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Temperatures of Λ Hyperons, K^0 and π^--Mesons Produced in C-C and Mg-Mg Collisions at 4.2 ÷ 4.3 AGeV/c

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ABSTRACT. Particle spectral temperatures for Λ hyperons, K^0 and π^--mesons produced either in the absence or presence of the Λ hyperons and K^0 mesons in the C-C and Mg-Mg collisions at incident momentum of 4.2÷4.3 AGeV/c have been determined focussing independently on either center-of-mass energy and transverse momentum distributions. For negative pions, the temperatures were found to be approximately the same, no matter whether the emission of those particles was associated with Λ and K^0 production or not. Results of the measurements have been compared to the results of simulations within the Quark-Gluon String Model. *© 2010 Bull. Georg. Natl. Acad. Sci.*

***Key words**: strange particles, collision , production, spectral temperature.*

The study of ultra-relativistic heavy-ion collisions is motivated mainly by the quantum chromodynamics (QCD) prediction that at sufficiently high energy density the excited nuclear matter undergoes a phase transition into a system of deconfined quarks and gluons (quark-gluon plasma, QGP) [1]. Neutral strange particles such as Λ and K^0 have proved over the past years to be a powerful tool for the study of reaction dynamics in high-energy heavy-ion collisions. Produced strange particles represent important probes of high-density nuclear matter formed in relativistic heavy-ion collisions. Thus, because of the production thresholds, strangeness is generated within early stages of a collision. Due to their longer mean free path, the strange particles are additionally likely to leave the colliding system earlier than other hadrons. Given the necessary contributions of the early high-density stages of a collision, to the strange production, the yields of strange particles have been linked theoretically to the nuclear equation of the state (EOS) of dense matter [2] and to the in-medium modifications of particle masses [3]. The temperature and density of nuclear matter are among the main parameters of the EOS determining the phase transition mechanism. The transverse momentum spectra should provide information about the condition of the system at freeze-out, in particular about the temperature and collective velocity of the system. To obtain the temperature of secondary hadrons in the experiment, one usually estimates the slope of inclusive spectrum.

In this paper, we present experimental results on the characteristics of Λ hyperons and K^0 mesons produced in the light-system C-C collisions at incident momentum of 4.2 AGeV/c, registered in the 2 m Propane Bubble Chamber (PBC-500) of JINR and of Λ hyperons produced in the Mg-Mg collisions at incident momentum of 4.3 AGeV/c, registered in the 2 m Streamer Chamber (GIBS Collaboration) of JINR. We concentrate on spectral temperatures of Λ hyperons, K^0 mesons and π^--mesons produced in association with Λ hyperons. The spectral temperatures of Λ hyperons have been studied before in the the semicentral C-C collisions [4].

In the next section, we address the details of our measurements. Temperatures of Λ's, K^0's and pions either co-produced, or not, with the hyperons are addressed in Section “Spectral Temperatures”.

Experimental data. The experimental data presented in this paper were obtained using a 2 m Bubble Chamber (PBC-500) and a 4π streamer spectrometer GIBS of JINR placed in the magnetic field of 1.5 T and 0.9 T, respectively.

When a V^0 event was deemed to be the charged-particle decay, $\Lambda \rightarrow p+\pi^-$, the momentum of the hyperon was reconstructed from decay products. The procedure resulted in the C-propane (C_3H_8) collisions of 873 Λ-hyperons and 375 $K^0 \rightarrow \pi^+\pi^-$, from which 602 Λ and 257 K^0 particles have been identified unambiguously in C-C. The weight factor was taken into consideration for the remaining particles of C-propane collisions. For the analysis of the spectral distributions of particles there are 687 Λ and 287 K^0 in the inelastic C-C interactions [5].

For the analysis 700 Λ-hyperons were selected from the Mg-Mg collisions.

Usually, for V^0 particles the following corrections were carried out:

1) the particles, whose decay occurred too close to the creation vertex or outside of the chamber effective region;

2) Identification efficiency further deteriorated for certain azimuthal directions;

3) the particles where lost in the forward c.m. hemisphere, for directions too close to the beam.

