ЯДЕРНАЯ ФИЗИКА, 2004, том 67, № 1, с. 108–113

VERY HIGH MULTIPLICITY PHYSICS

PROTON–PROTON INTERACTION WITH HIGH MULTIPLICITY AT ENERGY 70 GeV (PROPOSAL)

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Received May 21, 2003

The goal of the proposed experiment is to investigate the collective behavior of particles in the process of multiple hadron production in pp interaction $pp \to n_\pi \pi + 2N$ at the beam energy $E_{\rm lab} = 70$ GeV. The domain of high multiplicity $n_\pi = 30$–40 or $z = n/\bar{n} = 4$–6, will be studied. Near the threshold of reaction $n_\pi \to 69$, $z \to z_{\rm th} = 8.2$, all particles get a small relative momentum $\Delta q < 1/R$, where R is the dimension of the particles production region. As a consequence of multiboson interference a number of collective effects may show up: (a) drastic increase of partial cross section $\sigma(n)$ of n identical particles production is expected, comparing with commonly accepted extrapolation; (b) the jets formation consisting of identical particles may occur as a result of multiboson Bose–Einstein correlation (BEC) effect; (c) large fluctuation of charged $n(\pi^+, \pi^-)$ and neutral $n(\pi^0)$ components, onset of centauros or chiral condensate effects are anticipated; (d) increase of the rate of direct γ's as a result of the bremsstrahlung in partonic cascade and annihilation of $\pi^+\pi^- \to n\gamma$ in dense and cold pionic gas or condensate is expected. In the domain of high multiplicity $z \geq 5$, the major part of the centre-of-mass energy $\sqrt{s} = 11.6$ GeV is materialized leading to the high density thermalized hadronic system. Under this condition a phase transition to cold quark–gluon plasma (QGP) may occur. The search for QGP signatures like large intermittency in the phase-space particle distribution, an enhanced rate of direct photons will be performed. The experimental setup is designed for detection of rare high-multiplicity events. The experiment is carried out at the extracted proton beam of IHEP U-70 accelerator. The required beam intensity is $\sim 10^7$ s^{-1}. Assuming the partial cross section $\sigma(n_\pi = 35) = 10$–1 nb the anticipated counting rate is 10–1 events/h. The multiboson BEC enhancement may drastically increase the counting rate.

1. INTRODUCTION

The investigation of multiple particles production at high energy is one of the fundamental problems of hadron hysics. It is essentially a nonperturbative process. QCD gives only a qualitative picture of this phenomenon: hadron collision initiates a partonic cascade. The gluon strings that arise between colore partons eventually break and produce quark–atiquark pairs. At the final stage of the cascade development when the energy is exhausted the partons join together creating hadrons. The mechanism of the colore confinement is unknown. As a consequence at present it is impossible to calculate theoretically even the main parameters of the process: multiplicity distribution, the energy and mass spectra of particles. Some features of the reaction are described by different models: thermodynamic, hydrodynamic, partonic cascade, Redge poles, and so on. But none of these approaches are complete and their substantiation is far from being rigorous.

There exists an extensive literature on this subject. The theoretical approaches based on statistics and thermodynamics are reviewed in [1, 2]. The grounds for the phase transition search are presented in [3, 4]. The importance of the investigation of multiparticle production for understanding the hadron matter properties under extreme conditions, like high density and temperature, is stressed in [5]. Complete survey of the situation with particles correlation and intermittency can be find in [6]. Experimental data on multiplicity distribution and its phenomenological comprehension is given in [7].

The purpose of the proposed experiment "Thermalization" is to investigate the collective behavior of particles in the process of multiparticle production in pp (or pN) interactions

$$pp \to n_\pi \pi + 2N \qquad (1)$$

at the proton energy $E_{\rm lab} = 70$ GeV. At present the multiplicity distribution at this energy is measured

