Study of Multiparticle Production Processes in
Relativistic Nucleus-Nucleus Collisions by Using
Streamer Spectrometer

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A b s t r a c t o f D i s s e r t a t i o n

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Subject of the Research Work. Heavy ion reactions at high energies are able to create a strongly compressed and highly excited nuclear matter in laboratory. At such extreme conditions a number of new phenomena like phase transition of nuclear (hadronic) matter into the pion condensate, density isomers and a deconfined state of nuclear matter – the Quark-Gluon Plasma (QGP) are predicted theoretically. In the QGP quarks and gluons are no longer confined inside individual nucleons and mesons, but are free to wander over distances much longer than 1 fermi, the characteristic size of a hadron.

All phenomena mentioned above deal with collective behaviour of the nuclear matter. First the matter was observed to be flowing sidewards in the reaction plane due to the high pressure developed at the impact. Later it was also seen that the matter is squeezed out of the hot zone between the two nuclei in the orthogonal direction to the reaction plane. Collective flow effects in heavy ion collisions such as the transverse (directed) and elliptic (squeeze-out) flows are expected to provide insight into the properties of hot and dense nuclear matter and information about its Equation of State (EOS). The transverse (directed) and elliptic flow effects have been already observed for protons, light nuclei, pions, kaons, and Λ-hyperons in nucleus-nucleus collisions at the energies of (0.1–1.8) GeV/nucleon at BEVALAC (Lawrence Berkeley Laboratory - USA), GSI/SIS (Darmstadt, Germany), at 3.7 GeV/nucleon at Dubna (Joint Institute of Nuclear Research - Russia), at 2–14 GeV/nucleon at AGS BNL (Brookhaven National Laboratory – USA) and at 60 and 200 GeV/nucleon at CERN SPS (European Organization for Nuclear Research – Switzerland), and more recently by the STAR and PHENIX collaborations at RHIC BNL at $\sqrt{s_{NN}}=130$ GeV/nucleon. The elliptic flow of nucleons and pions was found to change its orientation from out-of plane at 1 A·GeV to in-plane at 11.6 A·GeV. Many different methods were proposed for the study of flow effects in relativistic nuclear collisions, of which most commonly used are the directed transverse momentum analysis technique developed by P.Danielewicz and G. Odyniec and the method of the Fourier expansion of azimuthal distributions proposed by Demoulins et. al. and S. Voloshin and Y.Zhang.

For an interpretation of the promising possible signatures of the quark-gluon plasma a better understanding of the reaction dynamics is mandatory. In order to investigate and understand the dynamics of relativistic nucleus-nucleus collisions, it is important to have information on the rapidity and transverse momentum distributions of nucleons participating in the interaction and of particles (mainly pions) produced in the collisions, all as a function of the size of the system and of the impact parameter. The transverse momentum and rapidity distributions provide information on the degree of stopping, thermalization, expansion and flow effects in the collisions. All of this information helps to obtain a consistent picture of the entire reaction process. The temperature and density of nuclear matter are among the main parameters of the EOS determining the phase transition mechanism. The strongly interacting hadrons are expected to decouple in the late stages of the collision. Their transverse momentum spectra should therefore provide information about the conditions 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 inclusive spectrum slope.

Pion production is the most important inelastic channel in relativistic heavy ion reactions. The yield of pions in the final state is connected, through the population of intermediate resonances, to the temperature within the reaction zone. Thus, although not directly related to the EOS, pions are an integral part of the effort to determine properties of nuclear matter. Because of their light masses and large cross sections for interaction in nuclear matter, $\pi^-$ mesons are expected to thermalize easily. Furthermore, their spectra are not affected as those of heavier
particles by a given collective flow velocity. The multiplicity and transverse momentum spectra of produced pions can provide information on properties of both the initial and final state properties of the hot hadronic matter. Thus, pions are a good probes for the study of properties of nuclear matter in heavy ion collisions. Moreover, pions also influence the production of the particles such as dileptons and high energy photons which themselves have been used as probes of EOS.

At high energies different dynamical mechanisms contribute to spectra of secondaries. Among them ”pionization” and fragmentation mechanisms are widely discussed. ”Pionization” means the existence of secondary pions with relatively low momenta and flat (almost isotropic) angular distribution in the centre of mass frame of colliding objects. The fragmentation component has sharply anisotropic angular distribution in the centre of mass frame. One of the principal problems in this direction is the separation of these two components. Up to now there exists no unique way to separate these mechanisms. Different authors propose different approaches and none of them seems to be satisfactory. The presentation of inclusive spectra in terms of light front variables provides a possibility to separate these two components.

**Aims of the Thesis:**

- Study of properties of $\pi^-$ mesons produced in C-C, F-Mg and Mg-Mg collisions at energy of 3.4 GeV/nucleon at a GIBS set-up of JINR/Dubna. Investigation of multiplicity distributions of $\pi^-$ mesons, characteristics of these distributions (the average multiplicity $<n_-$>, the dispersion of multiplicity distribution $D_{n_-}$, etc), average number of interacting nucleons $<Q>$ and ratio $R_-=<n_->/ <Q>$ in central C-C, F-Mg and Mg-Mg interactions. Study of average kinematical characteristics of $\pi^-$ mesons such as momentum, transverse momentum, emission angle, rapidity and corresponding distributions in Mg-Mg collisions. Analysis of rapidity distributions of pions in Mg-Mg interactions in various ranges of transverse momentum.
- Analysis of angular distributions of $\pi^-$ mesons in He-Li, He-C, C-Ne, C-Cu, C-Pb, Mg-Mg and O-Pb collisions at energy of 3.7 GeV/nucleon obtained by use of SKM-200 and GIBS spectrometers. Extraction of the anisotropy coefficient $a$. Study of the dependence of the $a$ on mass numbers of the projectile ($A_p$) and target ($A_T$), on kinetic energy in c.m.s and multiplicity of pions $n_-$.  
- Study of characteristics of protons in central He-Li, He-C, C-Ne, C-Cu and C-Pb collisions, namely the average values of momentum, transverse momentum, rapidity and emission angle.
- Extraction of temperatures of protons, $\pi^-$ and $\pi^+$ mesons from kinetic energy and transverse momentum ($P_T$) spectra in central He-Li, He-C, C-C, C-Ne, C-Cu, O-Pb and Mg-Mg collisions. Study of the dependence of temperatures of protons ($T_p$) and $\pi^-$ mesons ($T_{\pi^-}$) on the atomic numbers of projectiles and targets, rapidity and emission angle. The investigation of a correlation of pion kinematical characteristics with $\Lambda$’s momentum in the nucleon-nucleon (N-N) c.m. system in Mg-Mg collisions.
- Investigation of inclusive spectra of $\pi^-$ mesons in He(Li,C), C-Ne, C-Cu, Mg-Mg and O-Pb collisions in terms of light front variables in order to divide the phase space of secondary pions into two regions (parts) with the aim to separate ”pionization” and fragmentation mechanisms. Study of characteristics of momentum, angular and $P_T^2$ distributions of pions in these two regions with the aim to obtain information whether the characteristics are similar or different in these two parts.
- Investigation of the directed and elliptic collective flow effects of protons and $\pi^-$ mesons in central C-Ne and C-Cu collisions at energy of 3.7 GeV/nucleon by use of the transverse momentum technique developed by P.Danielewicz and G.Odyniec. Study of dependence of flow
parameter $F$ (the measure of the amount of collective transverse momentum transfer in the reaction plane) on the target mass number ($A_T$). Comparison of $F$ with flow data for various projectile/target configurations at GSI-SIS, AGS and SPS-CERN energies using the scaled flow $F_s = F/(A_P^{1/3} + A_T^{1/3})$. Extraction of the parameter $a_2$ of the anisotropy term $a_2 \cos 2\phi$ from azimuthal distributions of protons and $\pi^-$ mesons with respect to the reaction plane at mid-rapidity region in both C-Ne and C-Cu collisions. Study of the ratio $R$ of the number of particles emitted in the perpendicular direction to the number of particles emitted in the reaction plane, which represents the magnitude of the out-of-plane emission signal. Study of dependence of $a_2$ and $R$ on target mass numbers, rapidity and transverse momentum.

- Measurement of the differential transverse flow of protons and $\pi^-$ mesons in central C-Ne and C-Cu collisions. Investigation of the strength of differential transverse flow of protons and $\pi^-$ mesons.
- Comparison of obtained experimental results with predictions of the Dubna Intranuclear Cascade Model (DICM), Quark Gluon String Model (QGSM) and Hagedorn Thermodynamical Model.

Scientific Novelty
- The experimental data has been obtained on SKM-200 and GIBS set-ups of JINR by using the triggering system for selection of inelastic and central collisions, which are characterized by a large set of colliding pairs of nuclei $A_P(A_P = ^4He, ^{12}C, ^{16}O, ^{24}Mg) + A_T(A_T = ^6Li, ^{12}C, ^{20}Ne, ^{24}Mg, ^{64}Cu, ^{207}Pb)$ at a momentum of 4.3 and 4.5 GeV/c per nucleon, by the pure target-nuclei and also by different impact parameters.
- Properties of $\pi^-$ mesons produced in C-C, F-Mg and Mg-Mg collisions at energy of 3.4 GeV/nucleon at a GIBS set-up of JINR/Dubna has been studied. Multiplicity distributions of $\pi^-$ mesons, characteristics of these distributions (the average multiplicity $< n_-$), the dispersion of multiplicity distribution $D_{n_-}$, etc), the average number of interacting nucleons $< Q >$ and ratio $R_- = < n_- > / < Q >$ interactions were investigated. Study of average kinematical characteristics of $\pi^-$ mesons such as momentum, transverse momentum, emission angle, rapidity and corresponding distributions in Mg-Mg collisions has been carried out. Analysis of rapidity distributions of pions in Mg-Mg interactions in various ranges of transverse momentum was performed.
- Angular distributions of $\pi^-$ mesons in He-Li, He-C, C-Ne, C-Cu, C-Pb, Mg-Mg and O-Pb collisions at energy of 3.7 Gev/nucleon obtained by use of SKM-200 and GIBS spectrometers has been analysed. The anisotropy coefficient $a$ have been extracted. Study of the dependence of the $a$ on mass numbers of the projectile ($A_P$) and target ($A_T$), on kinetic energy in c.m.s and multiplicity of pions $n_-$ was performed.
- Characteristics of protons was studied in central He-Li, He-C, C-Ne, C-Cu and C-Pb collisions, namely the average values of momentum, transverse momentum, rapidity and emission angle.
- Temperatures of $\pi^-$ and $\pi^+$ mesons has been estimated from kinetic energy and transverse momentum ($P_T$) spectra in central He-Li, He-C, C-C, C-Ne, C-Cu, O-Pb and Mg-Mg collisions for the first time. The dependence of temperatures of protons ($T_p$) and $\pi^-$ mesons ($T_{\pi^-}$) on the atomic numbers of projectiles and targets, rapidity and emission angle has been investigated.
- Inclusive spectra of $\pi^-$ mesons in He(Li,C), C-Ne, C-Cu, Mg-Mg and O-Pb collisions in terms of light front variables $\xi^\pm$ and $\zeta^\pm$ have been investigated for the first time. In $\zeta^\pm (\xi^\pm)$ distributions the points $\tilde{\zeta}^\pm (\tilde{\xi}^\pm)$ have been singled out, which divide the phase space of secondary $\pi^-$ mesons into two regions with significantly different characteristics, in one of which the thermal equilibrium seems to be reached. Characteristics of $\pi^-$ mesons (the momentum, angular, $p_T^2$ -
distributions) in these two regions differ significantly.