Depending on the momentum region, corrections have been applied to the identified particles, in the form of weights, compensating for the losses. Additional information, on the V^0 identification and on the corrections, can be found in [6]. Technical details behind the separation of C-C collisions in propane, identification of charged pions and protons, application of different corrections and data processing, may be found in [5, 7].

The GIBS facility consisted of 2 meter streamer chamber with fiducial volume 2x1x0.6 m^3 and a triggering system. The spectrometer was triggered for central collisions (anticoincidence counters for projectile charged and neutral spectators emitted at angles $\theta_{ch}=\theta_n=2.4^0$). Technical details, identification of Λ hyperons and charged pions in Mg-Mg collisions, application of different corrections and data processing, may be found in [8, 9].

Spectral temperatures. In the following, we shall examine the thermal characteristics of spectral distributions of Λ hyperons and of negative pions either co-produced, or not, with the hyperons in C-C and Mg-Mg collisions at 4.2÷4.3 AGeV/*c*. The distributions can principally result from a superposition of local thermal distributions and collective velocity field at freeze-out. We examined whether the effective temperatures that could be associated with the distributions, depend on species, on associated production and on the method of analysis of distribution.

Two primary types of collective motion may have an essential practical impact on the spectral distributions. Thus, an incomplete stopping of initial nuclei, or transparency, gives rise to a longitudinal collective motion. In addition, collective expansion may develop in a reaction and be reflected in significant transverse radial flow. In the following, we shall examine both the spectral distributions in the net center of mass system (c.m.s.) energy and in the transverse momentum. The latter distributions are less likely to be affected by the longitudinal collective motion than the former. Moreover, we shall explore the potentially different conclusions when confronting data with different versions of the thermodynamic model, such as with the Hagedorn model, assuming particle freeze-out within a net c.m.s. volume common for all particles, and with a model of thermal transverse distribution. First, we analyze particle distributions in the net energy, in terms of the standard thermal model of freeze-out with the c.m.s.

For a gas in thermal equilibrium within the volume *V*, the distribution in momentum of different species *i* is [10-12]:

$$d^3N_i/dp^3 = (2S_i+1)V/(2\pi)^3 \cdot [\exp((E_i-\mu_i)/T) \pm 1]^{-1}$$

$$\rightarrow (2S_i+1)V/(2\pi)^3 \cdot \exp(\mu - m_i/T) \cdot \exp(-E_{ki}/T) \qquad (1)$$

where *V* represents the freeze-out volume, S_i is spin, μ_i is chemical potential, T is temperature, $E_i=\sqrt{m_i^2+p_i^2}$ is the particle energy, and $E_{ki} = E_i - m_i$ is the kinetic energy. The ± signs refer to fermions and bosons, respectively, and the arrow indicates the Boltzmann-statistics limit of $E_i-\mu_i \gg T$. In a nondegenerate system, the distribution is then exponential in the kinetic energy, with the temperature T determining the slope of the exponential,

$$d^3N/dp^3 = d^2N/p^2dpd\Omega=$$

$$=d^2N/pE\,dEd\Omega= \text{const} \cdot \exp(-E_k/T) \qquad (2)$$

Correspondingly, following the global freeze-out model, we can extract the freeze-out temperature by fitting an exponential to the scaled distribution of particles in energy:

$$(pE)^{-1}\, dN/dE_k = \text{const} \cdot \exp(-E_k/T) \qquad (3)$$

$$(pE)^{-1}\, dN/dE_k = A_1 \cdot \exp(-E_k/T_1) + A_2 \cdot \exp(-E_k/T_2) \quad (3a)$$

