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STUDY OF STRANGENESS PRODUCTION IN RELATIVISTIC NUCLEUS BEAMS AT JINR

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Strangeness produced in nucleus-nucleus (A_pA_T) collisions is argued to be a useful tool to study highly excited hadron matter.

It is predicted as an effective probe for quark-gluon plasma (QGP) formation in the stopping («baryon-rich») regime*) which could be realized at rather low energies of projectile nuclei ($E_p \simeq 2 \div 10$ A GeV) [1—4].

The production of Λ-hyperons and K^0_S-mesons has been investigated at JINR using the two-meter long streamer spectrometer and propane bubble chamber with various targets inside feducial volumes ($A_T \equiv {}^6$Li, ^{12}C, ^{20}Ne, Cu, Zr, Ta, Pb) exposed to nuclear beams ($A_p \equiv d$, ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg) of the Dubna Synchrophasotron at energies of $3.4 \div 3.7$ A GeV [6—12].

One might consider it to be the Nature's favour that the degree of thermalization (randomization) of hadron matter in AA-collisions could be easely estimated looking at the Λ-hyperon peculiarities in their angular distributions which are known to be forward-backward peaked in the initial reaction $NN \to \Lambda NK$ due to the leading effect of baryonic diquark.

As can be seen from Fig.1 the «centrally» produced $\Lambda(K^0_S)$ particles are emitted near isotropically in contrast to the forward (backward) peaked emission from noncentral CC-collisions which reproduce the particular feature of initial NN-interactions.

Very similar regularities have been observed in angular distributions of $\Lambda(K^0_S)$ particle energies also in the CM-system ($dE^*_{\Lambda,K}/d\text{Cos}\,\Theta^*$).

These effects, obtained first from our early Λ data and confirmed later by our K^0_S ones, suggest a full stopping with formation of a single thermalized source (fireball) in midrapidities of extremely central AA-collisions.

The study of Λ-hyperon polarization appears to be another profitable tool for examination of excited hadron matter. The polarization $\wp_\Lambda$ which is likely also due to the leading diquark effect, has been found to be rather large in pA-

*)This is not likely the case in baryon-free regime [5] predicted to be realized at much higher energies

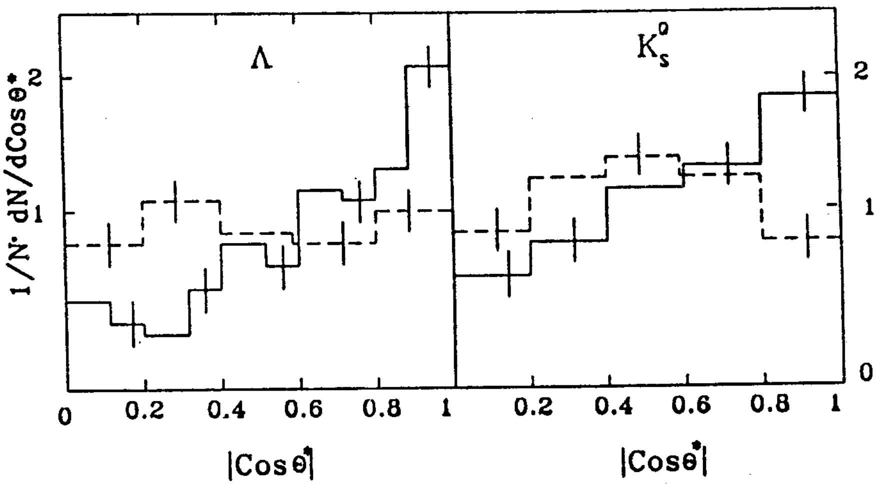

Fig. 1. Folded (in Cos Θ*) angular distributions of Λ-hyperons and K_S^0-mesons produced: in non-central *CC*-collisions — solid lines, and in central ones — dashed lines

interactions for a high P_T-region. This parameter $\wp_\Lambda$ is expected to vanish for Λ's from central *AA*-collisions with a formation of a thermalized fireball.

We have seen some increase of $|\wp_\Lambda|$ when increasing P_T of Λ's from non-central *AA*-collisions. As for centrally produced Λ's there is no polarization observed, within rather large errors though: $\Delta(\alpha\,\wp_\Lambda) \simeq 0.2$. Statistically richer data are needed for more significant results. Anyhow the obtained data support the above suggestion derived from the analysis of angular distributions.

