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FIRESTREAK MODEL PREDICTIONS FOR STRANGE PARTICLE AND LIGHTEST HYPERFRAGMENT PRODUCTION IN HEAVY ION COLLISIONS

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In the last three years many experimental and theoretical papers have emerged devoted to the production process of strange particles in heavy ion collisions. On the one hand, this is due to desire for getting a deeper insight into the dynamics of interacting nuclei, that is especially promissing in the near threshold energy region, in which strange particles can be considered as a messenger of information on the earliest stage of interaction [1]. On the other hand, this is reasoned by the theoretical predictions about a considerable increase in the yield of strange particles from the quark-gluon plasma, i.e., strange particles may serve as a sign for a possible hadron-quark phase transition [2,3].

In the present paper the yield of strange particles, antinucleons and lightest hyperfragments in the relativistic heavy ion collisions is considered within the nuclear firestreak model taking account of the associated nature of the production process.

Within the nuclear firestreak model the inclusive spectrum of particles of the type i produced in the collision of two nuclei can be represented as follows [4,5,6]

$$\frac{d\sigma_i}{d^3p} = \int d\eta \frac{d\sigma}{d\eta} L_{\vec{p}^* \to \vec{p}} f_i(p^*, \eta), \qquad (1)$$

where the geometry factor of distribution over "streaks" $\frac{d\sigma}{d\eta}$ is unambiguously determined by the distribution of nuclear density of colliding nuclei. The decay of each streak η in the proper system is described by the one-particle partition function $f_i(p^*,\eta)$, factor $L_{\vec{p}^* \to \vec{p}}$ makes the Lorentz boost of particle spectrum into the laboratory system. Assuming the produced particles to be a mixture of relativistic ideal gases in the thermodynamic equilibrium, we have

$$f_i(p^*,\nu) = \frac{V Z_{int}}{(2\pi)^3} [\exp(\frac{\sqrt{p^{*2}+m_i^2} - \mu_i}{\tau}) \pm 1]^{-1}, \qquad (2)$$

where $\mu_i \equiv \mu_i(\eta)$ and $\tau \equiv \tau(\eta)$ are the chemical particle potential and "streak" temperature, and the factor $Z_{int} = (2S_i+1)e^{E_0/\tau}$

takes into account excitation of internal degrees of freedom of a particle with spin S_i and its binding energy E_0. The assumption about chemical equilibrium allows one to express the chemical potential of any particle through three unknown ones: $\mu_i = \mu_i(\mu_p, \mu_n, \mu_K)$. In addition, in formula (2) temperature and volume of the system are unknown. For these five unknowns we have four (baryon number, charge, strangeness and energy) conservation laws. The interaction volume per one nucleon V is a free parameter fixed by a given "critical" or "break up" density ν_c of the "streak". According to refs. /4,5/, we assume $\nu_c = \sum_i \nu_i = 0.12\ fm^{-3}$.

One should be careful applying formula (2) to strange particles, antinucleons and for other cases when particles are produced in pairs or in associative manner /6/. It is only in the limit of the large volume of system, when the number of possible pairs is large, one may restrict oneself by a statistical account of the strangeness conservation law through its influence on temperature $\tau(\eta)$ and chemical potential $\mu_i(\eta)$ and thus to calculate the strange particle abundance by the same formula (2) like for nonstrange hadrons.