- The directed and elliptic collective flow effects of protons and π− mesons in central C-Ne and C-Cu collisions at energy of 3.7 GeV/nucleon has been obtained for the first time by use of transverse momentum technique developed by P. Danielewicz and G. Odyniec. Dependence of flow parameter \( F \) (the measure of the amount of collective transverse momentum transfer in the reaction plane) on the target mass numbers \( (A_T) \) was studied. Comparison of \( F \) with flow data for various projectile/target configurations at GSI-SIS, AGS and SPS-CERN energies using the scaled flow \( F_s = F/(A_p^{1/3} + A_T^{1/3}) \) has been carried out. The parameter \( a \) of the anisotropy term \( a_2 \cos 2\phi \) from azimuthal distributions of protons and π− mesons with respect to the reaction plane at mid-rapidity region in both C-Ne and C-Cu collisions has been extracted for the first time. The ratio \( R \) of the number of particles emitted in the perpendicular direction to the number of particles emitted in the reaction plane, which represents the magnitude of the out-of-plane emission signal was studied. The dependence of \( a_2 \) and \( R \) on target mass numbers, rapidity and transverse momentum has been investigated. The second Fourier coefficient \( v_2 = \langle \cos 2\phi \rangle \), which is related to \( a_2 \) via \( v_2 = a_2/2 \) and measures the elliptic flow, have been estimated both for C-Ne and C-Cu. The obtained results of the elliptic flow excitation function for protons in C-Ne and C-Cu collisions has been compared with the data in the available energy region of \( 0.2 \div 200.0 \) GeV/nucleon. The excitation function \( v_2 \) clearly shows an evolution from negative \( (v_2 < 0) \) to positive \( (v_2 > 0) \) elliptic flow within the region of \( 2.0 \leq E_{beam} \leq 8.0 \) GeV/nucleon and point to an apparent transition energy \( E_{tr} \sim 4 \) GeV/nucleon. The obtained collective flow effects show the persistence of these collective phenomena in the range of available energy, i.e. from the Bevalac and GSI/SIS up to Dubna, AGS, RHIC and SPS energies.

- The differential transverse flow of protons and π− mesons in central C-Ne and C-Cu collisions have been measured for the first time. The strength of protons and π− mesons differential transverse flow has been investigated.

Obtained experimental results have been compared with predictions of Dubna Intranuclear Cascade Model (DICM), the Quark Gluon String Model (QGSM) and Hagedorn Thermodynamical Model. The models satisfactorily describe different experimental results.

**Practical Value**

- Statistical programs of experimental data processing and analysis have been elaborated in High Energy Physics Institute of Tbilisi State University, which can be used for the processing and analysis of the data of the other experiments.

- Obtained experimental results can be used for planning and performing of new experimental investigations of nucleus-nucleus interactions at high energies and are important for checking-up (verifying) of the theoretical models, which give predictions about nucleus-nucleus collisions in detail.

**Structure and Basic Contents of the Thesis.** The thesis is based on results obtained on SKM-200 and GIBS set-ups. Results of investigation enriched the assumptions about the dynamics of nucleus-nucleus collisions.

The dissertation contains an introduction, 6 chapters, conclusions and referred bibliography. It consists of 251 pages, accounts 88 figures and 18 tables. The references include 212 items.

The experimental data obtained at the Laboratory of High Energies (LHE) of JINR/Dubna by the SKM-200-GIBS International Collaboration (Alma-Ata - Moscow - Dubna - Warsaw - Tbilisi) have been processed and analysed at LHE of JINR and at the High Energy Physics Institute of Tbilisi State University.

**Introduction** presents the subjects of the thesis, its aims and obtained results. Structure of
the thesis and its short overview are given.

Chapter 1 is devoted to description of the spectrometers SKM-200 and GIBS which have been constructed at the Laboratory of High Energies at JINR, Dubna. Spectrometers consist of a 2m streamer chamber placed in a magnetic field of $\sim 0.8$ T ($\sim 0.9$ T for GIBS) and a triggering system. Main elements of both spectrometers and the logic of triggering system are described and the physical parameters of spectrometers are compared. The streamer chamber was exposed to beams of $^4$He, $^{12}$C, $^{16}$O, $^{20}$Ne (SKM-200) and $^{12}$C, $^{19}$F, $^{24}$Mg (GIBS) nuclei accelerated in the synchrophasotron up to the energy of 3.7 GeV per incident nucleon.

Solid targets Li, C, Cu and Pb in the form of thin discs with thickness of $(0.2 \div 0.5)$ g/cm$^2$ (the thickness of Li was 1.5 g/cm$^2$) were mounted within the fiducial volume of the SKM-200 chamber. Neon-gass filling of the chamber, also served as a nuclear target. C, F, and Mg solid targets with thickness of 0.99 g/cm$^2$, 1.34 g/cm$^2$ and 1.56 g/cm$^2$, respectively, were used for GIBS set-up. The ”inelastic” trigger, consisting of two sets of scintillation counters mounted upstream and downstream from the chamber, was selecting all inelastic interactions of incident nuclei with a target. The ”central” triggering system was selecting events defined as those without charged projectile spectator fragments and spectator neutrons ($P/Z > 3$ GeV/c), emitted within a cone of half angle $\Theta_{ch}=2.4^0$ or $2.9^0$ and $\Theta_n=1.8^0$ or $2.9^0$ for SKM-200, and $\Theta_{ch}=\Theta_n=2.4^0$ for GIBS set-up.

The streamer chamber pictures were scanned twice at HEPI TSU and JINR/Dubna. Final results of scanning and measurement of events have been recorded on the Data Summary Tapes (DST) and then have been analysed by using the standard statistical programs HBOOK, PAW, etc. The data processing and analysis procedures are described in detail in the Chapter 1.

In Chapter 2 three models, namely the Dubna version of Intranuclear Cascade Model (DICM), the Quark Gluon String Model (QGSM) and Hagedorn Thermodynamic model, are described which have been used for comparison with the experimental results presented in the dissertation.

In the Intranuclear Cascade model each of colliding nuclei are represented as the Fermi gas of nucleons concluded in the potential well and particles are produced in the independent hadron-hadron collisions. Collision dynamic is traced in time by use of the Monte-Carlo technique. The model takes into account the simultaneous development of intranuclear cascades in both interacting nuclei. Mathematically, it is described by the relativistic Boltzmann equation for the one-particle distribution function of a mixture of gases. In the DICM the effect of Coulomb forces acting between the projectile and target nuclei is taken into account approximately.

The Quark-Gluon String Model (QGSM) allows to investigate hadron-nucleon, hadron-nucleus and nucleus-nucleus collisions at wide energy interval and especially in the range of intermediate energy ($\sqrt{s} \leq 4$ GeV). The Quark-Gluon String Models are the next generation of cascade models and are based on the formation of coloured field tubes or quark-gluon strings (the excited objects, consisted of quarks connected via gluon string) during the collision process, which decay into the observable hadrons. The QGSM is based on the Regge and string phenomenology of particle production in inelastic binary hadron collisions. To describe the evolution of the hadron and quark-gluon phases, the model uses a coupled system of Boltzmann-like kinetic equations. The Monte-Carlo solution of these system of equations corresponds to the direct modelling procedure of collisions. The procedure of event generation consists of 3 steps: 1. definition of configuration of colliding nucleons, 2. production of quark-gluon strings and 3. fragmentation (breakup) of strings into observed hadrons. The coordinates of nucleons are generated according to a realistic nuclear density. The sphere-nuclei are filled with the nucleons at a condition that the distance between them is greater than 0.8 fm. Nucleon momenta
are distributed in the range of $0 \leq P \leq P_F$. The maximum nucleon Fermi momentum is the following:

$$P_F = (3\pi^2)^{1/3} h \rho(r)^{1/3}$$

(1)

where $h=0.197$ fm·GeV/c. For main NN and $\pi$N interactions the following topological quark diagrams were used: binary, 'undeveloped' cylindrical, diffractive and planar. Binary process makes a main contribution. It corresponds to quark rearrangement without direct particle emission in the string decay. This reaction predominantly results in the production of resonances (for instance, $N + N \rightarrow N + \Delta^{++}$), which are the main source of pions. The QGSM simplifies the nuclear effects. In particular, coupling of nucleons inside the nucleus is neglected, and the decay of excited recoil nuclear fragments and coalescence of nucleons are not included.

The statistical bootstrap model (SBM) of Hagedorn represents the generalization of the thermodynamic two-fireball model. In the Hagedorn model instead of two fireballs, the infinite number of fireballs is considered, which are moving toward the c.m.system with different Lorentz factors. In the model two simple mechanisms have been used, the thermodynamics and relativistic kinematics and with the help of these mechanisms a large number of experimental data have been described. In the thermodynamic approach the production of particles is assumed to be due to geometry and available volume in the space phase.

Chapter 3 is devoted to a detailed study of pion production in central nucleus-nucleus collisions at energy of $3.4 \div 3.7$ GeV/nucleon. The advantage of $\pi^-$ mesons choice with respect to other particles in order to establish characteristics of collision dynamics, is shown. Besides, production of pions is the predominant production process at Dubna energies.

Discussion of possible sources of experimental biases and appropriate correction procedures is given. Sources of systematic errors are: admixture of nuclei with $Z < Z_{proj}$, trigger bias, collisions with gaseous $^{14}$N, depletion of narrow events, secondary interactions within solid targets, low momentum pions absorption, admixture of $e^-$, $K^-$ and $\Sigma^-$ and scanning losses. Inaccuracy of corrections was calculated, and systematic uncertainties of these corrections were found to be less than statistical ones. The total uncertainty of corrections depending on the trigger, material and the thickness of target has been estimated and was about $(1.5 \div 4.5)$%.

Results of study of multiplicity distributions of $\pi^-$ mesons, characteristics of these distributions (average multiplicity $< n_- >$, dispersion $D_n$, etc), the average number of interacting nucleons $< Q >$, the ratio $R_- = < n_- > / < Q >$, the dependence of $< Q >$ and $R$ on masses of colliding nuclei in central C-C, F-Mg and Mg-Mg interactions at energy of 3.4 GeV/nucleon are presented in Chapter 3. Results were obtained by scanning of streamer chamber pictures. Pictures were scanned twice, and a subsequent third scan was used to resolve ambiguities or discrepancies between the first two scans. Efficiency of scanning, defined as the ratio of the average number of particles obtained after the single scan to the average number of particles after the third scanning, turned out to be equal to 0.987 $\pm$ 0.013. $\pi^-$ mesons with $P > 50$ MeV/c have been registered. In order to reduce the systematic errors to the minimal values, caused both by secondary interactions within the solid target and by screening of the part of the event by the passing beam tracks, and to obtain the final result, from initial samples of events (1583 C-C, 1557 F-Mg and 6239 central Mg-Mg collisions) have been chosen the events with the following conditions: a) $N_q \leq Z_p + Z_t$, where $N_q = M - 2n_-$, $M$ - is the total number of observed charged particles and $n_-$ - is the number of negative pions; b) only one beam track enters the chamber. Finally obtained subsamples, called further the "refined" ("cleaned") events, formed about 70% from the initial ones. Besides average multiplicities and dispersions of multiplicity
distributions of pions in C-C, F-Mg and Mg-Mg collisions the average numbers of interacting nucleons (protons) \( < Q > \) and the ratios \( R = < n_- > / < Q > \) have been obtained also. The value of \( < Q > \) is defined by the formula:

\[
< Q > = < M > - 2 < n_- > - < n_S > - < n_b >
\]  

(2)

where \( < M > \) is the average number of all observed charged particles (excluding the identified \( e^+ \) and \( e^- \)), \( < n_- > \) - the average number of negative pions, \( < n_S > \) and \( < n_b > \) - average numbers of charged spectator fragments of projectile and target, respectively. \( < M > \) and \( < n_- > \) have been defined by the scanning results. The term \( < n_b > \) in (2) cuts off the evaporated part of the spectra of charged fragments, emitted from the target. Due to the convention of the definition of evaporated particle and in order to check the stability of results, for all targets two cut off levels have been determined: \( P/Z = 240 \) and \( 310 \) \( \text{MeV/c,} \) (which for protons correspond to \( E_{\text{kin}} = 30 \) and \( 50 \) \( \text{MeV} \)). As the difference in results obtained at two above mentioned limits does not exceed the statistical error, further have been presented the averaged values, which correspond to the level of cut off \( P/Z \approx 280 \) \( \text{MeV/c} \) (for protons \( E_{\text{kin}} \approx 40 \) \( \text{MeV} \)). Limits, which define the stripping particles (spectator fragments of the projectile), namely: the emission angle \( \Theta < 4^\circ \) and \( P/Z > 3 \) \( \text{GeV/c} \) in the rest frame of the projectile - approximately correspond to the upper energy limit \( (E_{\text{kin}} = 50 \) \( \text{MeV} \)) for \( b \) particles, emitted from the target. The contamination of evaporated (or stripping) particles with \( Z > 1 \) does not affect \( < Q > \), as in (2) they enter with equal weight in \( < M > \) and \( < n_b > \) (or \( < n_S > \)).