The dependence of hadron matter excitation upon a collision centrality has been studied by estimating parameters $\langle P_T \rangle_{\Lambda,K}$ and temperatures T_B extracted from Boltzmann-like spectra (or an inverse slope of invariant cross sections spectra T_0, treated often wrongfully as temperature). Our early analysis has revealed a considerable rise of T_B with degree of centrality: from $T_\Lambda = (75 \pm 8)$ MeV up to $T_\Lambda = (158 \pm 11)$ MeV which corresponds to $T_0 \simeq 200$ MeV. The same increase from $T_K = (73 \pm 11)$ MeV up to $T_K = (162 \pm 8)$ MeV has been observed when K_S^0 mesons have been used as «thermometer» [13]. This signifies a collective effect of the heating of hadronic matter (the created fireball) up to temperatures being near critical ones predicted for a phase transition into QGP.

Such a fireball appeared to be not only very hot but also rather dense.

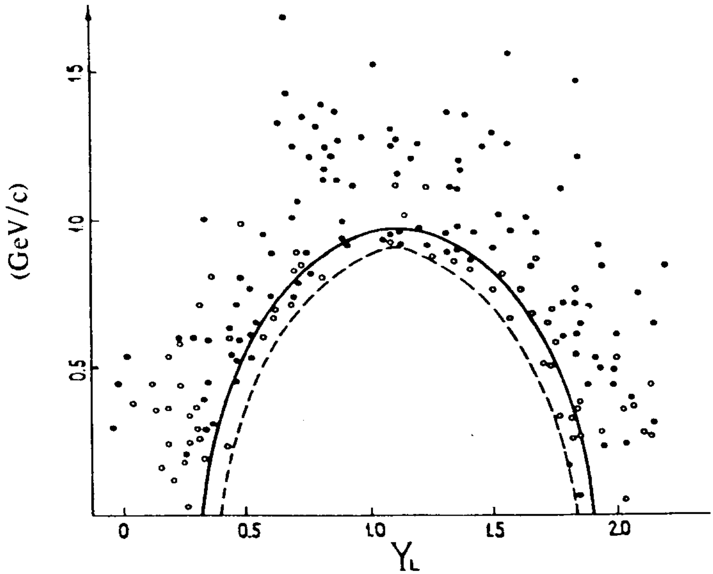

Fig.2. $P_T - Y_L$ plot for commulative Λ hyperons produced: in non central HeLi, CC-collisions selected from 264 Λ's (∘ ∘ ∘) and in central CNe, ONe, CCu, CZr collisions from 269 Λ's (• • •) at energies 3.4 A GeV and 3.7 A GeV outside kinimatical limits for NN interactions, outlined by the dashed and solid lines respectively

We have observed in central AA-collisions a considerable portion of Λ's with anomalously large P_T, emitted (rescattered) from midrapidities: above 12% compared with ~ 1% in noncentral collisions (see Fig.2).

Taking into account this effect some model dependent estimation could be obtained which gives for the baryonic density $\rho = (4 \pm 1)\rho_0$.

The search for a possible strangeness enhancement has been performed looking at the measured relative yields $(\langle n_\Lambda \rangle / \langle \pi^- \rangle)$ of Λ_k-hyperons with $P_T > 1$ GeV/c being beyond kinematical limits of reaction $NN \to \Lambda NK$ at 3.7 A GeV. This cut, used to eliminate the background of Λ's from NN-interactions, has been supported by theoretical considerations which have argued in favour of the study of strange particles with anomalously high $P_T(E_T)$ in order to search for QGP [14]. We have found that for such a set of Λ's, which is free of background Λ's from NN-interactions, the ratio $\langle n_\Lambda \rangle / \langle \pi^- \rangle$ increases by a factor of 9 ± 2 when going from peripherical AA-collisions to central ones.

Most of effects found in Dubna experiments are summarized in the Table and Fig.3 which illustrate dependences of main characteristics of produced Λ-hyperons upon the degree of nuclear collision centrality (upon the number of projectile nucleons-participants $\langle Q \rangle$).

