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HIGHLY EXCITED MATTER PROBED WITH STRANGENESS IN NUCLEUS-NUCLEUS COLLISIONS AT JINR

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The strangeness enhancement is considered to be an important signature of quark-gluon plasma (QGP) formation in the stopping (baryon-rich) regime of nuclear collisions [1] which could be realized at so low energies as 2-10 A GeV [1-4]. Our experiments demonstrate that some other peculiarities of strange particle behaviours can be also successfully used as an efficient tool to probe conditions which are needed for phase transitions.

The production of Λ hyperons and K^0_S mesons has been investigated at JINR in an open (4π) geometry using the two-meter long streamer spectrometer and propane bubble chamber with various targets inside feducial volumes (A_T=^{6}Li, ^{12}C, ^{20}Ne, Mg, Cu, Zr, Ta, Pb) exposed to nuclear beams (A_P = d, ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg) of the Dubna Synchrophasotron at energies of 3.3-3.7 A GeV[6-8].

In this brief analysis, more attention is focused on those effects found which provide valuable data on a highly excited matter.

One might consider it to be a 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$\rightarrow$ ΛNK due to the leading effect of baryonic diquark. Kaons from this reaction exhibit an analogous peculiarity but less pronounced one which becomes insignificant at much higher nucleon energies.

We have found from examinations of particle production data in AA-collisions that strongly peaked $dN_{\Lambda,K}/dCos\Theta^*$ distributions which reproduce the particular feature of initial NN-interactions, become more and more flat with increasing the degree of the collision centrality and change finally into near isotropic ones for the "centrally" produced $\Lambda(K^0_S)$ particles.

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

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

We have seen some increase of $|\wp_\Lambda|$ when increasing P_T of Λ's from noncentral 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.

Strange particles,produced directly in the studied energy region,serve as a perfect "thermometer"in contrast to protons and pions which are mainly originated from resonances and therefore have "distorted" spectra, rather insensitive to actual temperatures of the hadronic matter (especially in the case of π's). Besides, kaons (but not anti kaons, copiously produced at higher energies) are fairly penetrating probe with intranuclear mean free paths about 5 times longer than those of π's and can provide valuable information on behaviours of a dense fireball at its early stage.

The dependence of hadron matter excitation upon a collision centrality has been studied by estimating parameters $<P_T>_{\Lambda,K}$ and temperatures T_B extracted from Boltzmann-like spectra (or inverse slope parameters of invariant cross sections spectra T_0, treated often wrongfully as temperature). Our early analysis has revealed a considerable rise of T_B with the centrality degree from $T_\Lambda = (75 \pm 8)$MeV up to $T_\Lambda = (158 \pm 11)$MeV which corresponds to $T_0 \simeq 210$MeV. The same increase from $T_K = (73 \pm 11)$MeV up to $T_K = (162 \pm 8)$MeV has been observed if K^0_S mesons have been used as thermometer. 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. 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 $\sim 1\%$ from noncentral ones). Taking into account this effect some model dependent estimation could be obtained which gives for the baryonic density $\rho = (4 \pm 1)\rho_o$.

A search for a possible strangeness enhancement has been performed looking at the measured relative yields ($< n_\Lambda > / < n_{\pi^-} >$) of Λ-hyperons with $P_T >1$ GeV/c being beyond kinematical limits of reaction $NN \rightarrow \Lambda NK$ at 3.7 AGeV. 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[9]. We have found that for such a set of Λ's, which is free of background of Λ's from NN-interactions, the ratio $< n_\Lambda > / < n_{\pi^-} >$ increase by a factor of **10±1** when going from peripherical AA-collisions to central ones.

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 collision[10] which involve a twofold number of nucleons i.e. with twice as great released energy as in central CC collisions. The value of T_B=137±9 MeV has been found which does not differ within errors from obtained for central CC collisions.

This gives an indication that the temperature stops to raise approaching a plateau.