Values of \( < Q > \) obtained in this way from (2) correspond to the number of interacting protons of projectile and target with some admixture of heavier particles. Systematic error of \( < Q > \) due to the admixture of particles with \( Z=2 \) is estimated to be \( \leq 1 \% \). The dependence of \( < Q > \) on the target mass number \( A_T \) have been studied. For this purpose our result for C-C has been compared to the data of C-Ne, C-Cu, C-Zr and C-Pb collisions for the trigger T(2,0) obtained in our experiment at SKM-200 set-up earlier. The \( < Q > \) increases with \( A_T \). The data have been approximated with the empirical dependence \( C \cdot A_T^\alpha \), where the following values for the parameters \( C \) and \( \alpha \) have been obtained: \( C = 2.65 \pm 0.15 \), \( \alpha = 0.48 \pm 0.02 \). The Dubna version of Cascade Model (DICM) satisfactorily describes the data.

The ratio \( R_- = < n_- > / < Q > \) have been studied intensively at Berkeley experiments and in our experiment earlier. This ratio is interesting as in the number of models the pion multiplicity normalized on the number of interacting nucleons is calculated more simply then the total multiplicity. The calculation is especially simplified at \( A_P = A_T \), since in this case the center mass system does not depend on the impact parameter \( b \) in the collective models due to the symmetry of the colliding parts of the nuclei. Therefore, calculations for central collisions usually are carried out at \( b=0 \), avoiding the integration over \( b \).

The ratio \( x = A_P/A_T \) have been used for the quantitative analysis of the \( R_- \) dependence on the atomic numbers of colliding nuclei. Fig. 1 presents the dependence of \( R_- \) on \( A_P/A_T \). In Fig. 1 along with our result for C-C, F-Mg and Mg-Mg collisions the data of C-A_T, O-A_T and Ne-A_T collisions for the trigger T(2,0) obtained in our experiment at SKM-200 set-up earlier, are presented as well. One can see, that \( R_- \) depends on \( x = A_P/A_T \), increasing with \( A_P/A_T \). The data have been approximated (the solid line) with empirical dependence \( C \cdot (A_P/A_T)^\alpha \), where the following values for parameters \( C \) and \( \alpha \) have been obtained: \( C = 0.49 \pm 0.02 \), \( \alpha = 0.22 \pm 0.02 \). Crosses in Fig. 1 are the result of the calculation by the Dubna version of Intranuclear Cascade Model (DICM). One can see, that the model satisfactorily describes the data: the discrepancy with the model does not exceed 20\%.
Values of $R_-$ obtained for C-C, F-Mg and Mg-Mg interactions ($R_-=0.47\pm0.04$, $R_-=0.45\pm0.03$ and $R_-=0.46\pm0.03$, respectively) coincide with results obtained earlier at SKM-200 set up for symmetric and approximately symmetric systems of C-Ne, O-Ne and Ne-Ne ($R_-=0.44\pm0.03$, $R_-=0.50\pm0.04$ and $R_-=0.41\pm0.05$, respectively). The Propane Chamber collaboration at Dubna obtained the following values of $< Q >$ and $R_-$ in central C-C collisions at energy of 3.4 GeV/nucleon: $< Q >=8.92\pm0.05$, $R_-=0.35\pm0.01$. The value of $< Q >$ coincides with our result $< Q >=8.80\pm0.50$ and the disagreement in $R_-$ may be the consequence of systematic error in $< n_- >$ values of Propane collaboration for C-C collisions. In the energy interval of $E=0.4\div1.8$ GeV/nucleon for central Ar-KCl collisions it has been obtained that the $R_-$ increases linearly with $E_{cm}$:

$$R_-(E_{cm}) = \frac{<n_-(E_{cm})>}{<Q(E=1.8)>>} = 0.74 \cdot (E_{cm} - 0.1) \quad (3)$$

Extrapolating (3) to our energy ($E_{cm}=0.673$ GeV/nucleon), one can obtain $R_-=0.42$, which coincides with our result and extends the linear dependence of $R_-$ for symmetric pairs of nuclei, observed in Bevalac experiments, up to our energy of 3.6 GeV/nucleon and allows one to extend the region of comparison with the predictions of theory beyond the limits of Bevalac (LBL) energies. Results of $R_-$ for symmetric pairs of nuclei C-C, Mg-Mg are compared with the calculations of simple thermodynamic model, which takes into account the pionic degrees of freedom. The obtained values of $R_-$ coincide with the values calculated by using the thermodynamical model at $\rho/\rho_0 \sim 2$, where $\rho$ is the nuclear density at freeze-out temperature $T$ and $\rho_0$ is the normal (ground state) nuclear density.

A study of pion production in central Mg-Mg collisions is described in Chapter 3. The average kinematical characteristics of $\pi^-$ mesons such as multiplicity, momentum, transverse momentum, emission angle, rapidity, and corresponding distributions have been obtained. Experimental results have been compared with predictions of Quark-Gluon String Model. Mg-Mg interactions have been generated using Monte-Carlo generator COLLI, which is based on the QGSM. Events had been traced through the detector and trigger filter. Events had been generated for not fixed impact parameter $b$. From the impact parameter distribution we obtained the mean value of $< b > = 1.34$ fm. For the obtained value of $< b >$, we have generated a total sample of 6200 events. The results obtained by the model in two regimes (for $b=1.34$ fm) are consistent and it seems, that in our experiment the value of $b=1.34$ fm for Mg-Mg is most probable. From the analysis of generated events the pions with deep angles greater than 60° had been excluded, because efficiency of registration of such vertical tracks in the experiment is low. Comparison of $n_-$, $P$, $\Theta$, $P_T$ and $Y$ distributions allows to conclude, that the QGSM satisfactorily describes the spectra and experimental and model values of average kinematical characteristics coincide within the errors.

Two Lorenz invariant variables have been used to describe the main features of the $\pi^-$ mesons, produced in nucleus-nucleus collisions: the rapidity $Y$ and the transverse momentum $P_T$. For this purpose we investigated rapidity distributions in various regions of $P_T$: $P_T \leq 0.2$, $0.2 \leq P_T < 0.3$, $0.3 \leq P_T < 0.5$, $P_T \geq 0.5$. These distributions have the characteristic Gaussian form. Shape of $Y$ distributions changes with increase of the transverse momentum of $\pi^-$ mesons: the fraction of pions increases in the central region and decreases in fragmentational regions of colliding nuclei. Analysis of $Y$ distributions shows, that the central regions of these distributions are enriched with pions of large transverse momentum (as compared to fragmentational regions of colliding nuclei): $<P_T> = 0.184 \pm 0.004$ GeV/c for $Y < 0.2$, $<P_T> = 0.247 \pm 0.002$ GeV/c for...
0.7 ≤ \(y\) ≤ 1.6, \(\langle p_T\rangle = 0.189 \pm 0.003\) GeV/c for \(y > 2\). The QGSM reproduces the \(y\) distributions in the various regions of \(p_T\) quite well. Practically all theoretical models are based on the dependence of average kinematical characteristics on thicknesses of colliding nuclear layers. For the fixed \(A_T\) the thickness of nuclear matter is connected with the impact parameter \(b\). It is, therefore, desirable to study the dependence of kinematical characteristics of pions on the impact parameter and on mass numbers of colliding nuclei (\(A_P, A_T\)). As \(b\) is experimentally unmeasurable, its estimation can be obtained on the basis of the number of nucleons of the projectile participating in the interaction \(\nu_p\), which in turn is correlated with the multiplicity of observed \(\pi^-\) mesons \(n_-\). Therefore, the study of dependence of a given variable (\(p_T, y\), etc) on \(b\) can be qualitatively replaced by the study of the dependence of the same variable on \(n_-/A_P\). The variable \(n_-/A_P\) serves as the measure of the impact parameter at fixed \(A_T\). The Quark Gluon String model allows us to obtain the distribution of the impact parameter \(b\) for any given trigger mode and any \(n_-/A_P\) values. From the QGSM data of Mg-Mg collisions, it has been obtained, that the average impact parameter is strongly correlated with \(n_-/A_P\). Thus any observed dependence on the trigger mode or \(n_-/A_P\) can be translated into a dependence on the \(<b>\) value. Therefore, in a qualitative analysis one can investigate the dependence of kinematical characteristics on \(n_-/A_P\). A quantitative analysis of the shape of \(p_T\) and \(Y\) distributions have been carried out based on a study of the statistical moments of the distributions, namely the average values (\(\langle p_T \rangle\) and \(\langle Y \rangle\)) and the dispersions (\(D_{p_T}, D_{Y}\)). It has been shown, that in Mg-Mg collisions \(\langle Y \rangle\) does not depend on the multiplicity of pions, meanwhile \(\langle p_T \rangle\) slightly decreases with multiplicity. These average kinematical characteristics are similar to the characteristics of N-N collisions at the same energy. Obtained results for Mg-Mg interactions agree with our previous results for symmetric and approximately symmetric pairs of nuclei C-C, C-Ne, O-Ne, Ne-Ne. The QGSM reproduces the dependence of \(\langle Y \rangle\) and \(\langle p_T \rangle\) on \(n_-\) for Mg-Mg interactions.