To examine a further dependence of hadron matter excitation upon the total released energy, a study has been performed with an analysis P_T spectrum of Λ's from very central MgMg collisions [15] which involve a twofold number of nucleons (with twice as great released energy) than central *CC* collisions. The value of $T_B = 137 \pm 9$ MeV has been found from the mentioned analysis which does not differ within errors from $T_B = 158 \pm 11$ MeV obtained for central *CC* collisions.

Table

Effects observed with increasing of degree of collision centrality	Predicted as signals of ...
— flattening of angular distributions $dN_{\Lambda,K}/d\mathrm{Cos}\,\Theta^*$ and $dE^*_{\Lambda,K}/d\mathrm{Cos}\,\Theta^*$ from strongly forward-backward peaked to nearly isotropic ones; — Boltzmann-like Λ and K^0_S spectra; — decrease of Λ polarization to $\alpha \wp_\Lambda \simeq 0 \pm 0.2^{*)}$	stopping, randomization, thermalization (at least local)
— anomalous increase of transverse momenta $P_T(\Lambda)$ in midrapidities	increase of baryonic density to $\rho = (4 \pm 1)\rho_0$
— increase of relative yield of Λ's: $\langle n_\Lambda \rangle / \langle n_{\pi^-} \rangle^{*)}$ (beyond a background from *NN* interactions) by a factor of 9 ± 2	QGP formation (?)
— raise of Boltzmann temperatures of Λ's and K^0's from $T_B \simeq 75$ MeV up to ~ 160 MeV (to $T_0 \simeq 200$ MeV) with a cessation of further raise of T_B, approaching a plateau$^{*)}$	heating followed by possible first order phase transition and QGP + hadr. gas mixed phase formation (?)

*) Supported by recent BNL and CERN data [16,17]

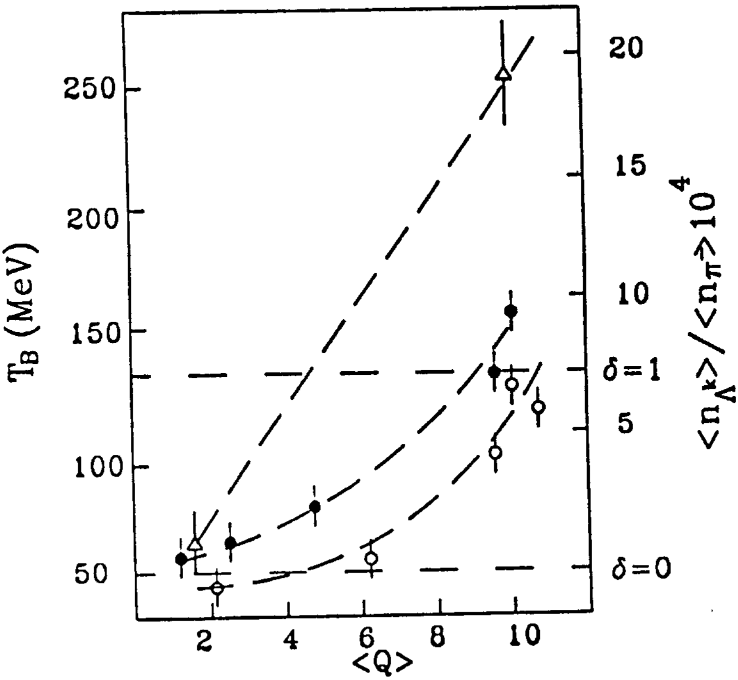

Fig.3. Dependences upon collision centrality (i.e., upon $\langle Q \rangle$ — average number of projectile nucleons-participants) of the following parameters: — the degree of flattening δ which $\delta = 0$ for the peaked distribution from $pp \to \Lambda K^{+} p$ and $\delta = 1$ for the isotropic distribution (open circles); — the Boltzman temperature T_B (black circles); —the relative yield $\langle n_{\Lambda_k} \rangle / \langle n_{\pi^-} \rangle$ of Λ hyperons with $P_T > 1$ GeV/c (triangles)

This gives an indication that the temperature stops to raise and seems to go to a plateau.

The recent data of the experiments at AGS BNL [16] and SPS CERN [17] have suggested the evidence for such a plateau extending to much higher energies as can be seen from Fig.4.