In the energy range under consideration the temperature of the hadron gas is not very high and the number of produced strange particles is small, therefore the associated nature of the production process should be taken into account properly. In our version of the firestreak model /6/ this requirement implies that the probability to produce any partner of association is defined by the probability to create the whole association of particles. In particular, if a strange particle of the type s can be produced through the channel k in association with a strange particle $\bar{s}_k$, then instead of (2) we have

$$\tilde{f}_s(p,\eta) = f_s(p,\eta) \sum_k \delta(s+\bar{s}_K) \int d^3p' d^3r' K(\vec{r},\vec{r}')\ f_{\bar{s}_K}(p',\eta'), \qquad (3)$$

where the summation is performed over all the channels satisfying the conservation law of strangeness, and $K(\vec{r},\vec{r}')$ is the correlation function. A similar problem in the statistical theory of high-energy hadron-hadron collisions has been considered by Hagedorn and Ranft /7/, who argued the locality of the correlation function $K(\vec{r},\vec{r}') \Rightarrow \delta(\vec{r}-\vec{r}')$. The relevant scale in the firestreak model is the volume per one baryon, i.e., $K(\vec{r},\vec{r}') \Rightarrow \delta(\eta-\eta')/B(\eta)$, where $B(\eta)$ is a number of baryons in the "streak" η. The finiteness of the interaction volume requires an exact conservation of strangeness within this volume. Since each nuclear "streak" is produced independently, the strangeness is conserved locally, thereby the properties of nuclear firestreak turn out to resemble those of hadron collisions.

In this approximation for $K(\vec{r},\vec{r}')$ formula (3) is reduced to $\tilde{f}_s(p,\eta) = f_s(p,\eta)\, V \sum \delta(s+\bar{s}_k) \cdot \nu_{\bar{s}_k}(\eta)$ with $\nu_i(\eta) = \frac{1}{V} \int d^3p' f_i(p',\eta')$, i.e., due to the associated nature of the production process the yield of strange particles is suppressed by a factor of $V \sum_k \delta(s+\bar{s}_k) \nu_{\bar{s}_k}$ in comparison with formula (2).

Since the production probability of strange particles is small, this version of the firestreak model /6/ reproduces all the results of papers /4,5/ for nonstrange hadrons.

It has been shown in our paper /6/ that the associated nature of strange particle production enables a good description of the available experimental data on relative abundance of particles with $s \neq 0$ in the Dubna and Berkeley energy ranges. In this case, for the widely discussed inclusive spectra of K^+-mesons produced in the Ne + NaF (2.1 GeV/nucleon) reaction, the discrepancy in the absolute yield is about twice as large as the measured values, but not 30-40 times as in the statistical model /8/ neglecting the associated property of strange particle production.

Recently, new data have been reported on a relative yield of Λ^0- and K^0_s-particles in central interactions of nuclei at 3.66 GeV/nucleon. In our calculations the central interactions were determined by the impact parameter $b/b_{max} < 0.25$. It is seen from fig. 1 that the theoretical predictions for the A-dependence of yields are in agreement with experiment, if the expe-

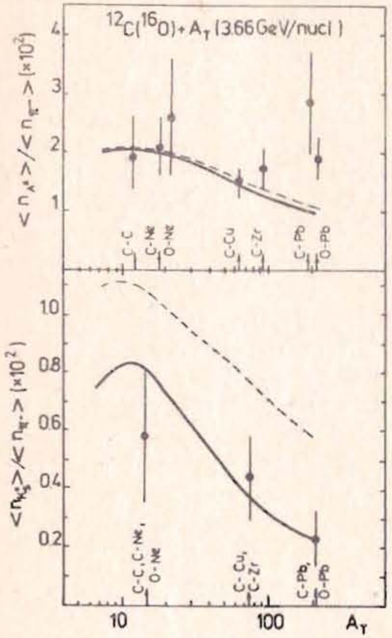

Fig. 1. Dependence of relative yields of K^0_s-mesons and Λ^0-hyperons on the target mass number in the central interaction initiated by carbon and oxygen ions with the projectile energy 3.66 GeV/nucleon. The experimental points are taken from paper /9/. The theoretical curves are given with (solid curve) and without (dashed curve) taking into account the experimental "window" for the observed momentum of particles which is $p_{K^0_s} > 0.61$ and $p_{\Lambda^0} > 0.46$ GeV/c, respectively.