Analysis of angular distributions of \(\pi^-\) mesons in He-Li, He-C, C-Ne, C-Cu, C-Pb, O-Pb and Mg-Mg collisions is presented in Chapter 3. The anisotropy coefficient \(a\) has been obtained from the \(\cos\Theta^*\) distributions of \(\pi^-\) mesons in c.m.s, approximating them by the ansatz:

\[
dN/d\cos\Theta^* = \text{const}(1 + acos^2\Theta^*)
\]

It has been shown, that the parameter \(a\) is similar for the symmetric (or approximately symmetric, \(A_P \sim A_T\)) system of nuclei (He-Li and Mg- Mg) and increases slowly with \(A_P\) and \(A_T\) for other pairs of nuclei. The dependence of \(a\) on kinetic energy in c.m.s \(E_{\text{kin}}^*\) and multiplicity of pions \(n_-\) has been studied. It has been shown, that the anisotropy coefficient increases linearly with \(E^*/E_{\text{max}}^*\) for all pairs of nuclei. In the range of 100 MeV pions are emitted isotropically. Dependence of the dispersion \(D_{\cos\Theta^*}\) on \(E^*/E_{\text{max}}^*\) is similar to the dependence of the coefficient \(a\) on \(E^*/E_{\text{max}}^*\). Increase of the dispersion \(D_{\cos\Theta^*}\) with \(E^*/E_{\text{max}}^*\) is well reproduced by the DICM. At small multiplicities of pions (\(n_- \leq \langle n_-\rangle\)), the degree of anisotropy is larger, than at high multiplicities (\(n_- > \langle n_-\rangle\)). Decrease of the parameter \(a\) for more central events (\(n_- > \langle n_-\rangle\)) indicates, that the angular distributions of pions become more isotropic for more central collisions (small impact parameters). The QGSM reproduces the angular distributions of pions well enough and the values of the anisotropy coefficient \(a\), extracted from the spectra generated by QGSM, agree with the experimental ones within the errors.

Chapter 4 is devoted to the analysis of the proton and \(\pi^-\) meson inclusive kinetic energy \(E_K\) and transverse momentum \(p_T\) spectra in central interactions of He, C and Mg nuclei with Li, C, Ne, Mg, Cu and Pb nuclei with the aim to determine their temperatures. One of the main
topics of the current relativistic heavy ion experiments is the determination of the properties of nuclear matter at high densities and temperatures. Such canonical parameters of the equation of state of nuclear matter (EOS), as temperature, density, pressure may be experimentally deduced from the system decay products alone. To obtain the temperature of secondary hadrons in the experiment one usually estimates the value of the inclusive spectrum slope.

Characteristics of the protons in central He-Li, He-C, C-C, C-Ne, C-Cu and C-Pb collisions have been studied. For this purpose, the identification of protons have been carried out in central C-Ne and C-Cu collisions. The statistical method of identification utilized in the neural nets method and based on the similarity of $\pi^-$ and $\pi^+$ mesons spectra have been used in order to separate $\pi^+$ mesons from protons. The admixture of $\pi^+$ mesons amongst the positive charged particles is about (25-27)%. After identification the admixture of $\pi^+$ mesons have been reduced to (5-7)%.

Temperatures of protons in He-Li, He-C, C-C, C-Ne, C-Cu and C-Pb central collisions have been determined. The proton and pion temperatures has been estimated by means of: 1) inclusive kinetic energy $E_K$ spectra and 2) transverse momentum $P_T$ spectra.

Non-invariant inclusive spectra $d^3\sigma/dp^3 = (E^*P^*)^{-1}dN/dE_K$ ($P^*$ is the momentum, $E^*$ the total energy and $E_K$ the kinetic energy of the particle in the c.m.s.) have been analysed. A simple exponential law was used to fit each experimental spectrum:

$$F(E_K) = (E^*P^*)^{-1}dN/dE_K = A \cdot \exp(-E_K/T)$$  \hspace{1cm} (5)$$

$T$ is related to average kinetic energy of a given type of particles and, thus, characterizes the nuclear matter temperature at that expansion stage, when such particles are emitted. Therefore, the $T$ parameter is usually called an average or inclusive temperature. It has been state, that transverse momentum distributions are preferable because of their Lorenz invariance during longitudinal boosts. Transverse momentum distributions were described by the following form:

$$dN/dP_T = \text{const} \cdot P_T \cdot E_T \cdot K_1(E_T/T) \simeq \text{const} \cdot P_T \cdot (T E_T)^{1/2} \cdot \exp(E_T/T)$$ \hspace{1cm} (6)$$

$$E_T = (P_T^2 + m^2)^{1/2}$$ \hspace{1cm} (7)$$

$K_1(X)$ is Mac-Donald’s function.

Temperatures has been determined from the noninvariant kinetic energy ($E_K$) and transverse momentum distributions of protons in the rapidity region of $0.4 \leq Y \leq 1.6$ for He-Li, He-C, C-C and C-Ne collisions and $0.3 \leq Y \leq 1.7$ for C-Cu and C-Pb. Proton temperatures $T_p$ increase with atomic numbers of projectile ($A_P$) and target ($A_T$) from $T_p = (118 \pm 2)$ MeV for He-Li to $T_p = (141 \pm 2)$ MeV for C-Pb. Results obtained from the experimental data have been compared
with the QGSM predictions. The QGSM slightly overestimates proton temperature for He-Li and for other pairs of nuclei gives values consistent with the experiment. The QGSM data show also the similar tendency for $T_p$ to increase with the mass numbers of projectile ($A_P$) and target ($A_T$) as experimental ones. Hagedorn thermodynamical model at our energy predicts proton temperatures $T_p = (135 \pm 138)$ MeV. From our results only proton temperatures in C-Ne ($131 \pm 1$ MeV), C-Cu ($135 \pm 2$ MeV) and C-Pb ($141 \pm 4$ MeV) collisions agree with the model predictions. The dependence of $T_p$ on the bombarding energy $E_{lab}$ for different pairs of nuclei from a series of experiments of Bevalac (LBL), GSI/SIS, Dubna (including our results), AGS and CERN/SPS has been studied.

Temperatures of $\pi^-$ mesons has been determined from the noninvariant kinetic energy ($E_K$) and transverse momentum distributions in the rapidity region of $0.5 \leq Y \leq 2.1$ for light nuclei pairs of He-Li, He-C and C-Ne. A single exponential fit describes the pion spectra and $T_{\pi^-}$ does not depend on $A_P$, $A_T$. The $T_{\pi^-}$ deduced from energy spectra is equal to $T_{\pi^-} \simeq 87$ MeV and from transverse momentum spectra to $T_{\pi^-} \approx 92$ MeV. Results obtained from the experimental data have been compared with the QGSM data. Distributions of QGSM data satisfactorily describe the experimental spectra and the QGSM gives consistent with experiment values of pion temperatures for He-Li, He-C and C-Ne. The pion experimental spectra in medium and heavy nuclei Mg-Mg, C-Cu, C-Pb (Fig. 2) and O-Pb show a concave shape which can not be described by single exponential law and a sum of two exponentials should be used to reproduce the data (with two temperatures $T_1$ and $T_2$). We have estimated the fraction $R_2$ of the pion yield that falls in the second exponent, determined by $T_2$. Values of $R_2$ are equal to: $R_2 = 0.12 \pm 0.03$ for O-Pb , $R_2 = 0.22 \pm 0.02$ for Mg-Mg, $R_2 = 0.24 \pm 0.02$ for C-Pb and $R_2 = 0.25 \pm 0.02$ for C-Cu. The QGSM reproduces the spectra of C-Cu, C-Pb and Mg-Mg interactions and the values of temperatures coincide with the experimental ones, only for Mg-Mg the value of $T_2$ is slightly underestimated. At our energy, the Hagedorn model predicts only one temperature $T_{\pi^-} = (115 \div 120)$ MeV, which agrees within the errors with our values of $T_2$. For C-Ne and C-Cu interactions the temperatures of identified $\pi^+$ mesons have been determined. One temperature have been observed in C-Ne and two temperatures in C-Cu collisions, similarly as for the $\pi^-$ mesons.

The concave shape of pion energy and transverse momentum spectra in central heavy ion collisions has been observed in many different experiments starting from Berkley and GSI energies up to AGS and CERN/SPS energies. This phenomena has been observed: in Ar-KCl collisions at a beam energy of 1.8 GeV/nucleon, La-La at E=1.53 GeV/nucleon and Au-Au at E=1.15 GeV/nucleon at Berkeley, in Au-Au and Ni-Ni collisions at E=1\div2 GeV/nucleon at GSI by FOPI collaboration at midrapidity (-0.1< $y^0$<0, where $y^0$=$y/y_{cm}$-1), in C-C and C-Ta collisions at E=3.4 GeV/nucleon at Dubna by Propane Bubble Chamber collaboration, in Au-Au collisions at E=10\div14 GeV/nucleon at AGS by E877, E866 collaborations. In ultrarelativistic heavy ion collisions the pion transverse momentum spectra also show a concave shape. Several hypothesis have been proposed in order to explain the concave shape of the spectra. These include the superposition of thermal pions and pions from the final-state $\Delta$ decays, higher resonances and the effect of baryons flow on the pions. Based on an equilibrium model calculations, it was also supposed, that the concave shape of the pion spectra may come from an isotropic hydrodynamical expansion of the hot compressed nuclear matter. The experimentally observed concave shape of the pion spectra is well reproduced within the framework of a hadronic transport model of B.A Li and W. Bauer. This model is based on solutions of a set of coupled transport equations for the phase-space distribution functions of nucleons, baryon
resonances ($\Delta$, $N^*$), and pions.

Dependence of the $T_{\pi^-}$ on emission angle in c.m. system $\Theta_{cm}$ have been studied in He-Li, He-C and C-Ne collisions. The $T_{\pi^-}$ falls off from $T_{\pi^-} \simeq 110$ MeV at $\Theta_{cm} = 30^0$ to $T_{\pi^-} \simeq 90$ MeV at $\Theta_{cm} = 90^0$ and then increases. The QGSM reproduces this dependence. Similar dependence have been obtained for Ar-KCl collisions at energy of $E = 1.8$ GeV/nucleon. Such behaviour have been interpreted as the effect of direct "corona" production of $\Delta$'s where the $\Delta$ escapes without further rescattering and subsequently decays into $N\pi$. This mechanism enhances the forward/backward yield of pions. The rapidity dependence of the $T_{\pi^-}$ shows a bell-shaped behaviour with the maximum at $Y = Y_{beam}/2$. The dependence on the rapidity is more evident for $T_2$ than for $T_1$ in Mg-Mg and C-Cu collisions. The QGSM reproduces the experimental results. Similar result have been observed for d-Ta, He-Ta, C-Ta inelastic collisions at energy of $3.4$ GeV/nucleon by the Propane Bubble Chamber collaboration of JINR and by FOPI collaboration at GSI in Ni-Ni collisions at $E = 1 \div 2$ GeV/nucleon.

The pion energy spectra are quite different from the corresponding proton spectra. The pion spectra exhibit the concave shape, whereas the proton spectra are convex shaped. This difference was first interpreted as due to the different source sizes at freeze-out time, later it was realized that pions mainly originate from the decay of the $\Delta$ resonance, and that their spectral shape is strongly influenced by the decay kinematics.

A correlation of pion kinematical characteristics with $\Lambda$'s momentum in the nucleon-nucleon (N-N) c.m. system was investigated in Mg-Mg collisions. Events with a $\Lambda$ produced within ($\Lambda^{in}$ events) and beyond ($\Lambda^{out}$ events) the N-N c.m. kinematical limits for nucleon-nucleon collisions were considered. Kinematical characteristics and temperatures of pions from $\Lambda^{in}$ and $\Lambda^{out}$ events do not reveal any significant difference when compared between and with corresponding characteristics and temperatures of pions produced in ordinary central Mg-Mg collisions. The QGSM reproduces the experimental results and reveal similar to experimental data trend.