The Hagedorn Thermodynamic Model [13,14] allows, in principle, for a set of fireballs displaced from each other in rapidity. In that model, particles with different momenta freeze-out within a volume that is of universal magnitude when assessed in the rest-frame for any given momentum, being the distribution in transverse momentum of the shape

$$dN/dp^{\perp} = const \cdot p^{\perp} m^{\perp} K_1(m^{\wedge}/T) \approx \approx const \cdot p^{\perp} (m^{\perp} T)^{1/2} \exp(-m^{\perp}/T) \quad (4)$$

$$dN/dp^{\perp} \approx A_1 \cdot p^{\perp} (m^{\perp} T_1)^{1/2} \exp(-m^{\perp}/T_1) + A_2 \cdot p^{\perp} (m^{\perp} T_2)^{1/2} \exp(-m^{\perp}/T_2) \quad (4a)$$

where K_1 is the MacDonald Function [15], the transverse mass is $m^{\perp} = \sqrt{m^2 + p^{\perp 2}}$ and the approximation above is valid for $m^{\perp} >> T$.

We shall fit the transverse spectra using the Hagedorn model and will display those fits in the context of spectra presented as distributions in transverse momentum.

Fig.1 shows the scaled E_k and $P^{4\%}$ distributions for Λs in the rapidity region |y|≤0.8 in C-C (Fig.1 a,b) and Mg+Mg (Fig.1 c, d) collisions, respectively. For Λs, we find the temperature of T≈102÷104 MeV in C-C collisions and T≈140÷144 MeV in Mg-Mg collisions, which are higher than the temperature for K^0 mesons (Fig.1 e, f) of the order of 94 MeV in C-C. From E_k-distributions for Λs have been obtained about 150 MeV in central (C-C + C-Ne + O-Ne, C-Cu + C-Zr and C-Pb + O-Pb) and inelastic (He-Li) collisions (SKM-200, JINR) [16]. Fig.1 (e, f) shows the distribution for K^0 mesons in the rapidity region |y|≤0.8 in C+C interactions. The distribution for π^- mesons either emitted in the presence or absence of Λs or of K^0s for C-C collisions have the same behaviour. What concerning the distributions of pions in Mg-Mg collisions can be well fitted by a sum of two exponentials (two temperatures T_1 and T_2) (Table 1). The temperatures are similar, but not the same, for different species. The regularities which are observed in analyzing the distributions, irrespectively of the spectrum or the thermal model, are that the π^--meson temperatures are lower than the Λ temperatures. As we have already indicated, the lower π^- temperatures may be attributed to the presence of collective motion, which has a stronger effect on the more massive protons than on pions.

The temperature for Λs are higher than for K^0 mesons, which are higher than for π^--mesons. The temperatures in Mg-Mg collisions are higher than in C-C, these results may be caused not only by the increase of the mass numbers, but also by the difference of the type of the interactions. Thus Mg-Mg interactions obtained with this set-up correspond to the central trigger. The fraction of such events is $\approx 4 \cdot 10^{-4}$ among all inelastic interactions (the energy yield is much greater in central interactions). The kinetic energy distributions have been described by one exponent T=85.0±1.2 (MeV) for π^- mesons in C-C collisions. Two temperatures (T_1=54.0±0.7 (MeV) and T_2=112.1±2.9 (MeV), with Λs)) have been obtained in Mg-Mg. The temperature of π^--mesons emitted in the absence of Λs, agrees with those (latter values of temperature) within the errors. The presence of two temperatures for pions is explained [5,10] by two mechanisms of pion production: direct (T_2) and via Δ resonance decay (T_1). It should be mentioned that the same effect has been observed in Ar-KCl collisions (1.8 AGeV) [17]. Some small temperatures have been obtained in the inelastic C-C for Λs and for π^--mesons associated with Λ production than in the semi-central C-C collisions [4].

For negative pions, the temperatures were found to be approximately the same, no matter whether the emission of those particles was associated with Λ production or not. Greater differences in deduced temperature values are found for the π^--mesons. This may be due to the combination of nonthermal features of spectra, rapidity cut, and nearly ultrarelativistic nature of pions in the collisions. The regularities which are observed in analyzing the distributions, irrespectively of the spectrum or the thermal model, are that the π^--meson and K^0 temperatures are lower than the Λ temperatures.