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up to the number of charged particles $n_{ch} = 20$ [8]. The corresponding scaling variable $z = n_{ch}/\bar{n}_{ch} = 3.5$. The kinematics limit is $n_{\pi,th} = 69$, $z_{th} = 8.2$. Here, $n_{\pi,th}$ is the maximal number of charged and neutral pions allowed by energy–momentum conservation. We plan to study the events with multiplicity $n_\pi = 30$–45, $z = 5$–6. At large multiplicity and near the threshold of the process (1), where all particles have a small relative momentum, the high particle density $f = (2\pi)^3 d^6n/dp^3dr^3 \approx \pi^{3/2}N/(V_pV_r)$ in the 6-dimensional phase space is reached. Here, N is number of particles in momentum–space volume V_pV_r. Note that in the system $h = c = 1$ the value f is dimensionless. The authors of [9–11] argue that the parameter f indicates the importance of multiparticle effects. The value f is the mean number of pions that interfere with one given pion and build the Bose–Einstein (BE) enhancement in the two particle correlation function. So, if $f \ll 1$, only the two particle correlation may be observed. Typically $f \approx 0.1$ for the mid-rapidity region and $p_\perp \approx \bar{p}_\perp$. Even at LHC energy in Pb–Pb collisions $\bar{f}$ is expected to be small in spite of huge multiplicity. This is due to large phase-space volume $V_pV_r \approx (4/3)^2\bar{p}^3\bar{r}^3$ occupied by secondary particles: $\bar{p} \approx 0.5$ GeV/c, $r \approx 10$ fm. In contrast to high energy A–A collision in our case of the pp collision the volume V_pV_r is by three order of magnitude less, since we expect to have $\bar{p} \approx 0.07$ GeV/c, $r \approx 2$–3 fm. So we anticipate to reach very high particle phase-space density $f \gg 1$. As a consequence, one expects to observe the collective effects connected with multiboson interference: broadening of the multiplicity distribution, anomalous fluctuation of charged and neutral components, the jets formation and so on.

In the region $z \geq 4$ the major part of center-of-mass energy $\sqrt{s} = 11.6$ GeV is transferred into mass of produced particles. The density of the created hadron system may be rather high, $\rho/\rho_0 \approx 5$–10. Here, ρ_0 is the density of nuclear matter in the ground state. According to the common notion the system under such condition supposed to be quark–gluon plasma (QGP). Figure 1 is taken from [12] to illustrate this statement.

The onset of QGP manifests itself, at least, by two signatures: large particles intermittency in phase space of rapidity–transverse momentum and an excess of the direct photons and lepton pairs. We plan to search for both of these signatures. The unique feature of QGP in our case is its low temperature. The closer we approach to the reaction threshold, the lower is the temperature and higher is the density of the system. The lower is the temperature the longer is lifetime of the system. The latter is especially important: the system must come to the equilibrium in order to reveal the QGP features.

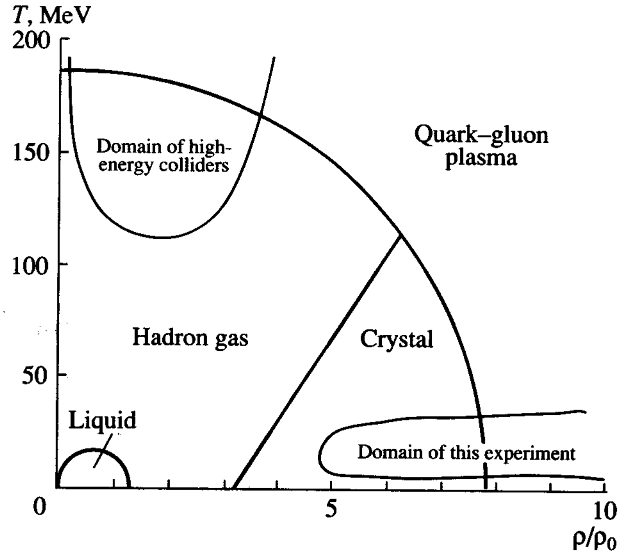

Fig. 1. Phase diagram of nuclear matter.

The further progress in understanding the dynamics of the multiparticle production process will come from further development of the experiment.

For the purposes of this experiment we plan to improve the setup Spectrometer with Vertex Detector (SVD) installed at the extracted proton beam of IHEP (Protvino) U-70 accelerator. The beam intensity is 10^7 s^{-1}. It incidents on hydrogen (or light nuclei) target and generates 10^4 s^{-1} pp (or pN) interaction. One should mention that it is difficult to make a reliable extrapolation of experimentally measured multiplicity distribution from the region $0 \leq z \leq 3.5$ to the region $z \geq 5$. We expect a partial cross section in the interval $4 \leq z \leq 5$ is about 10–1 nb. Then we can collect about 1–10 events/h. However, there are theoretical arguments favoring BE enhancement of the identical pions production. Then the counting rate will be much higher.