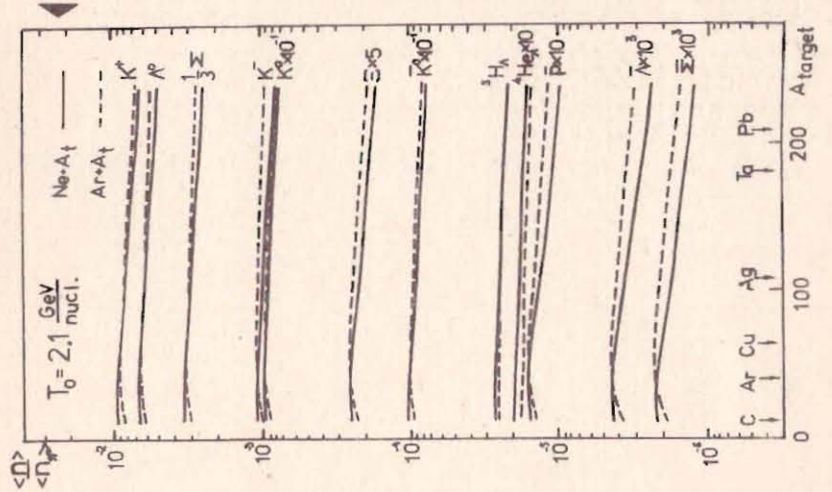

Fig.2. Firestreak model predictions for the A-dependence of relative yields of secondaries at 2.1 GeV/nucleon. Solid lines correspond to neon-induced, dashed lines - to argon - induced reactions.

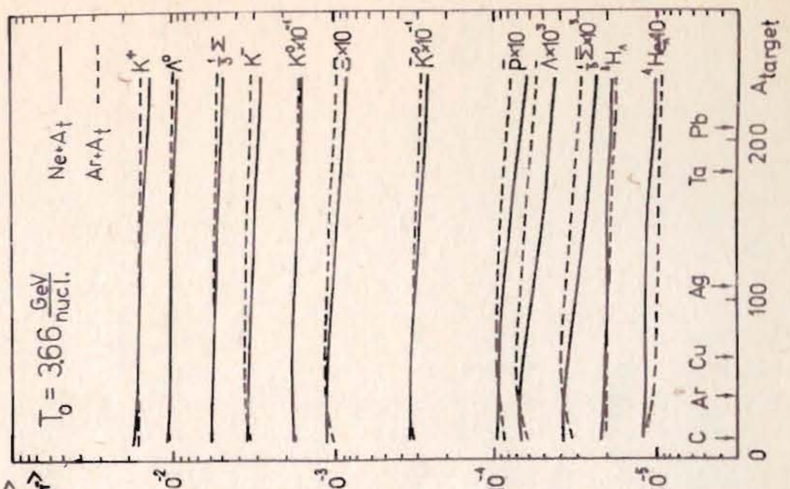

Fig.3. The same as in fig.2 but for the Dubna energy range, T_0 = 3.66 GeV/nucleon.

rimental limits on the magnitude of momentum of observed particles are taken into account.

The consideration of relative abundance of produced particles is highly useful for systematization and extrapolation of the data, since in this representation the dependence on the projectile-target combination almost disappears. Figures 2-3 show the A-dependence of particle abundance in the energy region of current intensive experimental investigations of strange particle production.

It is seen that even at the Dubna synchrophasotron energy the relative abundance of strange particles, antinucleons and lightest hyperfragments is thought to be independent of the mass numbers of colliding nuclei.