The recent date of the experiments at BNL[11] and CERN[12] have suggested the evidence for such a plateau extending to much higher energies as can be seen from Fig 1. Moreover in these experiments strangeness enhancement has been also observed in central AA-collisions,and not only for a relative yield of Λ's but for those of $K^\pm$ and $\bar{\Lambda}$ (with different cuts: P_T ≥ 0.1-0.5 GeV/c).

Main effects found in Dubna experiments are summarized in the Table bellow:

Effects observed with increasing of degree of collision centrality	Predicted as signals of...
flattening of angular distributions $dN_{\Lambda,K}/dCos\Theta^*$ and $dE^*_{\Lambda,K}/dCos\Theta^*$ 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 : $< n_\Lambda > / < n_{\pi^-} >$*) by factor **10±1** for $P_T(\Lambda) > 1$ GeV/c	QGP formation(?)
- raise of Boltzmann temperatures of Λ's and K^0's from $T_B \simeq 75$ Mev up to $\simeq 160$ MeV (to $T_0 \simeq 210$ MeV) with a cessation of further raise and approaching of T_B to a plateau*)	heating with first order phase transition and QGP+hadr.gas mixed phase formation(?)

*) supported by more recent data of BNL [11] and CERN[12]

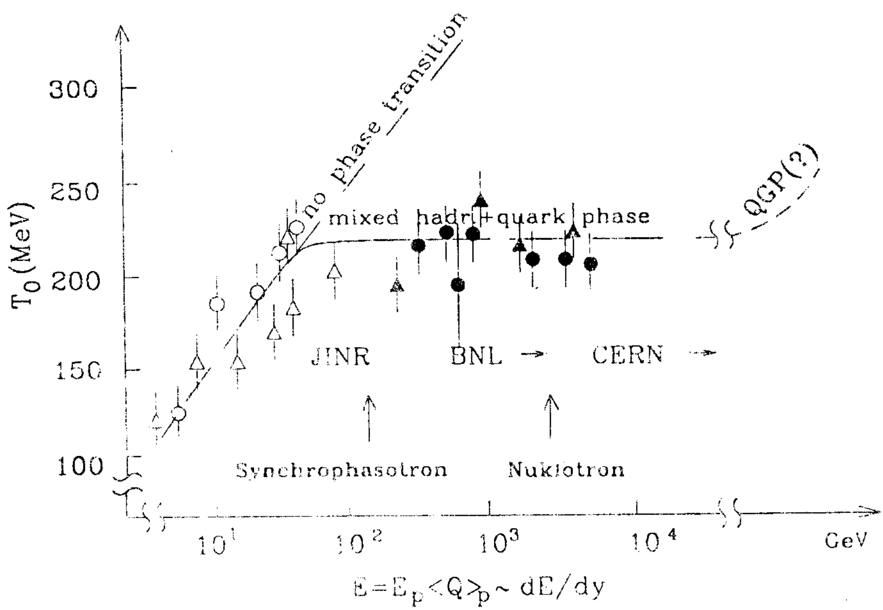

Figure 1: Inverse slope parameters T_0 versus $E=E_p <Q>$ where $<Q>$ the number of projectile nucleons-participants : open circles and open triangles — K^0_S and Λ JINR data; black circles and black triangles — neutral (charged) kaons and Λ data of BNL and CERN

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 strangeness abundant fireball(mixed phase) via first order transition. 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. We start the new round of our research to study the found effects and look for other ones, using much heavier projectile nuclei at 5–6 A GeV from our new superconducting Nuclotron which will provide about 1 TeV of the total energy released in central U-U collisions.

In this connection I would like to oppose the wide-spread statement "the higher–the better" when considering projectile energies wanted for the QGP formation, and adduce weighty arguments in favour of the baryon-rich regime at several GeV per nucleon:

— many models predict QGP creation at as low energies as 2–5 A GeV for some EOS;

—the alternative fundamental phenomenon (beside the deconfinement) is expected to cause QGP formation - the chiral symmetry restoration with its predicted high density/low temperature effects;

—such processes could more adequately reproduce (simulate) astrophysical phenomena (Big Bang, neutron star evolution, supernouva explosion);

—the strangeness (flavour) enhancement as QGP signature should be more pronounced within a high density enviroment due to the Pauli principle;

—the background contributions to studied QGP signals (e.g. from hadronic gas) are much smaller due to lower energies of secondaries.