In Chapter 5 the light front variables $\zeta^\pm$ and $\xi^\pm$, which define the so called horospherical coordinate system in the Lobachevsky space, have been used to study inclusive spectra of $\pi^-$ mesons in He(Li,C), C-Ne, C-Cu, Mg-Mg and O-Pb collisions. An important role in establishing of many properties of multiple particle production plays the choice of kinematic variables in terms of which observable quantities are presented. The variables which are commonly used are the following: the Feynman $x_F = 2p_z/\sqrt{s}$, rapidity $y = 1/2\ln[(E + p_z)/(E - p_z)]$, transverse scaling variable $x_T = 2p_T/\sqrt{s}$, etc. Unified scale invariant variables $\xi^\pm$ for the presentation of single particle inclusive distributions have been proposed, which are defined in the centre of mass frame as follows:

$$
\xi^\pm = \pm \frac{E \pm p_z}{\sqrt{s}} = \pm \frac{E \pm |p_z|}{\sqrt{s}}
$$

where $s$ is the usual Mandelstam variable, $E = \sqrt{p_z^2 + p_T^2 + m^2}$ and $p_z$ are the energy and the $z$-component of the momentum of produced particle. The upper sign in Eq. (8) is used for the right hand side hemisphere and the lower sign for the left hand side hemisphere. In order to enlarge the scale in the region of small $\xi^\pm$, it is convenient also to introduce the variables

$$
\zeta^\pm = \mp \ln|\xi^\pm|
$$

In the limits of high $p_z$ ($|p_z| \gg p_T$) and high $p_T$ ($p_T \gg |p_z|$) the $\xi^\pm$ variables go over to the well known variables $x_F$ and $x_T$. The principal differences of $\xi^\pm$ distributions as compared to
the corresponding $x_F$-distributions are the following: (1) existence of some forbidden region around the point $\xi^\pm=0$; (2) existence of maxima at some $\xi^\pm$ in the region of relatively small $|\xi^\pm|$. 3) existence of the limits for $|\xi^\pm| \leq m/\sqrt{\sigma}$. The maxima at $\tilde{\xi}^\pm$ are also observed in the invariant distributions $(1/\pi) \cdot dN/d\xi^\pm$ (Fig. 3). However, the region $|\xi^\pm| > |\tilde{\xi}^\pm|$ goes over to the region $|\xi^\pm| < |\tilde{\xi}^\pm|$ and vice versa (see Eqs. (8) and (9)). The value of maxima are observed at $\tilde{\xi}^\pm = 2.0 \pm 0.1$ for all pairs of nuclei. The $\tilde{\xi}^\pm$ is the function of the energy (see Eqs. (8), (9)) and does not depend on the mass numbers of the projectile ($A_P$) and target ($A_T$).

In order to study the nature of these maxima we have divided the phase space into two regions $|\xi^\pm| > |\tilde{\xi}^\pm|$ and $|\xi^\pm| < |\tilde{\xi}^\pm|$ and studied the $p_T^2$ and the angular distributions of $\pi^-$ mesons in these regions separately. The numbers of pions in these two regions are approximately equal. For example in C-Cu interactions in the region $|\xi^\pm| > |\tilde{\xi}^\pm|$ the number of pions is equal to $-1987$ and in $|\xi^\pm| < |\tilde{\xi}^\pm| - 2212$. The $p_T^2$ and the angular distributions of $\pi^-$ mesons differ significantly in $\xi^+ > \tilde{\xi}^+$ and $\xi^- > \tilde{\xi}^-$ regions. The angular distribution of pions in the region $\xi^- < \tilde{\xi}^+$ (Fig. 4) is sharply anisotropic in contrast to the almost flat distribution in the region $\xi^+ > \tilde{\xi}^+$ (Fig. 4). The flat behaviour of the angular distribution allows one to think that one observes a partial thermal equilibrium in the region $|\xi^\pm| > |\tilde{\xi}^\pm|$ ($|\xi^\pm| < |\tilde{\xi}^\pm|$) of phase space. The slopes of $p_T^2$-distributions differ greatly in different regions of $\xi^\pm$. For example in Mg-Mg interactions: $< p_T^2 > = (0.027 \pm 0.002)$ (GeV/c)$^2$ in the region $\xi^+ > \tilde{\xi}^+$; $< p_T^2 > = (0.103 \pm 0.009)$ (GeV/c)$^2$ in the region $\xi^- < \tilde{\xi}^-$. Thus the values of $\xi^\pm$ are the boundaries of the two regions with significantly different characteristics of $\pi^-$ mesons. To describe the spectra in the region $\xi^+ > \tilde{\xi}^+$ the Boltzmann

$$f(E) \sim e^{-E/T}$$

distribution has been used. The distributions $1/\pi \cdot dN/d\xi^+,$ $dN/dp_T^2$, $dN/d\cos\Theta$ have been fitted by Boltzmann distribution in the region $\xi^+ > \tilde{\xi}^+$ and the parameter $T$ is obtained by fitting the data. In order to determine how the characteristics vary the analysis has been carried out also for $\tilde{\xi}^+=1.9$ and 2.1. The results are similar, but the joint fit of the distributions is better for $\tilde{\xi}^+=2.0$ (presented on Fig. 4).

The spectra of $\pi^-$ mesons in the region $\xi^+ > \tilde{\xi}^+$ are satisfactorily described by the formulae which follow from the thermal equilibration. The same formulae when extrapolated to the region $\xi^+ < \tilde{\xi}^+$ deviate significantly from the data. Therefore in the region $\xi^+ < \tilde{\xi}^+$ the $p_T^2$-distributions has been fitted by the formula

$$\frac{dN}{dp_T^2} \sim \alpha \cdot e^{-\beta_1 p_T^2} + (1 - \alpha) \cdot e^{-\beta_2 p_T^2}, \quad (10)$$

and the $\xi^+$-distributions by the formula

$$\frac{1}{\pi} \cdot \frac{dN}{d\xi^+} \sim (1 - \xi^+)^n = (1 - e^{-|\xi^+|})^n \quad (11)$$

which is an analogue of the $(1 - x_F)^n$ dependence - the result of the well-known quark-parton model consideration, which for $\pi^-$ mesons gives the value $n=3$. The dependence $(1 - e^{-|\xi^+|})^n$ is in good agreement with experiment in the region $\xi^+ < \tilde{\xi}^+$ and deviates from it in the region $\xi^+ > \tilde{\xi}^+$. Thus in the $\xi^+ (\xi^-)$ distributions we have singled out points $\tilde{\xi}^+ (\tilde{\xi}^-)$ which separate in the phase space two groups of particles with significantly different characteristics. There are no such points in the $x_F$ and $y$-distributions. The dependence of $T$ on $(A_P A_T)^{1/2}$ has been studied.
It has been obtained that temperature decreases with the increasing of \((A_P \ast A_T)^{1/2}\) i.e. with increasing number of participating nucleons. The experimental results have been compared with the predictions of QGSM. The QGSM satisfactorily reproduces the experimental data for light and intermediate-mass nuclei.

The similar analysis of \(\pi^-\) meson spectra produced in p-C, He-C, C-C and C-Ta interactions at a momentum of 4.2 GeV/c/nucleon in the 2-metre Propane Bubble Chamber of JINR (Dubna) has been carried out in light-front variables. The results obtained by Propane collaboration coincide with ours.

Chapter 6 is devoted to the study of collective flow effects of protons and \(\pi^-\) mesons in central C-Ne and C-Cu interactions at a momentum of 4.5 GeV/c/nucleon \((E=3.7\) GeV/nucleon\). Two different signatures of collective flow have been predicted: a) the bounce off of compressed matter in the reaction plane (a sideways deflection of the spectator fragments - "bounce off"), as well as the directed flow of nucleons from the overlap region between the colliding nuclei (participants) in the reaction plane - "side splash"), called the sideward (also often termed directed) flow. b) the squeeze-out of the participant matter out of the reaction plane – the elliptic flow. Collective effects lead to characteristic, azimuthally asymmetric sideward emission of the reaction products. While the transverse flow in the reaction plane is influenced by the cold matter deflected by the overlap region of the colliding nuclei, the squeeze out is caused by the hot and compressed matter from the interaction region which preferentially escapes in the direction perpendicular to the reaction plane unhindered by the presence of the projectile and target spectators. A strong dependence of these collective effects on the nuclear equation of state (EOS) was predicted. Due to its direct dependence on the EOS, \(P(\rho, S)\), flow excitation functions can provide unique information about phase transitions: the formation of abnormal nuclear matter, e.g. yields a reduction of the collective flow. A directed flow excitation function as signature of the phase transition into Quark Gluon Plasma (QGP) has been proposed by several authors. The knowledge of EOS is of fundamental interest and is also essential for understanding of astrophysical phenomena such as the supernova explosions, the properties of the core of compact stars (neutron stars), the evolution of the early Universe and the formation of elements in stellar nucleosynthesis.

Many different methods were proposed for the study of flow effects in relativistic nuclear collisions, of which the most commonly used are the transverse momentum analysis technique developed by P.Danielewicz and G.Odyniec and Fourier analysis of the azimuthal distributions on the event-by-event basis in relatively narrow rapidity windows proposed by M.Demoulins, S.Voloshin and Y.Zhang. We have used the technique of P. Danielewicz and G. Odyniec in our analysis. The method involves two basic ideas: 1) to select the rapidity range and rapidity dependent waiting factors in the center of mass system, which provide the reaction plane closest to the real reaction plane, and 2) to remove trivial and spurious self-correlations from the projections. The reaction plane is defined by the transverse vector \(\vec{Q}\)

\[
\vec{Q}_j = \sum_{i \neq j}^n \omega_i \vec{P}_{\perp i}
\]

where \(i\) is a particle index and \(\omega_i\) is a weight. Pions are not included. The reaction plane is the plane containing \(\vec{Q}\) and the beam axis. The weight factor \(\omega_i\), depends on the rapidity of the emitted particle \(i\), so that the central rapidity region, where the particle emission is azimuthally symmetric, is omitted, and the forward and backward rapidity regions get weight with opposite signs: \(\omega_i\) is taken as 1 for \(y_i > y_c\), -1 for \(y_i < y_c\) and \(\omega_i = 0\) for \(-y_c < y_i < y_c\).
where the cutoff rapidity $y_c$ is usually chosen to be $y_c \approx 0.3y^{beam}$; $y_i$ is the rapidity of particle $i$. This choice leads to the result that the forward and backward moving particles, which are azimuthally anticorrelated if there is a collective transverse flow, will contribute equally to $\vec{Q}$. Autocorrelations are removed by calculating $\vec{Q}$ individually for each particle without including that particle into sum.

The transverse momentum of each particle in the estimated reaction plane is calculated as:

$$P_{xj'} = \frac{\sum_{i \neq j} \omega_i \cdot (\vec{P}_{ij} \cdot \vec{P}_{ii})}{|\vec{Q}_j|}$$  \hspace{1cm} (13)

The reaction plane have been defined for the participant protons i.e. protons which are not fragments of the projectile ($P/Z > 3$ GeV/c, $\Theta < 40^\circ$) and target ($P/Z < 0.2$ GeV/c). They represent the protons participating in the collision. As we study an asymmetric pair of nuclei, we chose to bypass the difficulties associated with the center-of-mass determination and carried out the analysis in the laboratory frame. The original weight $\omega_i$ have been replaced by the continuous function $\omega_i = y_i - <y>$ as in papers of Bevalac streamer chamber collaboration, where $<y>$ is the average rapidity, calculated for each event over all the participant protons. The value of the weight $\omega_i$ should be chosen to minimize the fluctuations of $\vec{Q}_j$ from the true reaction plane.

