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Dense Cold Nuclear Matter
Study with Cumulative Trigger.
Proposal

Experimental Study of Cumulative Process.**Proposal.**

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Experimental program for the study of dense cold matter is proposed. Droplets of such a matter are expected to be created in light ion collisions at the initial energy range of future facilities FAIR and NICA with extremely small but measurable cross section. Meson (or photon) production at high p_t and central rapidity region (double cumulative processes domain) is proposed as possible effective trigger (selection criteria) for such study.

Figs. - 6, References - 18

Изучение плотной холодной ядерной материи.**Предложение эксперимента** Препринт ИТЭФ-XX-09

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Предложена экспериментальная программа для изучения холодной ядерной материи. Образование небольших сгустков (дропплетов) такой материи ожидается при столкновении легких ионов с энергией масштабных энергий строящихся ускорительных комплексов FAIR и NICA. Сечение таких процессов невелико, но доступно для экспериментальных измерений. Предлагается высокоэффективный триггер на мезон (или фотон) с большим поперечным импульсом (p_t) в центральной области быстрот, соответствующий дважды кумулятивным процессам.

А почему не барионы?



холодной ядерной материи.

1. Introduction

Chromodynamics of media is the subject of research in relativistic nuclear physics field. From theoretical point of view it is very important to study the phase diagram structure in QCD in detail (see e.g. [1], Fig.1) and to find specific signatures in nuclear interactions indicating on the phase transitions presence. One of the main goals for experiments on heavy ion beams is discovery and study of new form of QCD matter – quark-gluon plasma (QGP) [2]. At present the mean experimentalists' efforts are bended on studying the phase diagram at high temperatures and low baryon densities (RHIC, LHC) [3]. This corresponds to the theory status ten years ago when the phase diagram consisted only of two regions: hadron phase and QGP. Since resently the progress in the theory led to the significant complication of the phase diagram. In particular, it led to the appearance of critical point [4]. Discovery of critical point at intermediate temperatures and densities is considered as one of the most important goals of FAIR and NICA projects. New phenomena are also predicted at high densities and low temperatures. In this phase space domain the first order phase transition and the existence of new phenomena like color superconductivity [5] is expected. Low temperatures and extreme densities are probably realized in the Nature within neutron stars. This region is hardly achieved in laboratory conditions by using standard experimental tools ~~for moving on phase diagram~~ like changing of the initial energy and masses of colliding nuclei, or selecting the impact parameters. Such tools don't provide possibility to study the whole phase diagram, but they specify some rather small area $T \pm dT$ versus $\rho \pm d\rho$.

Cumulative effect which has been discovered in 1970's [6] has been considered in terms of dense fluctuations of nuclear matter. Some properties of cumulative processes, such as strangeness enhancement, are similar to that expected for QGP. However interconnection of cumulative processes and QGP seems to be doubtful because of next arguments. Firstly, if high densities could be realized in cumulative processes, then only in short-lived fluctuations (named by D.I.Blohintsev "fluctons" [7]) could be created. Secondly, particles in such fluctuations must be highly virtual and they have large relative momentum. Thirdly, these (fluctons) are local few-nucleon fluctuations and it is inconsistently to consider them like a media (although existence of plasma droplets was already discussed, see for example [8]). Recognizing significance of these objections, ~~we will confine ourselves to a following remark. By overcoming them~~ we propose an effective trigger for extreme dense nuclear matter. Indeed if we could select (e.g. kinematically) a process where approximately ten nucleons being in volume of one nucleon, then the density of such formation would be tens times higher the standard nuclear density (0.17 nucleons/fm³). Our proposed program gives an idea how to overcome mentioned problems above.

2. General idea

We propose to make an event selection (trigger) with a photon (pion, kaon) at mid-rapidity and maximal transverse momentum by colliding light nuclei (from Helium to