2. PHYSICS PROGRAM

2.1. Multiparticle Process Near Kinematics Limit

Let us consider high enough multiplicity n_{crit} when in c.m.s. no energy remains for formation of the leading particles. Then all secondaries have equal energy $\sqrt{p_\perp^2 + p_l^2 + m^2}$ which we determine from the mean transverse momentum of pion $p_\perp \approx 0.3$ GeV/c as it was measured in soft hadron reactions. The longitudinal momentum is $p_l = \frac{1}{\sqrt{2}}p_\perp$. The critical

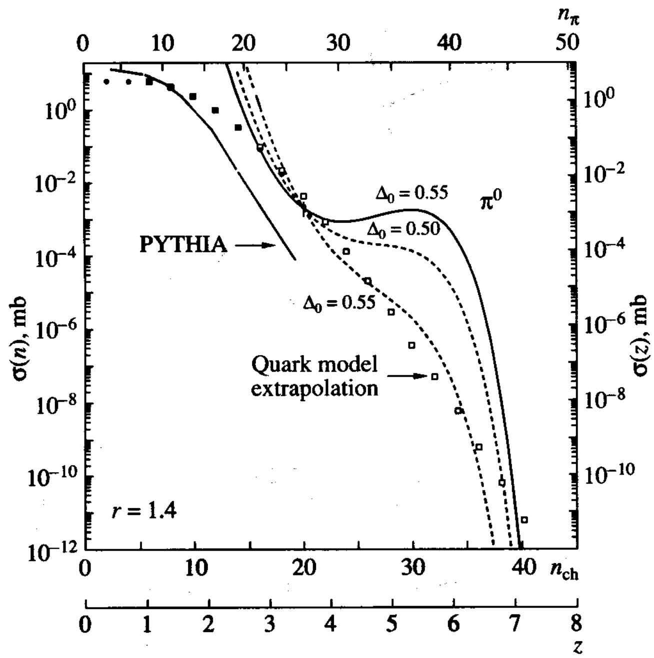

Fig. 2. Multiplicity distribution (partial cross section) in pp interaction. For details see text.

multiplicity is determined by relation $\sqrt{\bar{p}_\perp^2 + m_\pi^2} = (\sqrt{s} - 2m_N)/(n_{\text{crit}} + n_N)$. Here, $n_N = 2$ is the nucleon multiplicity. We get $n_{\text{crit}} = 23$. In the region $n \geq n_{\text{crit}}$ the particles in c.m.s. should have isotropic angular distribution and their energy distribution is Maxwell or BE. The corresponding temperature is $T = \frac{2}{3}E_{\text{kin}}$; $E_{\text{kin}} = (\sqrt{s} - 2m_N - n_\pi m_\pi)/(n_\pi + n_N)$. Here, n_π is pion multiplicity. T depends on pion multiplicity n_π and vanishes when $n_\pi \to n_{\text{th}}$. On this basis we develop the Monte Carlo (MC) event generator and calculated the angular and momentum distribution of the pion and nucleons. These data are necessary for the experiment planing. An example: at multiplicity $n_\pi = 50$ mean c.m. energy of all particles is 50 MeV and mean lab. emission angle $\bar{\theta}_\pi = 90$ mrad, $\bar{\theta}_N = 40$ mrad. These numbers indicate remarkable feature of apparatus: having very modest angular acceptance $\theta = 2\bar{\theta}_\pi = 200$ mrad it will detect 95% of all secondary products.

There is the experimental indication on onset of the thermalization regime at multiplicity $n_{\text{ch}} = 18$ [13].

2.2. Multiplicity Distribution

Topological cross section $\sigma(n_{\text{ch}})$ in pp interaction at 70 GeV at U-70 accelerator have been measured in two experiments [8], see Fig. 2. The calculation by the MC PYTHIA code is shown. One can see that standard generator predicts cross section $\sigma(z)$ which is in reasonably good agreement with experimental data at $z < 2$ but it underestimates the value of $\sigma(z)$ by two order of magnitude at $z \geq 3.5$.

An important task is the extrapolation of the function $\sigma(z)$ from the domain $z \leq 3.5$ to the domain of our interest $z \geq 5$. One of the successful approximation of the data at moderate energy is suggested in [14]. Authors make use of the additive quark model. It is assumed one quark–quark collision is described by Poisson function. Two and three qq-collision is represented by the convolution of Poisson functions.