Moreover in these experiments strangeness enhancement has been also observed in central *AA*-collisions, and not only for a relative yield of Λ_k's but for those of $K^{\pm}$ and $\overline{\Lambda}$ (with different cuts $P_T > 0.4 \div 0.5$ GeV/c).

This chain of the revealed effects, mentioned above, is predicted as signals of a stopping, thermalization and heating of hadronic matter with a formation of a dense and strangeness abundant fireball (mixed phase) via first order transition. Possibilities of such a transition under conditions (stopping, density, temperature, energy) similar to our ones have been considered in many theoretical

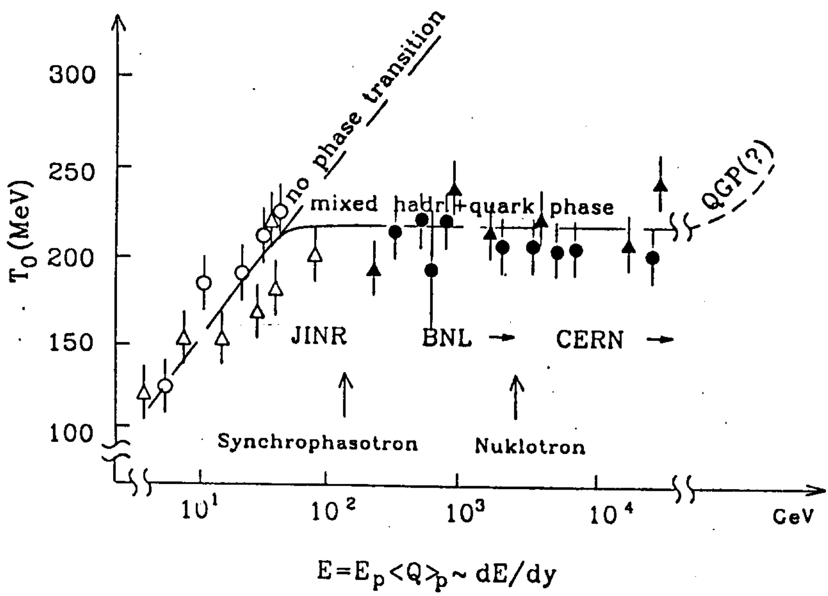

Fig.4. Inverse slope parameters T_0 versus $E = E_P \langle Q \rangle$: open circles and open triangles — K^0_S and Λ data of JINR; black circles and black triangles — neutral (charged) kaons and Λ data of BNL [16] and CERN [17] (to make an adequate comparision, the T_0 parameters, but not the Boltzmann temperatures T_B, are shown on this figure, because T_B values are not given in CERN papers)

papers. Nevertheless, even being confirmed by data of other groups, these results need more detailed comparative analyses and looking for possible alternative interpretations (beside QGP) to make final conclusions.

Anyway our data and other similar ones could be treated as a strong evidence for a creation of a hot and dense fireball (possibly mixed phase) in violent *AA*-collisions. This provides favourable conditions to search for Metastable Exotic Multihypernuclear Objects (MEMO's) [18] and Strange Quark Matter (SQM) states which are predicted to be considerably enhanced in such a fireball due to the expected strangeness enrichment [19]. Such an investigation, being of great importance itself, might give a proof of the QGP (mixed phase) formation [20].

At the first stage of this investigation we plan to look for *H*-dihyperon (the ground SQM state) and few baryon MEMO's by re-analyzing anomalous events which have been detected in an open (4π) geometry from central *AA*-collisions in streamer chambers and recorded in DST but failed to be fitted as decays of «usual» strange particles.

The requirement of a coexistence with 3 double hypernuclei, observed by now, provides the most probable properties of H-particle [21]: $M_H = 2.22$ GeV and $\tau \sim 1 \div 10$ ns with the main decay mode $H \to \Sigma^- p$ [22] followed by $\Sigma^- \to n\pi^-$.

Some computer programs have been elaborated for analysis of data:

— the program of the kinematical reconstruction of H decays to determine masses and to identify H particles by fitting;

— the code for the simulations of H production from a hot midrapidity fireball with a subsequent H decay in fedueial volumes of chambers to obtain detection efficiencies and H yeilds (their upper limits), which depend on the parameters T_B, τ, A_P/A_T and E_P.