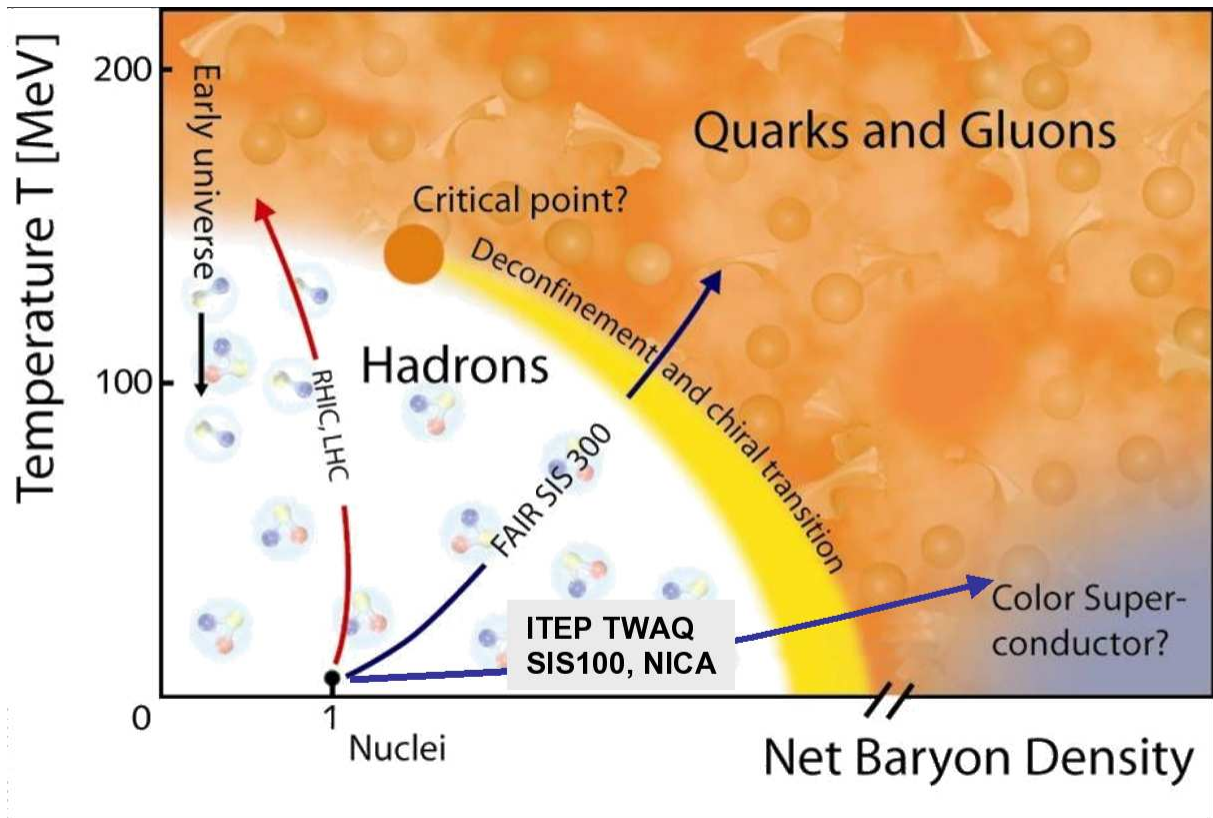


Figure 1: Phase diagram of nuclear matter.

Carbon) (Fig.2). Due to kinematical restrictions such criterion selects mainly flucton-flucton (FF) interaction (Fig.3). We should stress that production of cumulative particle is neither necessary nor sufficient condition for selection of dense baryon system. However, we expect that such selection procedure would increase signal (dense cold matter production) to background (ordinary hadronic matter) ratio for several orders of magnitude. The interaction of two fluctons produces a system (firewall) with real particles (nucleons). The internal energy of the secondary baryon system (recoil system) becomes minimal when the energy of the trigger particle tends to the maximum possible energy for present colliding nuclei reaction. Therefore the decay of this system (with very small internal energy) will be slow. The relatively slow decay of this system could restrict sort lifetime of this system at large relative momentum of secondary baryons. Thereby such a system should have high density and small size, and one can speak about medium, since the free path will be much smaller than the size of the system due to high density.

After realization of proposed event selection we suggest to proceed with a bright research program focused on properties of formed system in final state. Theoretically predicted properties of dense baryon system (some of them are listed below) should be checked experimentally. This list will probably become longer in future, but it seems already clear nowadays that spin(isospin) system's states, space-time characteristics, search of exotic particles (such as dibaryons), strangeness enhancement etc. should be studied. In this context it is important to mention research programs discussed in the mid 80's and related to cumulative process studies [9]. Some of these proposals (though with modifications)

and a list of considerations look the problems of today.

