the



TABLE II: Parameters of the fireball fitted to p+Ni data;  $\beta_3$ ,  $T_3$ , and  $\sigma_3$  correspond to fireball velocity in units of speed of light, its apparent temperature, and total production cross section, respectively. The upper row for each ejectile corresponds to beam energy 1.2 GeV, the row in the middle to 1.9 GeV, and the lowest one to the energy 2.5 GeV. Parameter F is the scaling factor of coalescence and evaporation contribution extracted from fit to the proton spectra. The numbers in parentheses show fixed values of the parameters. Note, that for the  $\alpha$  particles contribution of two additional moving sources should be added with parameters given in Table I. The columns described as  $F*\sigma_{INCL}$  and  $F*\sigma_{GEM}$  contain total production cross sections due to intranuclear cascade with the coalescence and due to evaporation from the target residuum, respectively. The total production cross section obtained by summing of all contributions is depicted in the column denoted by  $\sigma$ . In the case of alpha particles it contains also the contribution of the emission from slow and fast sources listed in Table I.

Ejectile	$\beta_3$	$T_3$ MeV	$\sigma_3$ mb	F	$F*\sigma_{INCL}$ mb	$F*\sigma_{GEM}$ mb	$\sigma$ mb	$\chi^2$
p	0.149(12)	38.9(2.1)	1071(61)	0.70(3)	1094	994	3159(61)	179
	0.156(10)	41.7(1.9)	1222(53)	0.70(2)	1139	1005	3366(53)	95.1
	0.163(8)	43.2(1.5)	1343(44)	0.79(2)	1286	1123	3752(44)	48.8
d	0.105(4)	32.5(8)	181(5)	[0.70]	202	174	557(5)	9.5
	0.099(3)	33.7(6)	234(5)	[0.70]	201	196	631(5)	3.2
	0.100(4)	35.8(8)	272(7)	[0.79]	220	225	717(7)	7.4
t	0.062(3)	21.9(6)	41.9(1.6)	[0.70]	40.9	28.9	111.7(1.6)	1.3
	0.055(3)	23.8(6)	59.8(2.1)	[0.70]	41.3	34.1	135.2(2.1)	1.4
	0.054(3)	25.0(6)	71.5(2.2)	[0.79]	45.3	39.4	156.2(2.2)	1.3
$^3\text{He}$	0.046(2)	22.9(5)	43.1(1)	[0.70]	31.2	32.6	106.6(1)	3.4
	0.039(2)	23.5(4)	60.5(1.2)	[0.70]	31.6	37.5	129.6(1.2)	3.3
	0.040(2)	25.0(5)	69.4(1.4)	[0.79]	34.5	43.1	147.0(1.4)	2.9
$^4\text{He}$				[0.70]	16.8	277	614(9)	7.3
				[0.70]	16.6	281	661(9)	4.7
				[0.79]	18.1	312	714(11)	4.4

target nucleus) and parameter  $B/d$  describing diffuseness of the transmission function through the Coulomb barrier are fixed at arbitrarily assumed values 0.07 and 4.8, respectively. Values of the fitted parameters are collected in the Table II.

The fit was performed for 7 scattering angles ( $16^\circ$ ,  $20^\circ$ ,  $35^\circ$ ,  $50^\circ$ ,  $65^\circ$ ,  $80^\circ$ , and  $100^\circ$ ). Results of the fit are presented in Fig. 5 for protons, deuterons and tritons, and in Fig. 6 for  $^3\text{He}$  and  $^4\text{He}$ . Since the spectra at various beam energies almost do not differ in the shape, the comparison of theoretical cross sections with the data is shown only for one beam energy, namely for 2.5 GeV. The left column on both figures represents cross sections for  $20^\circ$ , the column in the middle for  $65^\circ$ , and the right column the data measured at  $100^\circ$ . The proton spectra are shown in the upper row of the Fig. 5, the deuteron and triton data in the middle and lower row, respectively. The  $^3\text{He}$  data are depicted in the upper row of Fig. 6, whereas the  $^4\text{He}$  cross sections occupy the lower row of this Figure.