It is known, that the estimated reaction plane differs from the true one, in particular, due to the finite multiplicity. The component $P_x$ in the true reaction plane is systematically larger then the component $P_x'$ in the estimated plane. The correction factor $k$ is equal to $k_{corr}=1 / <\cos\Delta\phi>$, where $\phi$ is the angle between the estimated and true planes. $k$ is subject to a large uncertainty, especially for low multiplicity. According to the method of Danielewicz, for the definition of $<\cos\Delta\phi>$ we divided randomly each event into two equal sub-events, constructed vectors $\vec{Q}_1$ and $\vec{Q}_2$ and estimated the azimuth angle difference $\phi_{12}$ between these two vectors. $<\cos\Delta\phi> = <\cos\phi_{12}>$. The data did not allow to perform the analysis for different multiplicity intervals, therefore we defined the correction factors $k_{corr}$, averaged over all the multiplicities. The values of $k_{corr}$ are: $k_{corr}=1.27\pm0.08$ for C-Ne and $k_{corr}=1.31\pm0.04$ for C-Cu. For the estimation of $<\cos\Delta\phi>$ the alternative method have been applied also, which does not require the division of each event into two sub-classes.

$$<\cos\Delta\phi> \approx <\omega P_{x'} > [<W^2 - W > / <Q^2 - \sum(\omega_i P_{ii})^2>]^{1/2}$$  \hspace{1cm} (14)

where $W=\sum |\omega_i|$. These two methods yield consistent results within the errors. Fig. 5 shows the dependence of the estimated $<P_{x'}(Y)>$ on $Y$ for protons in C-Ne collisions. The average transverse momentum $<P_{x'}(Y)>$ is obtained by averaging over all events in the corresponding intervals of rapidity. The data exhibit the typical $S$-shape behaviour which demonstrates the collective transverse momentum transfer between the forward and backward hemispheres. The directed flow is an odd function of the rapidity. It is therefore linear near mid-rapidity. Furthermore, a saturation is observed near projectile and target rapidities, resulting in a typical $S$-shape.

From the mean transverse momentum distributions one can extract two main observables sensitive to the EOS. One of them is the mean transverse momentum averaged for positive values of rapidity $<P_x>_{y>0}$. A somehow equivalent observable is the transverse flow $F = \frac{d<P_x>}{dy}$, i.e. the slope of the momentum distribution at midrapidity. It is a measure of the amount of collective transverse momentum transfer in the reaction i.e. intensity of the nuclear interactions.
Technically $F$ is obtained by fitting the central part of the dependence of $<P_x'(Y)>$ on $Y$ with a sum of first and third order polynomial function. The coefficient of the first order term is the flow $F$. The fit was done for $Y$ between $0.4 \div 1.9$ for C-Ne and $0.2 \div 2$ for C-Cu. The straight line in Fig. 5 shows the result of this fit for the experimental data in C-Ne. The values of $F$ corrected by $k_{corr}$ are: $F=134\pm12$ (MeV/c) for C-Ne and $F=198\pm13$ (MeV/c) for C-Cu. The influence of the admixture of ambiguously identified $\pi^+$ mesons on the results have been analysed. The error in flow $F$ includes the statistical and systematical errors. The $F$ increases with atomic number of target $A_T$, which indicates on the rise of collective directed flow effect. The Quark Gluon String Model (QGSM) was used for a comparison with our experimental data. In the generator COLLII which is based on the QGSM, there are two possibilities to generate events: 1) at not fixed impact parameter $\tilde{b}$ and 2) at fixed $b$. The experimental and QGSM results coincide within the errors. For generated events the component in the true reaction plane $P_x$ had been calculated. In the model calculations the reaction plane is known a priori and is referred as the true reaction plane. The dependences of $<P_x(Y)>$ on $Y$ for not fixed impact parameter $\tilde{b}$ and at fixed $b=2.20$ fm. are shown on Fig. 5. For the visual presentation, we approximated these dependences by polynomials (the curves on Fig. 5). From the comparison of the dependences of $<P_x(Y)>$ on $Y$ obtained by the model in two regimes - for fixed and not fixed $\tilde{b}$, we conclude, that the results are consistent and it seems, that in our experiment the values of $b=2.20$ fm for C-Ne, $b=2.75$ fm for C-Cu are probable. The QGSM yields a significant flow signature, which follows trends similar to the experimental data. To be convinced, that the significant sidewards deflection in Fig. 5 (for both experiment and QGSM) is due to correlations within the events, and can not be the result of detector biases or finite-multiplicity effects, the $<P_x(Y)>$ on $Y$ has been obtained for events composed by randomly selecting tracks from different QGSM events (within the same multiplicity range) (Fig. 5). One can see from Fig. 5, that in these events there is no correlation with reaction plane. The values of $F$, obtained from the QGSM are $F=95\pm9$ (MeV/c) for C-Ne and $F=153\pm13$ (MeV/c) for C-Cu. The QGSM slightly underestimates the flow at our energies and predicts the increase of $F$ with atomic number of target $A_T$.

The comparison of our flow results for protons with flow data for various projectile/target configurations at GSI-SIS, AGS and SPS-CERN energies was made using the scaled flow $F_s = F/(A_{p}^{1/3} + A_{T}^{1/3})$. $F_s$ demonstrates a common scaling behaviour for flow values from different systems over all available energy region of $0.2 \div 200.0$ GeV/nucleon.

We have obtained also the mean transverse momentum per nucleon in the reaction plane in the forward hemisphere of the c.m. system $<P_x>_y>0$. The corrected (multiplied on $k_{corr}$ factor) values of $<P_x>_y>0$ are: $<P_x>_y=97\pm11$ (MeV/c) for C-Ne and $<P_x>_y=145\pm18$ (MeV/c) for C-Cu. The dependence of $<P_x>_y>0$ on beam energy and target/projectile mass was studied. Our results have been compared to the results on central Ar-KCl, Ar-BaI$_2$, Ca-Ca, Nb-Nb, Ar-Pb collisions from the Plastic Ball, Diogene and BEVALAC streamer chamber groups. The $<P_x>_y>0$ rises monotonically with $E_{beam}$, irrespective of the projectile/target configurations.

In view of the strong coupling between the nucleon and pion, it is interesting to know if pions also have a collective flow behaviour and how the pion flow is related to the nucleon flow. We have studied the flow effects of $\pi^-$ mesons. For this purpose the reaction plane was defined for the participant protons and the transverse momentum of each $\pi^-$ meson was projected onto this reaction plane. The data exhibit the typical S-shape behaviour as for the protons. The values of flow $F$ for $\pi^-$ mesons are: for C-Ne collisions $F = 29 \pm 5$ MeV; C-Cu $-F = -47 \pm 6$ MeV.
In C-Ne interactions the directed (sideward) flow of $\pi^-$ mesons is in the same direction as that of the protons, while in C-Cu collisions pions show the antiflow behaviour. The anticorrelation of nucleons and pions was explained by S.Bass et al. as due to multiple $\pi N$ scattering. However B.A. Li et al. show, that anticorrelation is a manifestation of the nuclear shadowing effect of the target and projectile spectators through both pion rescattering and reabsorptions. In our opinion, our results indicate that the flow behaviour of $\pi^-$ mesons in a light system C-Ne is due to the flow of $\Delta$ resonances, whereas the antiflow behaviour in a heavier C-Cu system is the result of the nuclear shadowing effect.

The preferential emission of particles in the direction perpendicular to the reaction plane (i.e. "squeeze-out") is particularly interesting since it is the only way the nuclear matter might escape without being rescattered by spectator remnants of the projectile and the target, and is expected to provide direct information on the hot and dense participant region formed in high energy nucleus-nucleus interactions. This phenomenon was predicted by hydrodynamical calculations, and first has been confirmed for charged particles by the Plastic Ball collaboration. Then this effect was clearly identified in the experiments at GSI set-ups KAOS, TAPS, FOPI, KAON, LAND and DIOGENE group at SATURNE by the observation of an enhanced out-of-plane emission of protons, neutrons, mesons and charged fragments.

In order to extend these investigations, the azimuthal angular distributions ($\phi$) of the protons and pions in C-Ne and C-Cu collisions have been studied. The angle $\phi$ is the angle of the transverse momentum of each particle in an event with respect to the reaction plane ($\cos \phi = P_x/P_t$). The analysis was restricted only to the mid-rapidity region by applying a cut around the center-of-mass rapidity. Fig. 6 shows distributions for protons in C-Ne and C-Cu collisions. For visual presentation the data of C-Cu were shifted upwards. For $\pi^-$ mesons the analysis was performed from 0 to 180° due to lower statistics than for protons. The azimuthal angular distributions for the protons and pions show maxima at $\phi = 90^0$ and $270^0$ with respect to the event plane. These maxima are associated with preferential particle emission perpendicular to the reaction plane (squeeze-out, or elliptic flow). Thus a clear signature of an out-of-plane signal is evidenced. The QGSM yields also a signature of the elliptic (squeeze-out) flow effects in C-Ne and C-Cu collisions for protons. Azimuthal distributions have been parametrized by a second order polynomial function:

$$\frac{dN}{d\phi} = a_0(1 + a_1 \cos \phi + a_2 \cos 2\phi)$$

(15)

the parameter $a_2$ of the anisotropy term $a_2 \cos 2\phi$ have been extracted. The anisotropy factor $a_2$ is negative for out-of-plane enhancement (squeeze-out) and is the measure of the strength of the anisotropic emission. The ratio $R$ of the number of particles emitted in the perpendicular direction to the number of particles emitted in the reaction plane, which represents the magnitude of the out-of-plane emission signal $R = (1 - a_2)/(1 + a_2)$ was also calculated. A ratio $R$ larger than unity implies a preferred out-of-plane emission. The $a_2$ and $R$ are increasing for both protons and $\pi^-$ mesons, with increasing the transverse momentum and the mass number of target $A_T$ and also with narrowing of the cut applied around the center of mass rapidity. The elliptic flow is more pronounced for protons than for $\pi^-$ mesons. Our results on rapidity, mass and transverse momentum dependence of the azimuthal anisotropy are consistent with analysis from Plastic Ball, FOPI in Ni-Ni, Xe-CsI, Au-Au collisions from 0.15 to 1.0 GeV/nucleon for protons, light fragments and $\pi^\pm$ mesons; KAOS in Au-Au at 1.0 GeV/nucleon for protons, light fragments, pions and kaons; KAON in Bi-Bi collisions at 0.4, 0.7 and 1.0 GeV/nucleon for $\pi^\pm$. 

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mesons; TAPS collaboration in Au-Au collisions at 1.0 GeV/nucleon for $\pi^0$ mesons and are confirmed by Isospin Quantum Molecular Dynamics model calculations.

The squeeze-out of nucleons perpendicular to the reaction plane is due to the high compression of nuclear matter in the central hot and dense reaction zone (it is genuinely collective effect, increasing linearly with $A$). Since the $\Delta$ resonances are expected to flow with the nucleons a similar anisotropy effects could be exhibited by their decay products, the pions. According to the microscopic transport model BUU, the mechanism of the azimuthal anisotropy of pions is found to be the shadowing effect of the spectator matter through both pion reabsorptions and rescatterings.

In experiments at AGS and at CERN SPS the elliptic flow is typically studied at midrapidity and is quantified in terms of the second Fourier coefficient $v_2 = <\cos 2\phi>$, which is related to $a_2$ via $v_2 = a_2/2$ and measures the elliptic flow. We have estimated $v_2$ both for C-Ne and C-Cu. The obtained results of the elliptic flow excitation function for protons in C-Ne and C-Cu collisions has been compared with the data in the available energy region of $0.2 \div 200.0$ GeV/nucleon. The dependence of the elliptic flow excitation function (for protons) on energy $E_{lab}$ is displayed in Fig. 7. The excitation function $v_2$ clearly shows an evolution from negative ($v_2 < 0$) to positive ($v_2 > 0$) elliptic flow within the region of $2.0 \leq E_{beam} \leq 8.0$ GeV/nucleon i.e. the transition from out of plane enhancement to preferential in-plane emission (Fig. 7) and point to an apparent transition energy $E_{tr} \sim 4$ GeV/nucleon. The elliptic flow at AGS for Au-Au (E895 at 6.0, 8.0 GeV/nucleon and E877 at 10.8 GeV/nucleon) and at the SPS for Pb-Pb collisions shows in-plane enhancement, both for protons and pions in the full rapidity range. Studies based on transport models have indicated that the value for $E_{tr}$ depends on the nuclear EOS at high densities. Using a relativistic Boltzman-Equation transport model of P.Danielewicz et. al., it has been found a softening of the EOS from a stiff form ($K \sim 380$ MeV) for beam energies below $E_{tr}$ to a softer form ($K \sim 210$ MeV) for beam energies above $E_{tr}$.