The preliminary estimations show that the search for H-particles and MEMO's could be performed at sensitivity levels being near (above) predicted yields.

Additional scannings of the available data will be likely required to look for MEMO's (after theoretical consideration of their main decay modes).

Our further plans in this research field are connected with a development of the new approach which has beeen proposed [23,24] and successfully realized [25] at JINR.

The previous («usual») methods in hypernuclear physics have to do with hypernuclei which are produced as fragments of a target nuclei being at rest. Therefore they have low energies and short ranges which makes impossible to observe directly decays of hypernuclei with $A > 14$ even in emulsions. The new approach offers relativistic hypernuclei produced in nuclear beams as fragments of projectile nuclei. Such hypernuclei have decay ranges large enough ($20 \div 30$ cm at Dubna energies) to use rather thick targets and to put various detectors in their path, including detected signals in a trigger.

Velocities of these hypernuclei are very close to those of projectile nuclei which makes possible to measure lifetimes by decay ranges and simplifies fairly their identification and analyses of their decays. All this creates very favourable conditions to hypernuclear studies.

Similar conditions could be obtained for a detection more complicated metastable strange objects formed in midrapidity fireball especially when $A_P > A_T$.

The streamer spectrometer used previously in such a study, is able to be triggered once per pulse and to detect only mesonic two body decays of the lightest hypernuclei because of the impossibility to discriminate background triggers from interactions of projectile nuclei in the gas filling the chamber when many-body mesonic and non-mesonic hypernucleus decays occur. To remove these drawbacks the triggering system has been constructed with a vacuum cavity (V) as decay volume and trigger detectors inside it. This system is designed

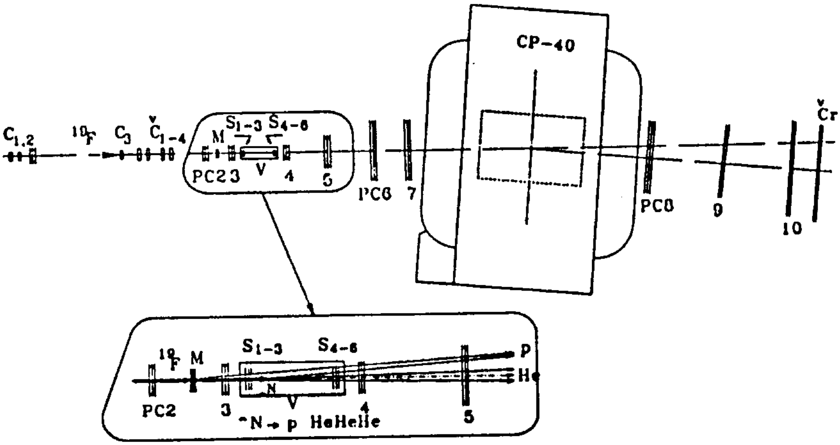

Fig.5. A lay-out of the designed experiment

to be incorporated in the wide apperture spectrometer (with fast coordinate and charge detectors), which has been used to study a fragmentation of relativistic nuclei from Synchrophasotron with hundreds triggers per pulse.

Figure 5 exhibits a lay-out of the designed experiment (with a production of $^{14}_{\Lambda}N$ in the target M by ^{19}F projectile and subsequent decay in V as an example). Two multiwire proportional chambers of three planes ($PC_{1,2}$), Cherenkov ($\check{C}_{1-4}$) and scintillation counters ($C_{1,2}$) will be used to measure the charge (Z) of A_p and coordinates of its track, eight MWPC's (PC_{3-10}) — to obtain the A/Z ratio for fragments-products of interaction/decay (by their rigidities in magnet CP-40), the set of 30 Cherenkov detectors ($\check{C}r$) — to determine Z of fragments.

Three levels of triggering will be used with the following logic: a decrease of the charge, increase of multiplicity detected by two sets of Si-microstrip dE/dx detectors S_{1-3} and S_{4-6} (as a results of a hypernuclear decay in vacuum volume V) and reconstruction of a vertex within V using fast processors.

Such a system will eliminate a background from any possible imitating processes. A final identification will be done by off-line analyses to reject any accident events.