It is obvious from inspection of Figs. 5, 6, that a very good description of the experimental data for all LCPs was achieved. It should be emphasized, that the values of the best fit parameters vary smoothly from ejectile to ejectile as well as from the one beam energy to another, thus the same mechanism seems to be responsible for the nonequilibrium processes for all these particles. It was, however, found that values of the parameters, necessary

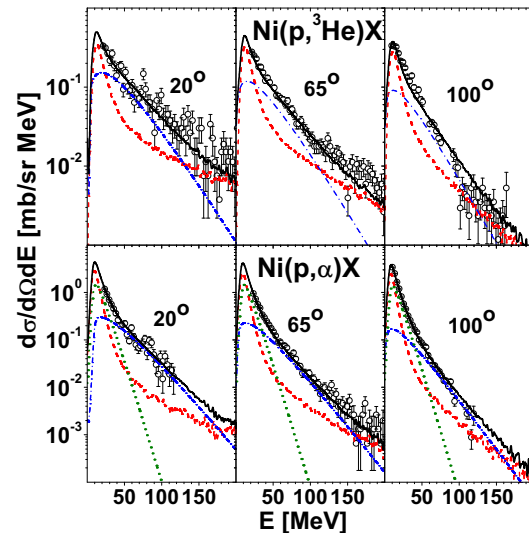


FIG. 6: Same as on Fig. 5 but for  $^3\text{He}$  and  $^4\text{He}$ . The dotted line for  $^4\text{He}$  denotes the contribution of an additional, slowly moving source.

to describe the alpha particle data differ from those for lighter LCPs. It turned out that (i) it is necessary to use two emitting sources instead one fireball for good data reproduction, and (ii) the parameters of these sources have quite similar values as those for IMFs (cf. Table

I). For this reason, it may be concluded that the alpha particles behave rather like IMFs than as LCPs.

Values of fireball velocity  $\beta_3$  and its temperature parameter  $T_3$  do not change systematically with the beam energy and their fluctuations are so small, that it is possible to assume that they do not change with the energy. Similar situation was observed for IMFs. Thus the energy averaged values of velocities and temperature parameters of all sources are collected in one figure - Fig. 7 - to allow for discussion of their dependence on the mass of ejectiles.

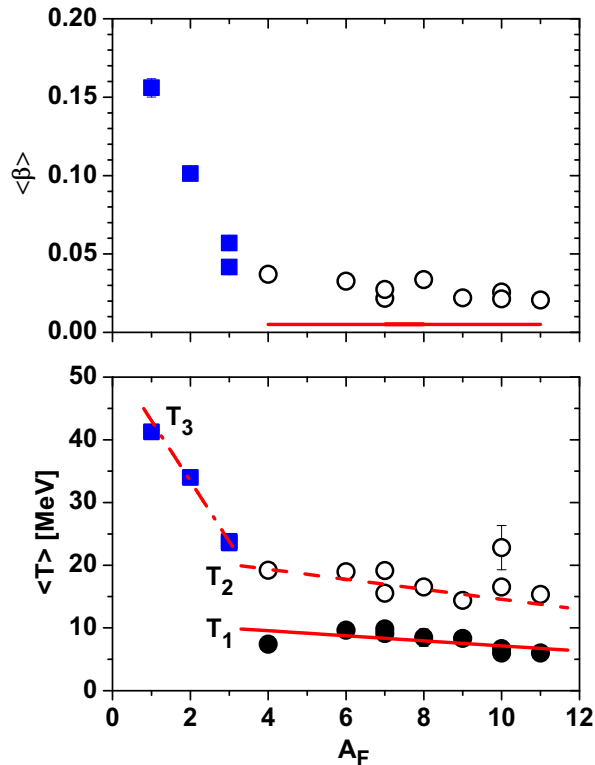


FIG. 7: In the lower panel of the figure the apparent temperature of the moving sources, averaged over beam energies is drawn as a function of the ejectile mass. Open circles and full dots represent values of temperature parameters  $T_2$  and  $T_1$  for fast and slow source, respectively. Full squares indicate temperature  $T_3$  of the fireball. The solid and dashed lines were fitted to the points representing the IMF's and  ${}^4\text{He}$ . Dash dotted line was fitted to points representing the LCP's. In the upper panel of the figure the dependence of the beam energy averaged velocity of the sources is drawn versus mass of ejectiles. The symbols and lines have the same meaning as for the lower part of the figure with one exception: The full dots are not shown because the velocity of slower source was fixed during analysis (at velocity  $\beta_1=0.005$  of heavy residuum of target nucleus after intranuclear cascade) and it is represented by solid line in the figure.