Thus, because of the rest-energy cost involved in strange production, the strange particles must typically emerge, from their production process, at low velocities relative to their environment. An early freeze-out for the hyperons may be facilitated by the lower interaction cross-sections with the environment, for the hyperons, than for other baryons. Because of the early freeze-out, the kinetic energies of hyperons might not tap much, in addition, the energy reservoir represented by the excess rest-energy in baryonic resonance excitations. During system expansion, that excess energy gets converted into the radial collective energy, but some of that conversion may take place only after the Λs have decoupled from the system. The rest-energy involved in strangeness production taxes also energies of other particles.

The results for spectra from the Quark Gluon String Model (QGSM) are compared to data in Fig. 1. The model is presented in detail in [18, 19]. The QGSM is based on the Regge and string phenomenology of particle production in inelastic binary hadron collisions.

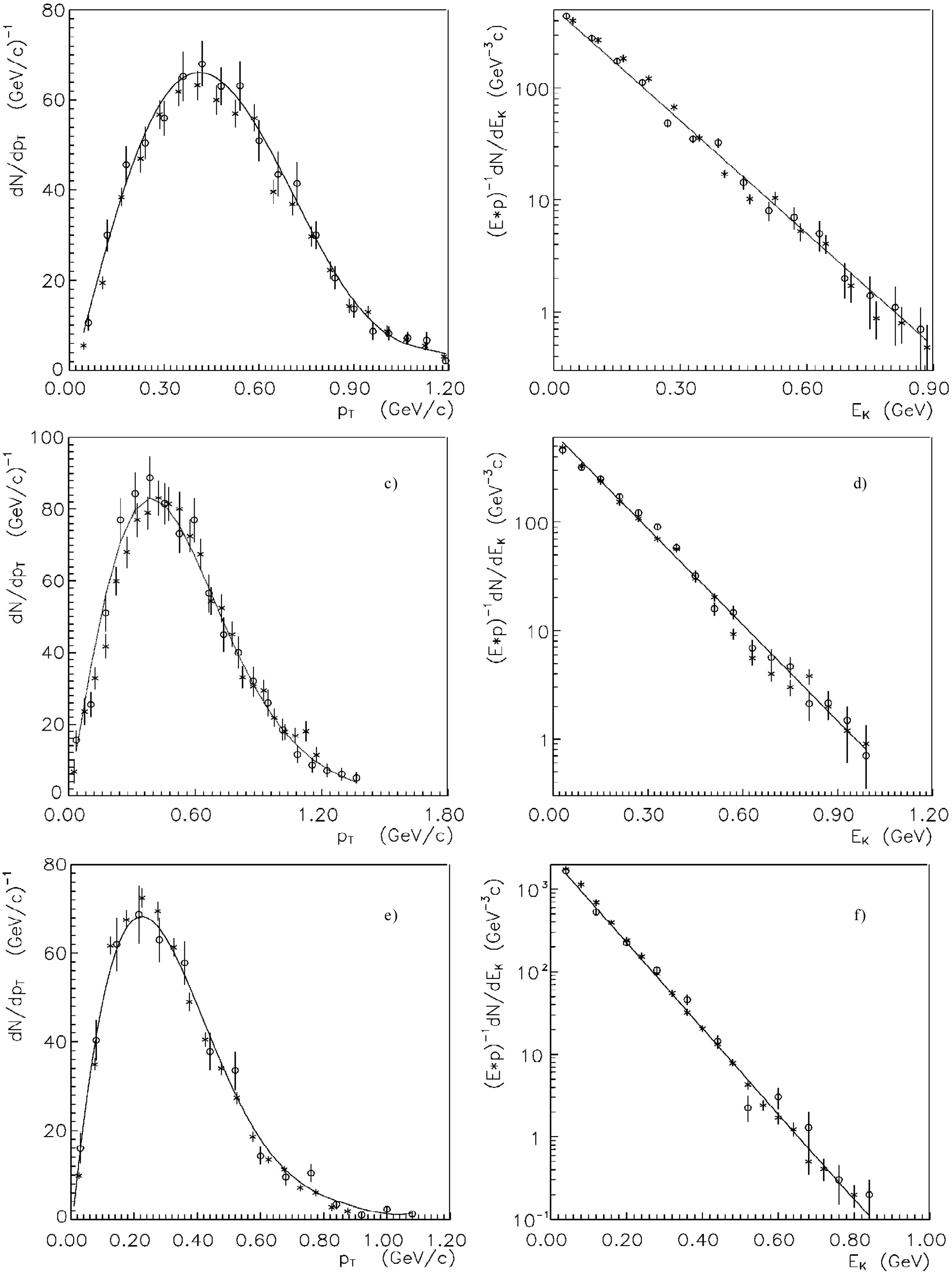

Fig. 1. Distributions in the transverse momentum (left panels) and scaled distributions in the cm. kinetic energy (right panels) of Λ hyperons emitted from C-C (a, b) and from Mg-Mg (c, d) collisions and of K° mesons emitted from C-C (e, f) collisions. Circles represent data and stars represent QGSM results. Lines represent thermal fits to the data, discussed in the text.

The model oversimplifies nuclear effects in that nucleon mean-field effects are ignored as well as nucleon coalescence into clusters. Within QGSM, nuclear densities are used for selecting coordinates of original nucleons. This is followed by the formation of quark-gluon strings which fragment into hadrons. Those hadrons rescatter. To simulate the model events, we have employed the COLLI Monte-Carlo generator [20] based on QGSM. To the generated events, a detector filter has been applied and, in the case of C-C and Mg-Mg collisions, a trigger filter. In the past, it has been found that the applied filters selected peaked distributions of impact parameters for the collision events, characterized by the average b-values of: b = 2.65 fm and 1.35 fm for inelastic C-C and central Mg-Mg events, respectively.