The comparison of relative yields of particles $R_i(T_0) = n_i/n_{\pi^-}$ at two projectile energies T_0 shows that for strange particles $R_s(3.66)/R_s(2.1) \approx 2$, whereas for hyperfragments $R_{HF}(3.6)/R_{HF}(2.1) = 0.5$. It does not mean that it is more "profitable" to observe hyperfragments at the Berkeley accelerator energy. An observation efficiency depends on the production cross section of a given particle σ_i, so the ratio $R_i(T_0)$ should be multiplied by $k_i = \sigma_{in} n_{\pi^-}$ and, consequently, an efficiency to observe strange particles will depend essentially on the combination of colliding nuclei. For the most popular Berkeley reaction Ar + Ar(1.8 GeV/nucleon), the mean multiplicity of negative pions $n_{\pi^-} = 2.3$ and the reaction cross section σ =925 mb,that provides $k^{Ar+Ar} = 2.1\cdot10^3$ mb. For the reactions initiated by a beam of carbon nuclei at the Dubna synchrophasotron we have $k^{C+C} = 0.9\cdot10^3$ and $k^{C+Ta} = 1.1\cdot10^4$ mb for the carbon and tantalum target, respectively. Thus, for the C+Ta(3.66 GeV/nucleon) reaction the strange particle cross section is ten times and of hyperfragments 2.5 times as large as in the Ar+Ar (1.8 GeV/nucleon) reaction. For the C+C (3.66 GeV/nucleon) collision the production cross section of strange particles becomes equal and the yield of hyperfragments is twice lower than the cross sections for the above-mentioned reaction at the Berkeley energy.

Table

Yield of super-hyperfragments relative to π^--mesons in two reactions at T_0 = 3.66 GeV/nucleon

reaction / fragment	$^{12}C + ^{12}C$	$^{12}C + ^{181}Ta$
$^{4}_{\Lambda\Lambda}He$	$7.6\cdot10^{-9}$	$6.0\cdot10^{-9}$
$^{6}_{\Lambda\Lambda}He$	$1.5\cdot10^{-11}$	$1.5\cdot10^{-9}$
$^{10}_{\Lambda\Lambda}B$	$1.8\cdot10^{-16}$	$1.4\cdot10^{-16}$

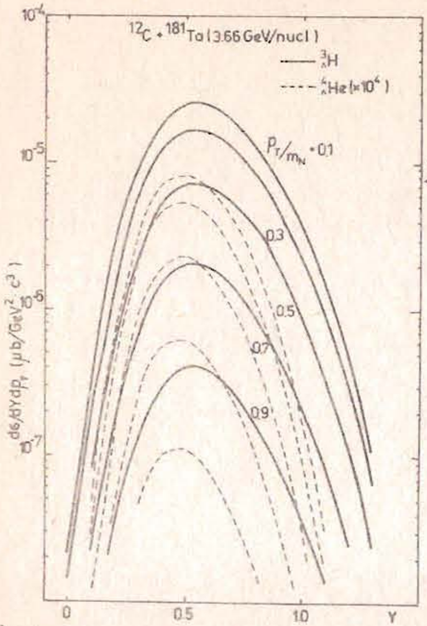

Fig. 4. Invariant inclusive distributions for hyperfragments $^{3}_{\Lambda}H$ (solid curve) and $^{4}_{\Lambda}He$ (dashed curve) produced in the $^{12}C + ^{181}Ta$ (3.66 GeV/nucleon) reaction.