The velocities and temperature parameters are

grouped in three distinctly separated sets corresponding to the slow source ( $\beta_1$  and  $T_1$ ), to the fast source ( $\beta_2$  and  $T_2$ ), and to the fireball ( $\beta_3$  and  $T_3$ ). The mass dependence - approximated by straight lines - is also different for each source. The slope of the mass dependence is the smallest for the slow source, of intermediate value for the fast source, and the largest for the fireball. The linear dependence of the temperature parameter on the mass of ejectiles is expected as a result of momentum conservation, i.e., the recoil of the source of a given mass appears during the emission of ejectiles of various masses. This linear dependence of the temperature parameter on the mass of ejectile allows for the extraction of recoil corrected temperature of the source -  $\tau$  and the estimation of the mass of the source  $A_S$ . If the mass of the source is constant - the same for all ejectiles - the determination of its mass and recoil corrected temperature is unambiguous. However, there are arguments that the source must have some distribution of masses with different average value for each ejectile. For example, the deuterons cannot be emitted by fireball consisted of only two nucleons but such emission may occur from the fireball built of three nucleons. The emission of protons, on the contrary, can appear both from two-nucleon and three-nucleon source, thus the mass of the fireball emitting protons is in average smaller than the mass of fireball emitting the deuterons. This may be a reason of strong decreasing of the fireball velocity with the mass of the ejectile as well as only slight decreasing of the velocity of the fast source with the mass of IMFs. A change of the mass of the fireball by one nucleon is very significant, because the fireball may be built of only several nucleons, whereas such a change for the source consisted of 20 or more nucleons is hardly to be observed in the mass dependence of the temperature parameter.

The given above arguments show that the extraction of the mass of the source and its recoil corrected temperature from the ejectile mass dependence of the temperature parameter should be taken with caution and treated only as a crude estimation. Such an estimation is discussed below and extracted parameters are compared with those, which were found in our previous study [2] of reactions induced by protons on the gold target.

#### IV. DISCUSSION

The parameters of linear functions describing the dependence on the ejectile mass of the temperature parameter  $T$  and velocity  $\beta$  of three sources are collected in the Table III. Those parameters, obtained in the previous study of reactions induced by protons on the gold target [2], are also listed in this Table.

It is clearly visible that *all properties of the fireballs for both targets are identical in the limits of errors*. This seems to be unexpected, especially as concerns masses of both fireballs, because of large difference between the mass of Ni and Au targets. However, according to the



TABLE III: Beam energy averaged temperature and velocity parameters of three sources of ejectiles for Au and Ni targets.  $T$  denotes apparent source temperature (in MeV),  $\tau$  - the temperature parameter corrected for the recoil,  $A_S$  represents mass number of the source, and  $\beta$  its velocity in units of speed of light. The symbol  $A$  indicates the mass number of the ejectile. Parameters with index 1 correspond to slow source, with index 2 to fast source, and with index 3 to the fireball.

Parameter	Au	Ni
$T_1$	11.1(3)	11.2(7) - 0.4(2)*A
$\tau_1$	11.1(3)	11.2(7)
$A_{S_1}$	$\sim 165$	28(15)
$\beta_1$	[0.003]	[0.005]
$T_2$	30.6(4) - 1.61(45)*A	22.5(6) - 0.8(1)*A
$\tau_2$	30.6(4)	22.5(6)
$A_{S_2}$	19(6)	28(4)
$\beta_2$	0.059(5) - 0.0034(6)*A	0.044(6) - 0.0021(7)*A
$T_3$	49.9(7) - 8.2(2.6)*A	52.7(1.1) - 9.6(4)*A
$\tau_3$	49.9(7)	52.7(1.1)
$A_{S_3}$	6(2)	5.5(3)
$\beta_3$	0.218(39) - 0.051(16)*A	0.209(11) - 0.053(5)*A

simple picture of the fireball, it is consisted of the nucleons which lie on his straight way through the target nucleus, therefore the mass of the fireball should scale as  $A^{1/3}$ . It means that the ratio of fireball masses for Au and Ni should be equal to  $\sim 1.5$ . This ratio, extracted from the phenomenological analysis, is equal to 1.1(7) what means, that in the limits of errors it is in agreement with the assumed picture of the mechanism.