The models mentioned above do not take in to account the effect of identical particles interference. Generally, the account of the multiboson effects is extremely difficult task. But there exists a simple analytically solvable model [9] allowing for a study of the characteristic features of multiboson systems under various conditions including those near the Bose condensation. The latter even is called some times as pion laser. The authors of [11] apply this model to study the influence of the Bose–Einstein correlation (BEC) on pion multiplicity, spectra, and two pion correlation function. Prediction of this model is shown in Fig. 2. Free parameters are: r — space dimension of the system and Δ — characteristic mean momentum of the particles. We see that model strongly favors the production of π^0 (so-called anticentauro event).

2.3. Multiboson Jets

We considered the influence of the BE statistics on pion multiplicity distribution. There is another interesting BEC effect which is widely discussed in literature. It is multiboson momentum (and angular) correlation. Preprint [15] is devoted to the analysis of the multipionic system. It was found that requirement of wave function symmetrization leads to the formation of an interference maximum with the momentum dispersion d_{cor} and the angular width θ_{cor}: $d_{\text{cor}} = C/(r\sqrt{n})$; $\theta_{\text{cor}} = d_{\text{cor}}/p_0$, p_0 is the mean momentum of the pion. The meaning of these formulas is that at $n \gg 1$ there is monochromatization in momentum space and angular collimation of the particles within the interference maximum.

Qualitatively similar effect is discussed in [16] but on rather different ground. The authors point out the possibility that at high enough energy density 3–6 GeV/fm^3 (which we hope will be easily achieved in our experiment) the produced pions can create certain coherent state — a classical pion field, the analog of the classical electromagnetic field. Thus one can expect rather characteristic picture: a large number of pion may emerge with almost the same momentum, creating a jet pattern in concrete collision. There may be jets consisting predominantly of the particles with only one sign (i.e., π^+, π^-, or π^0). This effects resemble a laser without optical resonator. Another analogy is the electromagnetic coherent superemission in spin oriented system in magnetic field.

2.4. Thermodynamics of the Hadron System

The emphasis of this proposal is the study of multiparticle process (1) at high multiplicity $n \geq n_{\text{crit}}$, where the leading particles must vanish and it is reasonable to assume that the system approaches the thermodynamic equilibrium state. The onset of this regime may be checked directly by measuring the degree of isotropy of particle angular distribution in c.m.s. and by evaluation the temperature T_i corresponding to different species of the secondaries: $i = \pi, K, p, \bar{p}, d$. The difference of the quantities T_i gives another criterion of equilibrium. The thermodynamics analysis of the hadron production is widely used for a long time. The main features of the multiparticle process seem to have got quantitative description. In particular the abundance of different particle species is explained from relativistic quantum molecular dynamics. The application of this kind of theories and models to the data analysis of the proposed experiment have a good ground since we plan to take a special measure to detect a multiparticle systems approaching the thermal equilibrium state. The deviation of the experimental observation from theoretical prediction will serve as a signal of a new physics.

2.5. Intermittency

The secondary particles have a nonuniform distribution in the momentum space. The particle density has statistical and dynamical fluctuations, i.e. the distribution has an intermittent character. The intermittency depends on the particle production mechanism. For instance, the resonances and the clusters in intermediate state give rise to fluctuations in the final state of the system. The theoretical considerations show the rise of intermittency near the phase transition point. It also depends on the hadronization process (i.e., confinement) and QCD vacuum properties. Thus, the experimental study of the intermittency may throw light on the complicated and hidden mechanism of particle production at high energy. The present project certainly has a direct connection with this topic, since high statistics of the high-multiplicity events makes it possible to carry out the precise investigation of the intermittency effect.

One should to distinguish stochastic and regular intermittency. The field source movement inside the medium with velocity greater than the phase velocity of the field quanta in this medium leads to wave production. In case of electromagnetic interactions it is a well known Cherenkov effect. Generalization of Cherenkov radiation to scalar and vector fields cases was developed in a number of papers. In particular, Cherenkov gluon radiation in QCD frames devised in [17]. The existence of color current, necessary for this phenomena, is confirmed by studying of hard processes. The Cherenkov type radiation can be emitted in the projectile and target particles. This leads to two peaks of dense groups of particles (spikes) distribution in rapidity phase space. At the same time the particle distribution at the azimuthal angle is uniform. It is so called ring events. Indication on existence of such phenomenon was reported in a number of papers (see, e.g., [18]). A double-peak shape in the pseudorapidity particle distribution for pp collisions has been observed in agreement with the coherent gluon-jet emission model. Therefore high luminosity and high multiplicity trigger in "Thermalization" setup is very important to collect enough statistic for study the ring events. The accurate data will give possibility to determine confinement radius and refractive index of hadron matter.