The method of differential flow analysis was suggested as the complementary approach to the standard transverse momentum analysis of P.Danielewicz and G.Odyniec and was first used by the E877 collaboration. Let $N^+(N^-)$ be the number of particles emitted in the same (opposite) direction of the transverse flow near projectile rapidity, then the ratio $R(p_t) = (dN^+/dp_t)/(dN^-/dp_t)$ as a function of $p_t$ is a direct measure of the strength of differential flow near the projectile rapidity. It has been shown experimentally that more detailed information about the collective flow can be obtained by studying this ratio. It was shown theoretically by Li et al. that the ratio $R(p_t)$ at high $p_t$ is particularly useful in studying the EOS of dense and hot matter formed in relativistic heavy-ion collisions. We examine the transverse momentum spectra of protons detected on the same ($dN^+/dp_t$) and opposite ($dN^-/dp_t$) side of the transverse flow (reaction plane) in central C-Ne and C-Cu interactions, respectively. These protons are not used in the definition of the reaction plane. Only protons emitted in the rapidity intervals of $1.7 < Y < 2.4$ for C-Ne and $1.3 < Y < 2.7$ for C-Cu, respectively, were considered. The chosen rapidity ranges are around the projectile rapidity of $Y_{proj} = 2.28$. In these rapidity ranges particles with high transverse momenta must have suffered very violent collisions and thus originate most likely from the very hot and dense participant region. On the other hand, particles with low transverse momenta are mostly from cold spectators. A clear excess of protons emitted to the same side of the directed flow for both C-Ne and C-Cu collisions has been obtained. In both collisions the spectra show typical exponential behaviour for $p_t \geq 0.2$ GeV/c. The spectra for particles in the same and opposite directions of the transverse flow are approximately parallel to each other at $p_t$ larger than about 0.7 GeV/c. To study the strength of differential transverse flow, we
compare the ratios $R(p_t)$ as a function of $p_t$ for C-Ne and C-Cu collisions. The ratios increase gradually at low $p_t$ and reach a limiting value of about 1.9 and 2.5 in the reaction of C-Ne and C-Cu, respectively. The values of $R(p_t)$ are greater than one in the whole transverse momentum range, indicating that protons are emitted preferentially in the flow direction at all transverse momenta. It is an unambiguous signature of the sideward collective flow. These findings are similar to those observed by the E877 collaboration for protons in central Au-Au collisions at a beam energy of 10.8 GeV/nucleon. The similar behaviour show the spectra of QGSM generated data for C-Ne and C-Cu collisions and coincide with the experimental ones. From the transverse momentum distributions of protons emitted in the reaction plane to the same and opposite side of the transverse flow the temperatures and flow velocity $\beta$ have been extracted in C-Ne and C-Cu collisions. The observations are in qualitative agreement with predictions of a transversely moving thermal model. In the whole range of transverse momentum studied, pions are found to be preferentially emitted in the same direction of the proton transverse flow in the reaction of C-Ne, while an anti-flow of pions is found in the reaction of C-Cu due to stronger shadowing effects of the heavier target. The differential flow data for both protons and pions provide a more stringent testing ground for relativistic heavy-ion reaction theories.

The Main Results of the Thesis

1. Multiplicity distributions of $\pi^-$ mesons, characteristics of these distributions (average multiplicity $< n_-$, dispersion $D_{n_-}$, etc), average number of interacting nucleons $< Q >$ and the ratio $R_-=< n_- > / < Q >$ have been obtained in central C-C, F-Mg and Mg-Mg interactions at energy of 3.4 GeV/nucleon with use of the spectrometer GIBS. Values of $< Q >$ increase with the target mass number $A_T$. Values of $R_-$ obtained in C-C, F-Mg and Mg-Mg interactions coincide with results obtained earlier at SKM-200 set-up for symmetric and approximately symmetric systems of C-Ne, O-Ne and Ne-Ne. Values of $R_-$ coincide with values calculated by using the simple thermodynamical model. Empirical dependence of $R_-$ on masses of interacting nuclei $(A_P, A_T) R_- = C \cdot (A_P/A_T)^\alpha$, obtained for inelastic collisions at lower Bevalac (LBL) energies up to 2 GeV/nucleon, have been qualitatively confirmed at our energy of 3.4 GeV/nucleon. The Dubna Cascade Model reproduces the dependence of $R_-$ on $A_P/A_T$. It has been shown, that linear dependence of $R_-$ on the energy in c.m. system $E_{cm}$ observed at Bevalac for the various symmetric pairs of nuclei up to 1.8 GeV/nucleon is continued up to our energy of 3.4 GeV/nucleon. Obtained values of $R_-$ allows one to extend the region of comparison with predictions of theory. Obtained results on $< Q >$ and $R_-$ for C-C collisions agree with results of the 2-Metre Propane Chamber collaboration for C-C at the same energy of $E=3.4$ GeV/nucleon.

2. A study of pion production in central He-Li, He-C, C-Ne, C-Cu, C-Pb, O-Pb and Mg-Mg collisions was carried out. Average kinematical characteristics of $\pi^-$ mesons such as multiplicity, momentum, transverse momentum, emission angle, rapidity and corresponding distributions have been obtained for Mg-Mg. The Quark Gluon String Model (QGSM) satisfactorily describes experimental results. It has been shown that in Mg-Mg collisions the average rapidity $< Y >$ does not depend on the multiplicity of pions, meanwhile the average transverse momentum $< P_T >$ slightly decreases with multiplicity. These average kinematical characteristics are similar to characteristics of N-N collisions at the same energy. Results for Mg-Mg interactions coincide (agree) with our previous results for symmetric and approximately symmetric pairs of nuclei C-C, C-Ne, O-Ne, Ne-Ne obtained at SKM-200 set-up. The QGSM reproduces the dependence of $< Y >$ and $< P_T >$ on $n_-$ for Mg-Mg. Rapidity distributions of pions in various regions of $P_T$ have been investigated. Shape of $Y$ distributions changes with increase of the transverse momentum of $\pi^-$ mesons: the fraction of pions increases in the central region
and decreases in fragmentational regions of colliding nuclei. Y distributions become narrower. Analysis of Y distributions shows that central regions of these distributions are enriched with pions of large transverse momentum (as compared to fragmentational regions of colliding nuclei). The QGSM reproduces Y distributions in various regions of P_T well enough. Analysis of angular distributions of \( \pi^- \) mesons in He-Li, He-C, C-Ne, C-Cu, C-Pb, O-Pb and Mg-Mg collisions have been performed. The anisotropy coefficient \( a \) has been obtained. It has been shown that the parameter \( a \) is same for the symmetric (or approximately symmetric, \( A_P \sim A_T \)) system of nuclei (He-Li and Mg- Mg) and increases slowly with the mass number of projectile \( A_P \) and target \( A_T \) for other pairs of nuclei. The QGSM reproduces angular distributions of pions well enough and values of the \( a \) extracted from the spectra generated by QGSM agree with experimental ones within the errors. Dependence of \( a \) on kinetic energy in c.m.s \( E_{kin}^* \) and multiplicity of pions \( n_- \) has been studied. Anisotropy coefficient increases linearly with \( E^*/E_{max}^* \) for all pairs of nuclei. In the range of 100 MeV pions are emitted isotropically. These results qualitatively agree with predictions of the Dubna Intranuclear Cascade Model. At small multiplicities of pions \( n_- \leq < n_- > \), the degree of anisotropy is greater, than at high multiplicities \( n_- > < n_- > \). Decrease of the parameter \( a \) for more central events \( n_- > < n_- > \) indicates, that angular distributions of pions become more isotropic at small impact parameters \( b \rightarrow 0 \).

3. Identification of protons have been carried out in central C-Ne and C-Cu collisions. The statistical method of identification utilized in the neural nets method and based on the similarity of \( \pi^- \) and \( \pi^+ \) mesons spectra have been used in order to separate \( \pi^+ \) mesons from protons. After identification the admixture of \( \pi^+ \) mesons have been reduced to (5-7)%.

4. Characteristics of protons in central He-Li, He-C, C-C, C-Ne, C-Cu and C-Pb collisions have been studied. Average values of momentum \( < P > \), transverse momentum \( < P_T > \), rapidity \( < Y > \) and emission angle \( < \Theta > \) have been obtained. Experimental results have been compared with predictions of the Quark-Gluon String Model. The model satisfactorily describes main characteristics and the spectra of protons, though slightly underestimates \( < P > \) and overestimates \( < \Theta > \).

5. Temperatures of protons and \( \pi^- \) mesons in He-Li, He-C, C-C, C-Ne, C-Cu, C-Pb, O-Pb and Mg-Mg central collisions have been determined from kinetic energy \( E_k \) and transverse momentum spectra. Proton temperatures \( T_p \) increase with mass numbers of projectile \( A_P \) and target \( A_T \) from \( T_p = (118 \pm 2) \) MeV for He-Li to \( T_p = (141 \pm 2) \) MeV for C-Pb. The proton temperature \( T_p \) in C-Ne, C-Cu and C-Pb collisions agrees with prediction of the Hagedorn thermodynamic model. Experimental results have been compared with the QGSM. The QGSM agrees with experimental temperatures of protons and reproduces dependence of \( T_p \) on \( A_P, A_T \). For light nuclei He-Li, He-C and C-Ne, the spectra of \( \pi^- \) mesons are described by a single exponential law and temperatures of pions \( T_{\pi^-} \) does not depend on \( A_P, A_T \). Temperatures obtained from energy spectra, are \( T_{\pi^-} \simeq 87 \) MeV and from \( P_T \) spectra, \( T_{\pi^-} \simeq 95 \) MeV. The QGSM describes experimental results well. For C-Cu, C-Pb, O-Pb and Mg-Mg interactions the shape of energy and transverse momentum spectra of \( \pi^- \) mesons are concave and the sum of two exponentials \( (T_1, T_2) \) is necessary to reproduce the data. The relative yield of the high temperature component \( (T_2) \) is \( \simeq 24\% \) for C-Cu, C-Pb and Mg-Mg interactions. The QGSM data of C-Cu, C-Pb, O-Pb and Mg-Mg collisions also exhibit concaved shape and two temperatures have been obtained from spectra. Values of temperatures extracted from the QGSM data coincide with experimental ones. Dependence of the \( T_{\pi^-} \) on emission angle in c.m. system \( \Theta_{cm} \) and on rapidity \( Y \) has been studied for He-Li, He-C, C-Ne, Mg-Mg and C-Cu collisions. \( T_{\pi^-} \) falls off from \( T_{\pi^-} = 110 \) MeV at \( \Theta_{cm} = 30^0 \) to \( T_{\pi^-} = 90 \) MeV at \( \Theta_{cm} = 90^0 \) and then increases. Such behaviour
has been interpreted as the effect of direct "corona" production of $\Delta$'s. Rapidity dependence of the $T_{x'}$ shows a bell-shaped behaviour with the maximum at $Y=Y_{beam}/2$. Dependence on the rapidity is more evident for $T_2$ than for $T_1$ in Mg-Mg and C-Cu collisions. The QGSM reproduces experimental results. Correlation of pion kinematical characteristics with $\Lambda$'s momentum in the nucleon-nucleon (N-N) c.m. system was investigated in Mg-Mg collisions. Events with a $\Lambda$ produced within ("$\Lambda^{in}$" events) and beyond ("$\Lambda^{out}$" events) the N-N c.m. kinematical limits for nucleon-nucleon collisions were considered. Kinematical characteristics and temperatures of pions from $\Lambda^{in}$ and $\Lambda^{out}$ events do not reveal any significant difference when compared between and with corresponding characteristics and temperatures of pions produced in ordinary central Mg-Mg collisions. The QGSM reproduces experimental results and reveals trend similar to experimental data. For C-Ne and C-Cu interactions temperatures of identified $\pi^+$ mesons have been determined. One temperature have been observed in C-Ne and two temperatures in C-Cu collisions, similarly as for $\pi^-$ mesons.