The equality of velocities of fireballs and their temperatures for both targets may be treated as consequence of the same momentum and energy transfer from the bombarding proton to the group of nucleons forming the fireball. Such an explanation is in line with the fact of the same beam energies for both targets and small difference in the thickness of the nuclear matter placed on the way of bombarding proton. Therefore, this equality may be interpreted as the argument in favor of assumed model of the reaction.

The recoil corrected temperatures of slow sources for Ni and Au targets are also the same. Of course, the mass  $A_{S_2}$  of the slow source is completely different in the case of Au target ( $\sim 165$ ) and Ni target ( $\sim 28$ ). Therefore the recoil correction of the temperature parameter could be neglected for the Au target but is visible in the ejectile mass dependence of the temperature parameter  $T_1$  for the Ni target. This difference of source masses reflects also on the velocity of the slow source  $\beta_1$ .

The largest differences appear for the fast source. It should be, however, pointed out that the parameters do not differ in average more than  $\sim 50\%$ . Taking into consideration the fact of limited accuracy of extraction of values of the parameters it may be claimed that the parameters of the fast source are similar for both targets.

The above considerations concern *velocity and temper-*

TABLE IV: Averaged over IMFs ratio of cross section  $\sigma_i$  for energy  $E$  to the same cross section measured at proton beam energy 2.5 GeV on Au and Ni targets. The  $\sigma_i$  is equal to  $\sigma_1$  (slow source),  $\sigma_2$  (fast source) or  $\sigma \equiv \sigma_1 + \sigma_2$  (total production cross section)

Ratio of $\sigma_i$ to $\sigma_i(2.5 \text{ GeV})$	at E/GeV	Au	Ni
$\sigma_1$	1.2	0.39(3)	0.63(8)
	1.9	0.75(6)	0.85(12)
$\sigma_2$	1.2	0.23(3)	0.63(9)
	1.9	0.57(6)	0.82(11)
$\sigma_1 + \sigma_2$	1.2	0.33(2)	0.57(6)
	1.9	0.66(4)	0.81(8)

*ature of three sources for Au and Ni targets and show, that this parameters, which are almost independent of the beam energy in the studied proton energy range 1.2 - 2.5 GeV, are very similar for both targets.*

In the following the behavior of production cross sections will be discussed. As it was shown on Fig. 4, cross sections for all IMFs increase in average by factor  $\sim 1.7$  when proton beam energy increases from 1.2 GeV to 2.5 GeV. This is true for the total production cross sections as well as for the contributions of individual emitting sources, however, the spread (among various IMFs) of the ratio of given cross section to that measured at 2.5 GeV is smaller for total production cross section than for individual sources. The ratios of the cross sections measured at 1.2 and 1.9 GeV to those measured at 2.5 GeV are listed in Table IV.

It is clear from examination of Table IV that the IMF production cross sections measured for Au target increase stronger with beam energy than those for Ni target. This can be understood as an effect caused by difference between threshold energies for fragmentation of both targets. To illustrate this effect the excitation function for  $^7\text{Be}$  production is shown on Fig. 8 as a typical example. It is seen that fragmentation starts at lower energies on Ni target than on Au target. Therefore the studied range of beam energy (1.2 - 2.5 GeV) corresponds for Ni target to the region where the production cross section starts to saturate, whereas for Au target this is region where the production cross section starts to rise quickly. Furthermore, the leveling of the production cross section for the Ni target appears at lower value than that for Au target. Both these effects cause that the total production cross sections should rise more quickly for the Au target than for Ni target, in accordance with present observations.