It has been estimated that this approach will increase data taking rate by a factor of $10^2 \div 10^3$ and make possible to detect heavier hypernuclei and double ones which are predicted [26] to be formed at E_p = 5 A GeV (Nuclotron) about 10 times more frequent than at E_p = 14.5 A GeV (AGS) due to a good overlap between momentum distributions of Λ's and nuclear fragments.

The triggering system for a detection of relatively light metastable SQM states and MEMO's is designed to be somewhat different taking into account peculiarities of their decays (e.g., two section decay volume will be created). This system (with appropriate trigger detectors and electronics) will be constructed as rather detached one to make possible using it not only with JINR spectrometers at Nuclotron but also with other proper ones in nuclear beams at AGS (BNL), SPS (CERN) and possibly at KEK.

It should be emphasized that the considered approach aims to detect metastable strange objects in (nearly) open geometry and to identify them revealing strangeness by particular decays, whereas few other experiments, proposed thus far [27] (except P-864 to AGS) intend to search for SQM by unusual A/Z ratio which is not necessary a peculiar feature of SQM but also of other possible anomalous forms of matter.

In any case the experiments mentioned in [19] are unable to distinguish between MEMO's and SQM states and cannot detect objects with $\tau < 10$ ns.

The above considered results were obtained in 1982—1989 in nuclear beams of JINR Synchrophasotron which is able by now to accelerate nuclei up to ^{32}S to an energy $E_p \simeq 4$ A GeV, but the most part of the proposed research plans will be performed at the JINR Nuclotron.

The Nuclotron, a strong focusing synchrotron with a superconducting magnetic system, was successfully tested in 1993 and will gain in the near future following main designed parameters:

maximum energy: for protons — 12 GeV, for nuclei — 6 A GeV;
duration of beam pulse from slow extraction — up to 10 s.;
duty cycle — up to 75%;
momentum spread — $\Delta p/p = 10^{-3}$;
effectivity of slow extraction — 96%;
intensities (per pulse): $p \sim 10^{11}$, $^{24}Mg \sim 10^8$, $^{84}Kr \sim 10^7$, $^{238}U \sim 10^5$.

Hereafter main setups are listed which are appropriate or directly designed to detect strange particle/objects expected to be formed in nuclear beams of the Nuclotron (including fragments with an unusual A/Z ratio as potential candidates to SQM states):

- SPHERE — a multipurpose 4π detector with forward magnetic spectrometer, MWPC's, MWDC's, Pb glass calorimeter, dE/dx and TOF scintillation hodoscopes, Cherenkov counters;
- GIBS — a hybrid spectrometer with 2m long streamer chamber, dE/dx scintillation counter, MWPC's;
- ANOMALON — a multipurpose spectrometer, MWPC's, Cherenkov hodoscope, scintillation counters, TOF;

- PAMIR — a magnetic spectrometer with Cherenkov dE/dx detectors as an active target, Si strips as a vertex detector, MWPC's, Pb glass hodoscope (calorimeter), TOF, liquid argon calorimeter;
- INESS ALPHA — a magnetic two-arm spectrometer with MWPC's, scintillation telescopes, TOF, threshold Cherenkov counters;
- SYAO — a nuclear recoil spectrometer with telescopes of dE/dx Si-detectors, arrays of plastic scintillators and NaI (Tl) crystals;
- DISC — a magnetic two-arm spectrometer with $\Delta E-E$ detectors, TOF, threshold Cherenkov counter;
- KASPIY — a magnetic spectrometer with MWPC's and MWDC's, $\Delta E-E$ detectors, scintillation telescopes, TOF, Cherenkov plexiglass and lead glass counters.

All these setups being used in experiments at Synchrophasotron, provide promissing possibilities for widespread studies of hot and dense matter with strangeness as an effective probe in nuclear beams of the Nuclotron*).