6. The light front variables $\zeta^\pm$ and $\xi^\pm$, which define the so called horospherical coordinate system in the Lobachevsky space have been used to study inclusive spectra of $\pi^-$ mesons in He(Li,C), C-Ne, C-Cu, Mg-Mg and O-Pb collisions. In $\zeta^\pm (\xi^\pm)$ distributions the points $\zeta^\pm (\xi^\pm)$ have been singled out, which divide the phase space of secondary $\pi^-$ mesons into two regions with significantly different characteristics, in one of which the thermal equilibrium seems to be reached. Separation points are the points of maxima in corresponding $\xi^\pm (\zeta^\pm)$-spectra (or corresponding paraboloids in the phase space). Characteristics of $\pi^-$ mesons (momentum, angular, $p_T^2$ - distributions) in these two regions differ significantly. In particular, secondary pions with $|\zeta^\pm| > |\zeta^\pm| (|\xi^\pm| < |\xi^\pm|)$ have almost flat angular distribution in the centre of mass frame, whereas pions with $|\zeta^\pm| < |\zeta^\pm| (|\xi^\pm| > |\xi^\pm|)$ are produced sharply anisotropically. Thus one can say that the problem of separation of "pionization" and fragmentation components seems to be solved. Corresponding temperatures of pions $T$ are extracted through fitting of data by the Boltzmann distribution. Dependence of the temperature on mass numbers of projectile ($A_P$) and target ($A_T$) nuclei have been studied. The temperature decreases with increase of ($A_P * A_T$)$^{1/2}$. Experimental results have been compared with predictions of the QGSM. The QGSM satisfactorily reproduces experimental data for light and intermediate-mass nuclei. The use of light front variables can help to distinguish different dynamical contributions, or test basic principles in other types of analysis, such as two-particle correlations, HBT-interferometry and transverse flow studies.

7. The transverse momentum technique have been used to analyse charged particle exclusive data event by event in the central C-Ne and C-Cu interactions at a momentum of 4.5 GeV/c/nucleon (E=3.7 GeV/nucleon). Results for protons and $\pi^-$ mesons are presented in terms of the mean transverse momentum projected onto the estimated $<P_{x'}>$ and corrected $<P_x>$ reaction planes as a function of rapidity $Y$ and normalized rapidity $Y/Y_{proj}$ ($Y_{proj}$ - is the rapidity of the projectile in the laboratory system). Observed dependences of the $<P_x>$ on rapidity for protons and $\pi^-$ mesons show typical S-shape behaviour reflecting the presence of the directed flow effects. The directed flow effect is larger for protons than for $\pi^-$ mesons. In C-Ne interactions the directed (sideward) flow of $\pi^-$ mesons is in the same direction as that of protons, while in C-Cu collisions pions show the antiflow behaviour. From the dependence of $<P_{x'}>$ on $Y$ (respectively $<P_x>$ on $Y/Y_{proj}$) we have extracted the flow $F$, defined as the slope at midrapidity for both protons and $\pi^-$ mesons. It is a measure of the amount of collective transverse momentum transfer in the reaction. Due to uncertainties in determination of the reaction plane correction factors $k_{corr}$ have been estimated by two methods, which
yield consistent results. The $F$ increases with atomic number of target $A_T$, which indicates on rise of collective directed flow effect. The Quark Gluon String Model (QGSM) was used for comparison with experimental data. The QGSM yields a signature of sideward (directed) flow effects in C-Ne and C-Cu collisions for protons. The QGSM underestimates the value of flow $F$. The estimated $< P_x' >_{y>0}$ and corrected (multiplied on $k_{cor}$ factor) $< P_x >_{y>0}$ values of the mean transverse momentum in the reaction plane in the forward hemisphere of the c.m. system have been obtained. Values of $< P_x >_{y>0}$ had been compared with results at lower energies of 0.4 - 1.8 GeV/nucleon for various projectile/target configurations. The $< P_x >_{y>0}$ increases with the beam energy. Comparison of our flow results for protons with flow data for various projectile/target configurations at GSI-SIS, AGS and SPS-CERN energies was made using the scaled flow $F_s = F/(A_T^{1/3} + A_T^{1/3})$. $F_s$ demonstrates a common scaling behaviour for flow values from different systems over all available energy region of 0.2 ÷ 200.0 GeV/nucleon.

8. A clear signature of elliptic flow (squeeze-out) have been obtained from azimuthal distributions of protons and $\pi^-$ mesons with respect to the reaction plane at mid-rapidity region in both, C-Ne and C-Cu collisions. The QGSM yields also a signature of the elliptic flow effects in C-Ne and C-Cu collisions for protons. Azimuthal distributions have been parametrized by a second order polynomial function, the parameter $a_2$ of the anisotropy term $a_2 \cos 2\phi$ have been extracted. The ratio $R$ of the number of particles emitted in the perpendicular direction to the number of particles emitted in the reaction plane, which represents the magnitude of the out-of-plane emission signal $R = (1 - a_2)/(1 + a_2)$ was also calculated. The elliptic flow was shown to increase with the transverse momentum, mass number of target $A_T$ and also with narrowing of the rapidity range. It is more pronounced for protons than for $\pi^-$ mesons. The second Fourier coefficient $v_2 = < \cos 2\phi >$, which is related to $a_2$ via $v_2 = a_2/2$ and measures the elliptic flow, have been estimated both for C-Ne and C-Cu. Obtained results on the elliptic flow excitation function for protons in C-Ne and C-Cu collisions has been compared with data in the available energy region of 0.2 ÷ 200.0 GeV/nucleon. The excitation function $v_2$ clearly shows an evolution from negative ($v_2 < 0$) to positive ($v_2 > 0$) elliptic flow within the region of 2.0 ÷ $E_{beam}$ ≤ 8.0 GeV/nucleon and point to an apparent transition energy $E_{tr} \sim 4$ GeV/nucleon.

9. The differential transverse flow of protons and pions in central C-Ne and C-Cu collisions were measured. The strength of proton differential transverse flow is found to first increase gradually and then saturate with increase of transverse momentum. Observations are in qualitative agreement with predictions of a transversely moving thermal model and transport BUU model. In the whole range of transverse momentum studied, pions are found to be preferentially emitted in the same direction of the proton transverse flow in the reaction of C-Ne, while an anti-flow of pions is found in the reaction of C-Cu due to stronger shadowing effects of the heavier target. The differential flow data for both protons and pions provide a more stringent testing ground for relativistic heavy-ion reaction theories.

Approbation of the Work. Basic results of the dissertation were reported at: Seminars in the High Energy Physics Institite of the Tbilisi State University and in the Laboratory of High Energies of JINR/Dubna; International Conference of Advances in Nuclear Physics and Related Areas, July 8-12, Thessaloniki, Greece, 1997; International Conference on Particle and Nuclear Physics, November 14-19, Cairo, Egypt, 1997; International Symposium in Elementary Particle Physics dedicated to the memory of G.Chikovani, September 21-23, Tbilisi, Georgia, 1998; On the 1999 European School of Young Scientists in High Energy Physics, 22 August - 4 September, Casta-Papiernicka, Slovac Republic, 1999; On the Seventh International Conference in Nucleus-Nucleus Collisions, July 3-7, Strasbourg, France, 2000. The results are published as 14 scientific
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Figure 1: The dependence of the $R_\approx = \langle n_\approx \rangle / \langle Q \rangle$ on the $A_P/A_T$. $\circ - C - A_T$, $\star - O - A_T$, $\triangle - Ne - A_T$, $\ast - F-Mg, Mg-Mg$. The data for C-C, C-Ne, C-Cu C-Zr, C-Pb, O-Ne, O-Pb, Ne-Ne and Ne-Zr are for the trigger T(2,0). The solid line - the result of approximation of the data by $C \cdot (A_P/A_T)^\alpha$. $+$ - calculation by the Dubna Cascade Model (DCM).
Figure 2: Noninvariant kinetic energy spectra of $\pi^-$ mesons in C-Cu and C-Pb collisions. 
$\circ$ – the experimental data, $\ast$ – QGSM generated data for fixed $b=2.75$ fm (C-Cu) and $b=3.90$ fm (C-Pb). full lines – the result of fitting by (5).
Figure 3: The $\zeta^\pm$ distribution of $\pi^-$ mesons from Mg-Mg interactions. $\circ$ – experimental data, $\star$ – QGSM data. The curve – result of polynomial approximation of the experimental data.
Figure 4: The \( \cos \Theta \) distribution of \( \pi^- \) mesons from Mg-Mg interactions. \( \bigcirc \) – experimental data for \( \zeta^+ > \tilde{\zeta}^+ \) \( (\tilde{\zeta}^+ = 2.0) \); \( \bigotimes \) – the QGSM data for \( \zeta^+ > \tilde{\zeta}^+ \); \( \bigtriangleup \) – experimental data for \( \zeta^+ < \tilde{\zeta}^+ \); squares – the QGSM data for \( \zeta^+ < \tilde{\zeta}^+ \). Dashed lines: fit of the experimental data by the Boltzmann distribution. Solid lines: fit of the QGSM data by the Boltzmann distribution.
Figure 5: The dependence of $\langle P_x' \rangle$ on $Y_{Lab}$ for protons in C-Ne collisions. $\circ$ – the experimental data, $\triangle$ – QGSM generated data for fixed $b=2.20$ fm, $\ast$ – QGSM generated data for not fixed $\tilde{b}$, squares – events composed by randomly selected tracks from different QGSM events (within the same multiplicity range). The solid line is the result of the approximation of experimental data by sum of first- and third-order polynomial function in the interval of $Y$ - 0.4 ÷ 1.9 . The dashed curves for visual presentation of QGSM events (short dashes - for fixed $b$, long dashes - for not fixed $\tilde{b}$) - result of approximation by the 4-th order polynomial function.
Figure 6: The azimuthal distributions with respect to the reaction plane of midrapidity protons $dN/d\phi$. ○ for C-Ne ($-1 \leq y_{cm} \leq 1$), △ for C-Cu ($-1 \leq y_{cm} \leq 1$) interactions, * the QGSM data. Also shown are the fits using the function $dN/d\phi = a_0(1 + a_1\cos\phi + a_2\cos2\phi)$. 
Figure 7: The dependence of the Elliptic flow excitation function $v_2$ on energy $E_{lab}/A$ (GeV): $\star$ – FOPI, $\circ$ – MINIBALL, $\bullet$ – EOS, $\diamond$ – E-895, $\ast$ – E-877, $\oplus$ – NA49, $\triangle$ – C-Ne, C-Cu (our results).