2.6. Direct Photons

The direct photons (DP) as definition are not a decay product of any known particles. In accordance with quantum electrodynamics they may be emitted in the process of charged particle scattering. In particular quark–quark and quark–gluon interaction leads to photon emission. The higher is the density and longer is the system lifetime, the more of DP it should emit. This simple picture explains why so many experimental and theoretical efforts are devoted to the DP study. The phenomenon of the DP is discovered, but, it seems, nothing unusual has been found up to now: the DP rate agrees with general theoretical expectation. But there is one exception. It is low-energy photons $p_\perp \leq 0.1$ GeV/c, $x \leq 0.01$. One can cite at least three publications, where the low-energy photon spectrum is measured and the photon rate 5–7 times exceeds theoretical prediction. It is K^+p and $p\bar{p}$ interaction at 70 GeV and π^+p and K^+p interaction at 250 GeV [19]. The excess of DP may be connected with some unknown physical process. It is especially interesting to investigate DP in proposed experiment, since we are going to deal with a high-density system. The quark–gluon cascade leading to high-multiplicity final state has large number of steps (rescattering, loops, and so on) and each of them is connected with bremsstrahlung. Apart of this at high density an additional source of γ's is predicted [20]: the charged pions annihilation $\pi^+\pi^- \to n\gamma$. This process if being discovered may

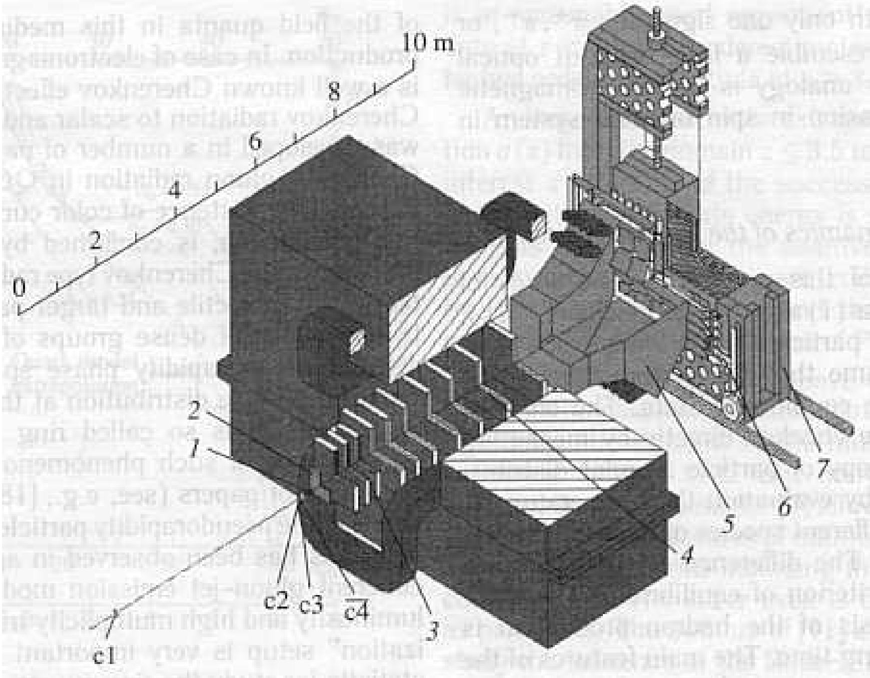

Fig. 3. Schematic of the experimental setup — SVD: c1, c2 — beam monitor; c3 — nuclear and hydrogen targets; $\overline{c4}$ — silicon vertex detector; *1*, *2* and *3*, *4* — tracker of the magnetic spectrometer, drift tubes and proportional chambers; *5* — threshold Cherenkov counter; *6* — scintillation hodoscope; *7* — electromagnetic calorimeter.

serve as one of the tool of the density and temperature measurement.

3. EXPERIMENTAL SETUP

The experiment will be carried out at improved setup SVD installed at the extracted proton beam of IHEP (Protvino) U-70 accelerator [21]. The physics program dictates the following requirements to the apparatus.

1. The setup is capable to detect with high efficiency the events with large charged and (or) neutral multiplicity 20–50 particles. Photon multiplicity is up to 100. The energy threshold of γ's detection is 50 MeV.