The temperatures from fits to the QGSM spectra are further compared to those for data in Table I. It is apparent that the model describes adequately the measured spectra (Fig. 1). In addition, the model reproduces variation of the temperatures with species and with thermodynamic models fitted to different spectra.

The temperatures of strange particles (K^0 mesons and Λs) have been obtained by different collaborations. In Ni-Ni collisions at 1.93 AGeV, measured at GSI SIS, the FOPI Collaboration [18] has arrived at the temperatures of 119 ± 1(MeV) and 114 ± 1(MeV), when fitting $m^{\perp}$-spectra of Λs and of K^0 mesons, respectively, around midrapidity. In Pb-Pb collisions at 20 AGeV, 30 AGeV, 40 AGeV, 80 AGeV and 158 AGeV, measured at CERN SPS, the NA49 Collaboration [21] has arrived at the temperatures of Λs of 244 ± 3 (MeV), 249 ± 2 (MeV), 258 ± 3 (MeV), 265 ± 4 (MeV), 301 ± 4 (MeV), when fitting $m^{\perp}$-spectra of Λs, respectively, around midrapidity. One can see that the temperature of Λs significantly increases with energy and colliding system mass [22]. In principle, a somewhat stronger radial collective motion in a larger system could be responsible for the increase in temperature of baryons.

Conclusions. The spectral temperatures have been determined for Λs, K^0 mesons and negative pions produced either in the absence or presence of the strange particles in C-C and Λs and negative pions produced either in the absence or presence of the Λs in Mg-Mg collisions at 4.2÷4.3 AGeV/c, measured using the Propane

Table 1.

The temperatures of Λ hyperons emitted from C-C and from Mg-Mg collisions and of K^0 mesons emitted from C-C collisions and π^--mesons, produced either in the presence or absence of Λs and of K^0 mesons (inferred from different spectra following different thermal-model assumptions discussed in the text).