Two last points make very favourable the effect/background ratio especially for sub-near threshold effects at the Nuclotron energies as the processes of the production of $\bar{\Lambda}$, Ξ, Ω, ϕ-meson, H-dihyperon which are planned to be studied as possible QGP signals.

I believe most of physicists to be convinced now that more concerted approaches are necessary to attack efficiently as complicated problems as the QGP and strange matter, using not only distinct signatures but also different phase trajectories to reach QGP (mixed phase) with a following adequate comparision of data obtained at various energies.

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Странность как пробник сильно возбужденного вещества
в исследовании ядро-ядерных взаимодействий в ОИЯИ

В результате изучения особенностей характеристик Λ- и K^{o}-частиц, рожденных в центральных соударениях ядер при $E \cong 3{,}3 \div 3{,}7$ АГэВ на синхрофазотроне, были обнаружены эффекты, которые предсказываются как сигналы термализации адронного вещества, его уплотнения и разогрева до больцмановской температуры $T_B \cong 160$ МэВ ($T_0 \cong 210$ МэВ) с ее выходом на плато, которое простирается, как показали более поздние работы БНЛ и ЦЕРН, до $E_p \cong 200$ АГэВ. При этом наблюдалось увеличение относительного выхода Λ в области средних быстрот, что также указывает на возможное образование смешанной фазы, обогащенной странностью. Полученные данные продемонстрировали, что странность является эффективным пробником сильно возбужденного вещества при больших плотностях, т.е. в режиме, который, согласно многим моделям, может привести к фазовому переходу в кварк-глюонную плазму при сравнительно низких энергиях (2÷5 АГэВ), что обеспечивает благоприятное отношение «сигнал/фон». Это преимущество должно проявиться еще более ярко на нуклотроне (5÷6 АГэВ) в экспериментах с тяжелыми ядрами, планируемых для более детального изучения обнаруженных эффектов и исследования других «странных» сигналов КГП, таких как образование $\bar{\Lambda}$, Ξ, Ω, φ, H-частиц вблизи порога. Планируемые эксперименты позволят более адекватно воспроизвести некоторые астрофизические процессы и получить информацию не только о деконфайнменте, но и о другой возможной причине образования КГП — о восстановлении киральной симметрии с его эффектами, ожидаемыми при больших ρ и малых T_B.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Highly Excited Matter Probed with Strangeness
in Nucleus-Nucleus Collisions at JINR

Studies of characteristics of Λ and K particles, produced in central collisions of nuclei from the synchrophasotron ($E = 3.3 \div 3.7$ AGeV) have revealed effects predicted as signals of the hadronic matter thermalization, compression and heating up to Boltzmann temperatures $T_B \cong 160$ MeV ($T_0 \cong 210$ MeV) with approaching the plateau which is then seen throughout more recent AGS/SPS results, up to E=200 AGeV. An increase of the relative Λ yield in midrapidities has been observed as well which is also an evidence for a formation of the strangeness abundant mixed phase. The obtained data demonstrate that the strangeness is an efficient probe of the highly excited/compressed matter, i.e. in the baryon-rich regime, which requires (according to many model predictions) for the phase transition into Quark Gluon Plasma, rather low energies (2 ÷ 5 AGeV) and would provide favourable signal/background ratios. This advantage is expected to be more pronounced in Nuclotron experiments at 5 ÷ 6 AGeV which aim to examine the observed effects with heavier nuclei and to study other QGP signals including near-threshold production of $\bar{\Lambda}$, Ξ, Ω, φ, H partricles. The planned experiments could simulate more adequately some astrophysical processes and provide information not only about the deconfinement but about another phenomenon which also is predicted to provoke a QGP formation, namely the chiral symmetry restoration with its expected high density/low temperature effects.

The investigation has been performed at the Laboratory of High Energies, JINR.

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