2. The trigger system is capable to select the rare events with multiplicity $n_\pi = 20$–50. The coefficient of suppression of low-multiplicity events $n_\pi < 20$ is 10^3.

3. The magnetic spectrometer has resolution $\delta p/p \approx 1\%$ in the momentum interval $p = 0.3$–4.0 GeV/c.

The setup schematic is presented in Fig. 3. The apparatus consists of the following main parts.

The position sensitive beam monitor.

The liquid hydrogen target has diameter of 2 cm and length of 2.5 cm. The apparatus test and some data collection may be done with nuclear target.

The vertex detector consists of 10 planes of silicon strip detectors with space resolution of 2.5–5.0 μm.

The trigger solution is obtained from combination of amplitude signals and number of hits in strip detectors and electromagnetic calorimeter signal.

The magnet has the bending power 1.5 T m and aperture $X \times Y = 130 \times 160$ cm.

The tracker of the magnetic spectrometer consists of 25 planes of drift tubes and proportional chambers.

4. CONCLUSION

The goal of the proposed experiment "Thermalization" is the investigation of collective behavior of particles in the process of multiple hadron production in pp (or pN) interaction $pp \to n_\pi \pi + 2N$ at the beam energy $E_{\rm lab} = 70$ GeV. The domain of high multiplicity $n_\pi = 30$–50 or $z = n/\bar{n} = 4$–6, will be studied. Near the threshold of reaction $n_\pi \to 69$, $z \to z_{\rm th} = 8.2$, all particles get small relative momentum $\Delta q < 1/R$, where R is the size of the particles production region. As consequence of multiboson interference a number of collective effects may show up.

The physics objectives of the experiment are as followers:

1. Search for a new phenomena.

a) Drastic broadening of the multiplicity distribution $\sigma(z)$ is expected due to effect of BEC. In the region $n_\pi \geq 40$, $z \geq 5$ the actual cross section $\sigma(z)$ may exceed by three order of magnitude the extrapolated function $\sigma_{\text{extr}}(z)$. The latter is calculated on the basis of QCD or qq-collision model without inclusion of the BEC effect.

b) The BEC may manifest itself by formation of narrow jets of identical particles or "cold spots" in momentum space. The other notions for this effect are pion laser, classical boson field, boson condensate.

c) The particle sources may be two types: chaotic and coherent. The precision measurement of the two particle correlation function $R(q)$ makes possible to determine the sources parameters: chaoticity, space–time size, primordial correlation length and time. The latter is dynamic characteristics of the hadron matter.

d) The large variation of the π^+, π^-, π^0 multiplicity is expected in framework of BEC. The multiplicity fluctuations may also manifest classical pionic field production or onset of chiral condensate.

2. The systematic and precision study of known phenomena.

a) The direct photons especially with low energy $E_\gamma \leq 100$ MeV may manifest a new physics, in particular, existence of the QGP.

b) The study of stochastic intermittency is the instrument for phase transition search and also search for BEC effect of the cold spot type.

c) The existence of events with regular intermittency, so called ring events, is published. This effect is referred as a gluonic Cherenkov radiation. It needs confirmation. If it really exists it will be a genuine probe of the hadronic matter properties.

d) The measurement of the production rate of the particles of different species π, K, p, d, $\bar{p}$ gives data for test and development of thermodynamics models. Simultaneous analysis of the differential cross section and BEC functions makes possible to disentangle the hadronic system size, temperature, and expansion rate.

The experiment will be carried out at 70-GeV proton beam of IHEP U-70 accelerator. The apparatus design is essentially based on the fact that at high multiplicity the all secondary particles have sharp forward collimation. In spite of modest setup size it is expected that at least 70% of all particles drops in to apparatus aperture and will be detected.

The apparatus includes liquid hydrogen target, silicon vertex detector, magnetic spectrometer, electromagnetic calorimeter. The multilevel trigger system is designed to select the rare events with high charged and neutral multiplicity $n_\pi \geq 20$. The target luminosity is 10^{30} cm^{-2} s^{-1} at the beam intensity 10^7 s^{-1}.

The magnet spectrometer provides high momentum resolution $\delta p \leq 5$ MeV/c which is crucially important for BEC investigation.

The counting rate of the events with total multiplicity 40 is expected to be 10 events/h. If scenario of BEC is realized, than counting rate will be essentially higher.

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