It is interesting to examine how large are the contributions of individual reaction mechanisms for emission of LCPs, i.e., the preequilibrium stage of the reaction described by intranuclear cascade and coalescence of nucleons into composite particles, the fireball emission, and the evaporation. As it is seen in Fig. 9 (right column) the contribution from intranuclear cascade and coalescence is for Ni target almost equal to that from evapo-

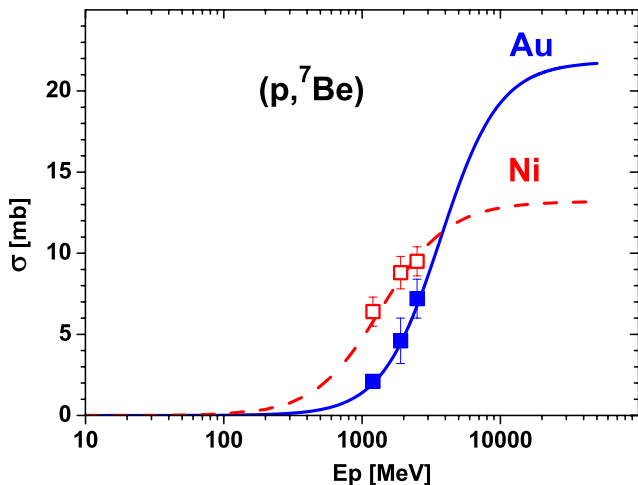


FIG. 8: Energy dependence of production cross section of  ${}^7\text{Be}$  ejectiles in proton induced reactions. The lines show results of compilation of  ${}^7\text{Be}$  production cross sections [4], the symbols represent experimental data of the present experiment (open squares) for Ni target and the data published by Budzanowski *et al.* [2] (full squares) for Au target. The solid and dashed lines depict the excitation functions from Ref. [4] for Au and Ni targets, respectively.

ration and exhausts about 30% of the total production cross section for all studied beam energies and ejectiles. The first of these contributions decreases several percent with the energy, whereas the evaporation contribution is almost independent of the energy. The contribution of the fireball is slightly larger ( $\sim 40\%$ ) and increases several percent in the studied energy range. These variations are more pronounced for tritons and  ${}^3\text{He}$  than for protons and deuterons.

This picture is quite different from energy behavior of separate reaction mechanisms of LCPs production for the Au target (cf. Fig. 9, left column), with exception of the evaporation contribution ( $\sigma_{GEM}$  on the figure) which is almost energy independent similarly as for Ni target. The coalescence contribution decreases with beam energy ( $\sim 10\%$  for p,d,t, and  $\sim 30\%$  for  ${}^3\text{He}$ ) but fireball contribution increases (also  $\sim 10\%$  for p,d,t, and even more for  ${}^3\text{He}$ ). Moreover, the coalescence contribution for Au target is in average larger, and the fireball contribution smaller than for Ni target. Such a behavior of relative contributions of various processes might suggest that they depend rather on the proton beam energy per nucleon of the target than on the beam energy itself, similarly as it is in the case of the total production cross section (cf. Figs. 8 and 9).