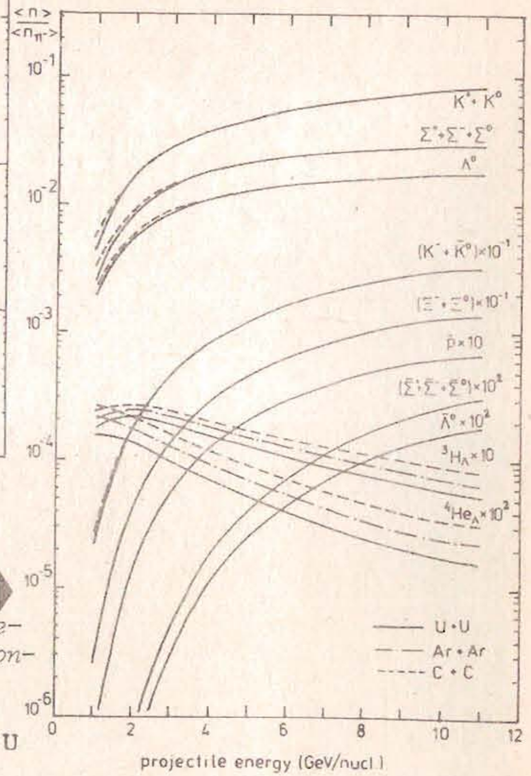

Fig. 5. Firestreak model predictions for the energy dependence of the yield of secondaries in the collision of C+C *(dashed curve),* Ar+Ar *(dashed-point curve), and* U+U *(solid curve).*

The model allows one to evaluate the production probability of superphyperfragments, i.e., hyperfragments with strangeness $|S| = 2$. These predictions are represented in the Table for the carbon beam available at Dubna. Using the data given in the Table for the C+Ta (3.66 GeV/nucleon) reaction, we get for instance, for the production cross section of a superhyperfragment of helium-4 $\sigma_{^{4}_{\Lambda\Lambda}He} = k^{C+Ta} \cdot R_{^{4}_{\Lambda\Lambda}He}(3.6) \simeq 0.07\,\mu b$.

It should be noted that the statistical mechanism considered leads to the production of hyperfragments in the middle rapidity region (see fig.4). In the general case this mechanism is not unique. Hyperfragments can possibly be produced due

to the hypercharge-exchange collision of nucleons of a projectile or a target-nucleus. However, in this case the kinematics of the reaction is different: the yield of hyperfragments will have maximum near the rapidity of the projectile or target, respectively.

Figure 5 represents the energy dependence of particle abundance. With increasing energy of a projectile the curves tend to saturation because of existence of the limiting temperature in the Pomeranchuk version of the statistical model used to describe a nuclear "streak" decay.

So, an essential point of the generalization of the firestreak model to the production of strange particles, antiparticles, hyperfragments and super-hyperfragments is the consideration of the associated nature of the production process and the requirement of a local fulfillment of the conservation law of strangeness. The degree of a local conservation of strangeness is of the fundamental nature. For the heavy-ion collisions it can be estimated experimentally from the effective mass distribution of K^+K^-- or $\Lambda\Lambda$-pairs as for the case of hadron-hadron collisions /7/.

The local fulfillment of the conservation law of strangeness implies that the hypothesis on chemical equilibrium of strange particles with nonstrange hadrons should also be of the local nature. This assumption is much weaker than the assumption about the chemical equilibrium in the whole interaction volume /8/.

The firestreak model provides a self-consistent and rather satisfactory description of the available experimental data on a relative abundance of particles. The afore-made predictions can be used for the experimental verification and further development of the model and for the identification of signals of a possible transition of hadrons to the state of quark-gluon plasma by searching for essential deviations from these predictions.

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Предсказания модели файрстрика для рождения странных частиц и легчайших гиперядер в столкновении тяжелых ионов

В рамках модели ядерного файрстрика с учетом ассоциативного характера процесса образования странных частиц даны предсказания относительных выходов каонов, гиперонов, антинуклонов и легчайших гиперфрагментов для различных комбинаций сталкивающихся ядер вплоть до энергии 10 ГэВ/нуклон. Эти результаты могут быть использованы для идентификации сигналов возможного фазового перехода адронов в состояние кварк-глюонной плазмы.

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Firestreak Model Predictions for Strange Particle and Lightest Hyperfragment Production in Heavy Ion Collisions

The predictions are made for relative abundance of kaons, hyperons, antinucleons, and lightest hyperfragments for various combinations of colliding nuclei up to 10 GeV/nucleon within the firestreak model taking account of the associated nature of the strange particle production. These results may be used to identify the signs of a possible phase transition of hadrons into the quark-gluon plasma.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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