I am very grateful to all my colleagues participated in the mentioned Dubna experiments giving results, analyzed in this work which was supported by the Russian Foundation for Fundamental Investigations (RFFI), grant No.93-02-15583

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*)Research programs for these and other setups are outlined in [28]

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Оконов Э.О. E1-93-443

Исследование образования странности в пучках релятивистских ядер в ОИЯИ

Проведен анализ экспериментальных данных по образованию странности в ядро-ядерных взаимодействиях при 3,4 ÷ 3,7 А ГэВ в их сравнении с более поздними результатами, полученными в БНЛ и ЦЕРН при бóльших энергиях. Основное внимание уделено примечательным изменениям свойств рожденных Λ- и K^0-частиц при увеличении степени центральности столкновений: уплощение их угловых распределений вплоть до изотропных; увеличение относительного выхода Λ с $P_T \geq 1$ ГэВ/с (т.е. вне пределов фона от NN-взаимодействий) ~в 10 раз; появление значительной доли Λ (около 10%) с аномально большими P_T; повышение больтцмановской температуры $T_{\Lambda,K}$ от ~ 75 МэВ с выходом на плато при $T_{\Lambda,K}$ ~ 160 МэВ, которая соответствует параметру обратного наклона $T_0 \simeq 200$ МэВ и близка к критической для фазового перехода в кварк-глюонную плазму (КГП). Обнаруженные эффекты, подтвержденные экспериментами в БНЛ и ЦЕРН, ожидаются как сигналы процессов торможения, термализации и нагревания адронного вещества с образованием сильно разогретого и уплотненного файербола (смешанной фазы) путем фазового перехода первого рода.

Окончательное заключение потребует более детальных исследований и поисков альтернативных интерпретаций (помимо КГП). Тем не менее рассмотренные результаты являются сильным указанием на формирование высоковозбужденного файербола, который является, согласно предсказаниям, интенсивным источником образующихся странных объектов. Для поиска легких состояний странного кваркового и гиперядерного вещества на имеющемся экспериментальном материале, полученном с помощью стримерных спектрометров, были разработаны программы с целью анализа аномальных событий, зарегистрированных в центральных столкновениях ядер. Для регистрации более тяжелых странных объектов в ядерных пучках Нуклотрона и для увеличения скорости набора статистики в $10^2 \div 10^3$ раз подготавливается эксперимент, в котором развивается эффективный метод (предложенный и успешно реализованный в ОИЯИ) с использованием сконструированной триггерной системы и одного из имеющихся спектрометров с быстрыми координатными и зарядовыми детекторами.

Работа выполнена в Лаборатории высоких энергия ОИЯИ при поддержке РФФИ (грант 93-02-15583)

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Okonov E.O. E1-93-443

Study of Strangeness Production in Relativistic Nucleus Beams at JINR

The experimental data on strangeness production in nucleus-nucleus collisions at 3.4 ÷ 3.7 A GeV are analyzed and compared with more recent results of BNL and CERN at higher energies. The main attention is given to remarkable changes in properties of produced Λ- and K-particles when a degree of the collision centrality increases: the flattening of their angular distributions up to nearly isotropic ones; the enhancement of the relative yields of Λ's with $P_T \geq 1$ GeV/c (i.e. beyond a background from NN-interactions) by a factor of about 10; the occurrence of a considerable portion of Λ's (~10%) with anomalously high P_T; the increase of Boltzmann temperatures $T_{\Lambda,K}$ from 75 MeV with approaching a plateau at $T_{\Lambda,K}$ ~ 160 MeV, which corresponds to the inverse slope parameter $T_0 \simeq 200$ MeV and is near to the predicted critical temperature for the phase transition into quark-gluon plasma (QGP). The found effects confirmed by the data of BNL and CERN experiments, are expected as signals of a stopping, thermalization and heating of hadron matter with a formation of a hot and dense fireball/mixed phase via first order phase transition. Although more detailed studies and searches for alternative interpretations (beside QGP) are necessary to make a final conclusion, the considered results provide a strong evidence for a creation of a high excited fireball which is predicted to be a prolific source of strange objects formed. Programs of analyses are elaborated to examine anomalous events from central nucleus-nucleus collisions detected in streamer spectrometers, in order to look for light states of strange quark/hypernuclear matter. To detect heavier strange objects in Nuclotron nuclear beams and to increase data taking rate by a factor of $10^2 \div 10^3$, an experiment is designed, in which the effective approach, proposed and successfully realized at JINR, is planed to be developed using the constructed trigger device and an existing spectrometer with fast charge and coordinate detectors.

The investigation has been performed at the Laboratory of High Energies, JINR, and supported by the RFFI (under grant 93-02-15583).

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