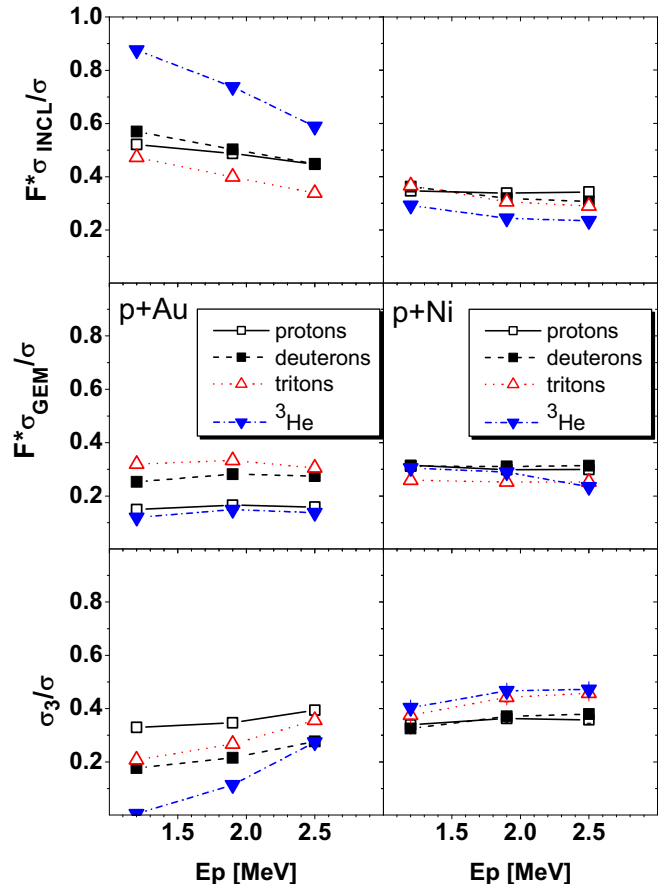


FIG. 9: Energy dependence of various reaction mechanisms for protons (open squares), deuterons (full squares), tritons (open triangles) and  ${}^3\text{He}$  (full triangles). The relative contribution of the fast stage of the reaction, i.e., intranuclear cascade and coalescence of nucleons into LCPs  $\sigma_{INCL}/\sigma$  is presented in the upper panel of the figure, evaporation contribution from the equilibrated residuum of the intranuclear cascade  $\sigma_{GEM}/\sigma$  is shown in the middle panel, whereas the contribution of fireball emission  $\sigma_3/\sigma$  is depicted in the lower panel.

## V. SUMMARY AND CONCLUSIONS

A new, extensive set of double differential cross sections  $d^2\sigma/d\Omega dE$  for the production of LCPs and light IMFs ( ${}^6\text{He}$ ,  ${}^6,7,8\text{Li}$ ,  ${}^7,9,10\text{Be}$ ,  ${}^{10,11}\text{B}$ , and C) in collision of protons with Ni target has been measured at three beam energies (1.2, 1.9, and 2.5 GeV). The data were analyzed using two-step microscopic model - intranuclear cascade with possibility to take into account coalescence of nucleons into LCPs, followed by evaporation of particles from the equilibrated residual nuclei. Since the model could not satisfactorily reproduce the spectra measured for seven scattering angles;  $16^\circ$ ,  $20^\circ$ ,  $35^\circ$ ,  $50^\circ$ ,  $65^\circ$ ,  $80^\circ$ , and  $100^\circ$ , the phenomenological analysis has been per-

formed assuming the emission of LCPs from the fireball, i.e., fast and hot source built of several nucleons moving in the forward direction, as well as emission of IMF from two slower and colder sources, which were interpreted as prefragments of the target appearing due to break-up of the target. An excellent description of all data has been achieved with smoothly varying values of the parameters from ejectile to ejectile. Due to such good reproduction of energy and angular dependencies of  $d^2\sigma/d\Omega dE$  by model calculation it was possible to determine total production cross sections for all studied ejectiles. They are listed in Table I and II for IMFs and LCPs, respectively.

It turned out that the competition of the emission from the fireball with the coalescence process and evaporation of particles from the equilibrated remnant of intranuclear cascade is crucial for a proper description of the data for LCPs. The emission of IMFs from a fast moving source was necessary to reproduce the high energy part of the experimental spectra. Moreover, the emission of IMFs from a slow moving source, which emits particles with spectra similar to those of evaporated IMFs from the equilibrated residua of intranuclear cascade, improved significantly the description of the low energy part of the spectra.

In summary, a large contribution of the nonequilibrium processes, which are not contained in the two-step microscopic model, has been established. Properties of these processes are compatible with hypothesis of emission of ejectiles from three moving sources: The light, fast, and hot source - a fireball, which appears as result of knock-out of group of nucleons lying on the straight way of the impinging proton through the nucleus, and two slower and colder sources, which are created due to break-up of

the target remnant after emission of the fireball.

All the discussed above effects are very similar to those observed by present authors for another nuclear system, namely p+Au in the same range of beam energies [1, 2]. As it was mentioned in the Introduction, the Ni target is significantly different from Au target. Thus the observation of analogous reaction mechanisms in both nuclear systems suggests that this mechanism appears generally. Properties of this mechanism are in many aspects the same for Ni and for Au targets but some clear differences are also present. Therefore further investigations should be performed for other nuclei and beam energies to achieve reasonable progress toward the understanding of the fragmentation phenomenon, and to allow for good description of the production cross sections of LCPs and IMFs.

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