A_P-A_T	Particles	Spectrum origin	Number of particles	Temperature T (MeV)	
				dN/dE_K	$dN/dp^{\perp}$
C-C	Λ	Data	687	104.1±2.2	102.21±3.9
	| y | ≤ 0.8	QGSM	7578	105.0±1.0	106.0±1.7
	π^- with Λ	Data	1146	86.0±1.2	90.2±1.8
	| y | ≤ 1	QGSM	12005	85.8±1.0	91.2±1.0
	π^- without Λ	Data	23781	86.2±0.8	92.6±2.0
	| y | ≤ 1	QGSM	66820	89.0±1.0	93.1±0.8
	K^0	Data	287	92.6±2.8	96.3±3.5
	| y | ≤ 0.8	QGSM	9354	91.8±0.3	94.8±0.5
	π^- with K^0	Data	583	87.4±3.0	91.7±5.4
	| y | ≤ 1	QGSM	16397	84.6±0.6	89.0±0.9
Mg-Mg	Λ	Data	700	143.7±7.5	140.1±3.2
	| y | ≤ 0.8	QGSM	3482	137.2±0.8	138.4±2.8
	π^- with Λ	Data	5427	54.0±0.7 (T_1) 112.1±2.9 (T_2)	63.6±7.0 (T_1) 115.1±10.3 (T_2)
	| y | ≤ 1	QGSM	21083	48.9±1.0 (T_1) 106.3±1.0 (T_2)	55.8±3.7 (T_1) 102.7±2.1 (T_2)
	π^- without Λ	Data	9837	56.7±0.1 (T_1) 115.2±2.2 (T_2)	65.2±4.6 (T_1) 116.6±7.6 (T_2)
	| y | ≤ 1	QGSM	52527	50.7±0.5 (T_1) 106.3±1.0 (T_2)	54.7±4.4 (T_1) 110.6±1.4 (T_2)

Bubble Chamber and streamer spectrometer GIBS of JINR at Dubna. Both the c.m. kinetic energy and the transverse momentum spectra have been examined, as well as the Hagedorn thermodynamic model used to fit data. The temperatures for Λs are higher than for K^0 mesons (92.6±2.8 (MeV)), which are higher than for π^--mesons.

The temperatures in Mg - Mg collisions T_Λ=143.7±7.5 (MeV) are higher than in C-C T_Λ=104.1±2.2 (MeV). The kinetic energy distributions have been described by one exponent T=85.0±1.2 (MeV) for π^- mesons in C-C collisions, two temperatures (T_1 =54.0±0.7 (MeV) and T_2=112.1±2.9 (MeV), with Λs) have been obtained – in Mg-Mg. The temperature of π^--mesons emitted in the absence of Λs, agrees with ones (latter values of temperature) within the errors. Experimental results have been compared to the results of collision simulations within the Quark-Gluon String Model which combines string decays with a hadronic interaction cascade. The model describes the observations rather well.

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ფიზიკა

C-C და Mg-Mg დაჯახებებში 4.2÷4.3 A გევ/c იმპულსის დროს დაბადებული Λ ჰიპერონების, K^0 და π^--მეზონების ტემპერატურები

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(წარმოდგენილია აკადემიის წევრის ა. ხელაშვილის მიერ)

შესწავლილია Λ ჰიპერონების, K^0 მეზონების და მათთან ერთად და მათ გარეშე C-C და Mg-Mg დაჯახებებში 4.2÷4.3 Aგევ/c იმპულსის დროს დაბადებული π^--მეზონების ტემპერატურები კინეტიკური ენერგიის და განივი იმპულსის განაწილებების მეშვეობით. Λ ჰიპერონებთან ერთად და მათ გარეშე დაბადებული უარყოფითი პიონებისათვის მიღებული ტემპერატურები თითქმის ერთი და იმავე სიდიდისაა. ექსპერიმენტული შედეგები კარგადაა აღწერილი კვარკ-გლუონური სიმური მოდელით (QGSM).

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