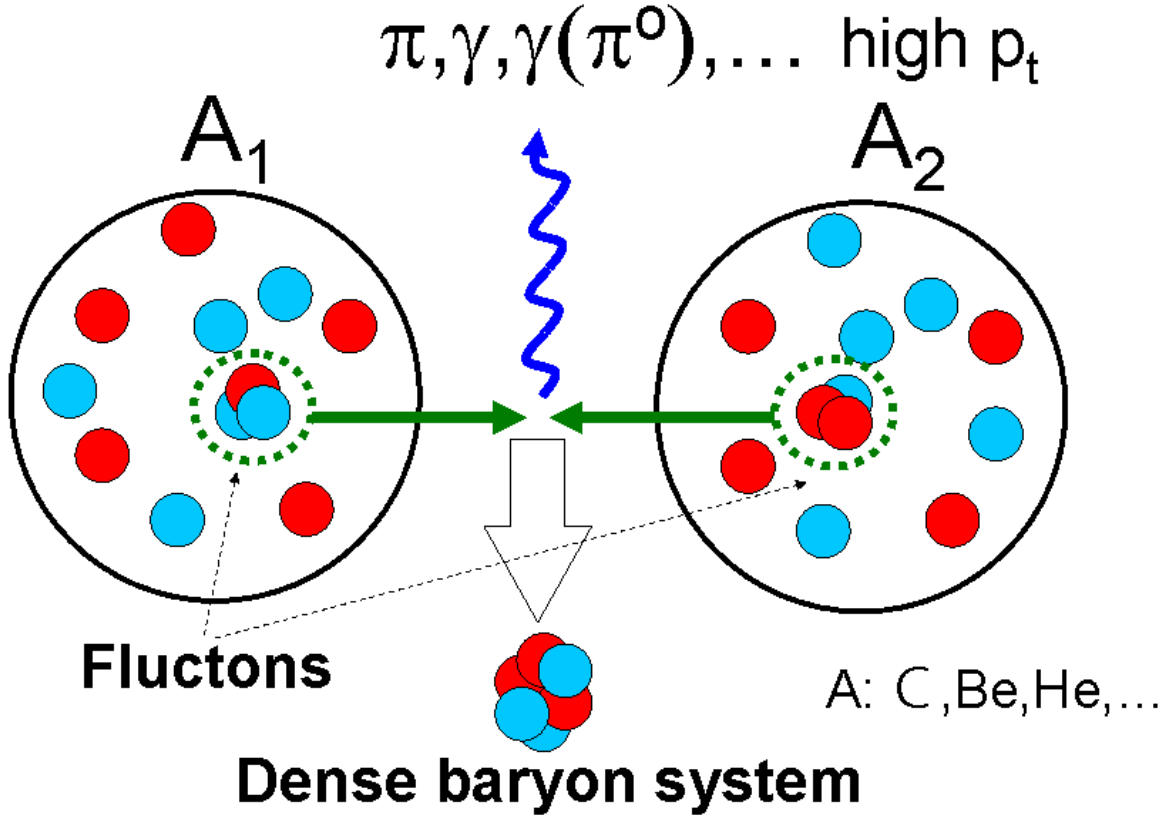


Figure 2: Scheme of the process.

Reality of an effective trigger for the selection of flucton-flucton interaction was experimentally proven in FLINT (FLuctonINTeraction) experiment in ITEP [10]. The trigger realization in FLINT was based on high p_t photon registration in mid-rapidity range using lead-glass electromagnetic calorimeter. Type of the calorimeter is uncritical, but its energy resolution should be good enough (-100-150 MeV) for cumulative photon spectra measurements. Maximal order of cumulateness $X_{sum} = X_1 + X_2$ (where X_i is the minimal number of participating nucleons from colliding nucleus $i=1,2$) achieved at the first stage of the experiment was about $X_{sum} = 5$ (Fig.4). The cross section of the reaction decreased by 2 ÷ 3 order of magnitude when X_{sum} increased by one unit. The value $X_{sum} \sim 7 - 8$ could be accessible experimentally with large acceptance detector at ion-ion interaction rate $\sim 10^8 sec^{-1}$. The nature of the triggered photon is not important for the study. It could be direct photon or the photon from unstable particle decay (mainly from π^0). The kinematical limit (or X_{sum}) of photon production is very close pion one. Pion, kaon or even ϕ -meson trigger is also possible from physical point of view, and the possibility of practical realization should be discussed.

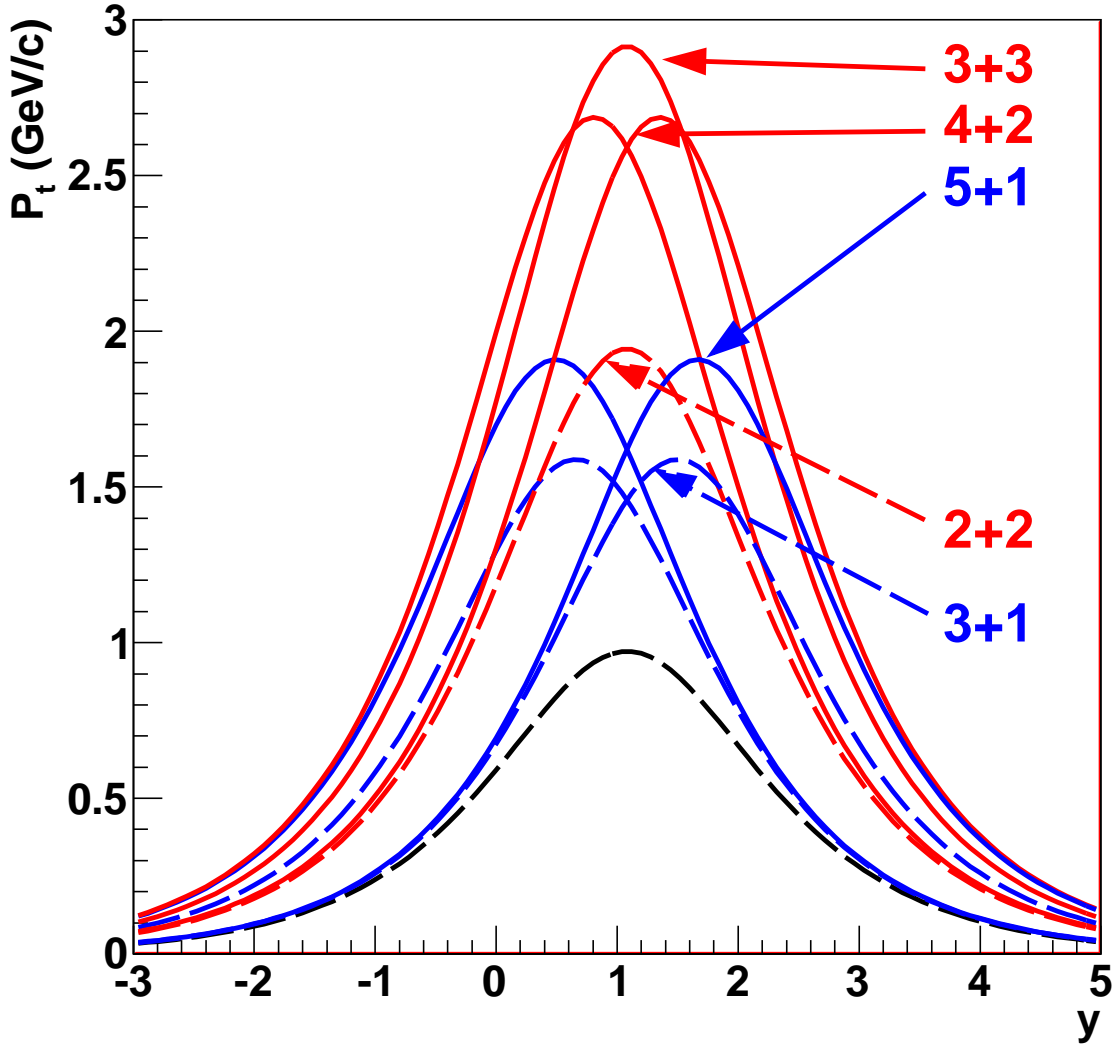


Figure 3: Kinematical limits for $iN+jN \rightarrow \pi^0 + X$ ($i + j \leq 8$) processes at beam energy 6 AGeV. (N+N-black line, N+F-blue and F+F red curves).

3. Specific features of the proposed program

Proposed trigger is only the tool to move us into phase diagram domain not studied yet. One needs to realize the width of the experimental program to study the dense baryonic system which is expected to be produced in the selected events. Each signature of the dense cold matter should be checked experimentally and the total experimental program can be as wide as the existing program for the high temperature plasma study (RHIC, LHC, FAIR). The detector should be adequate to different task which is proposed to study various properties of the dense baryon system. This requirement is specific for each task and will be discussed below separately.

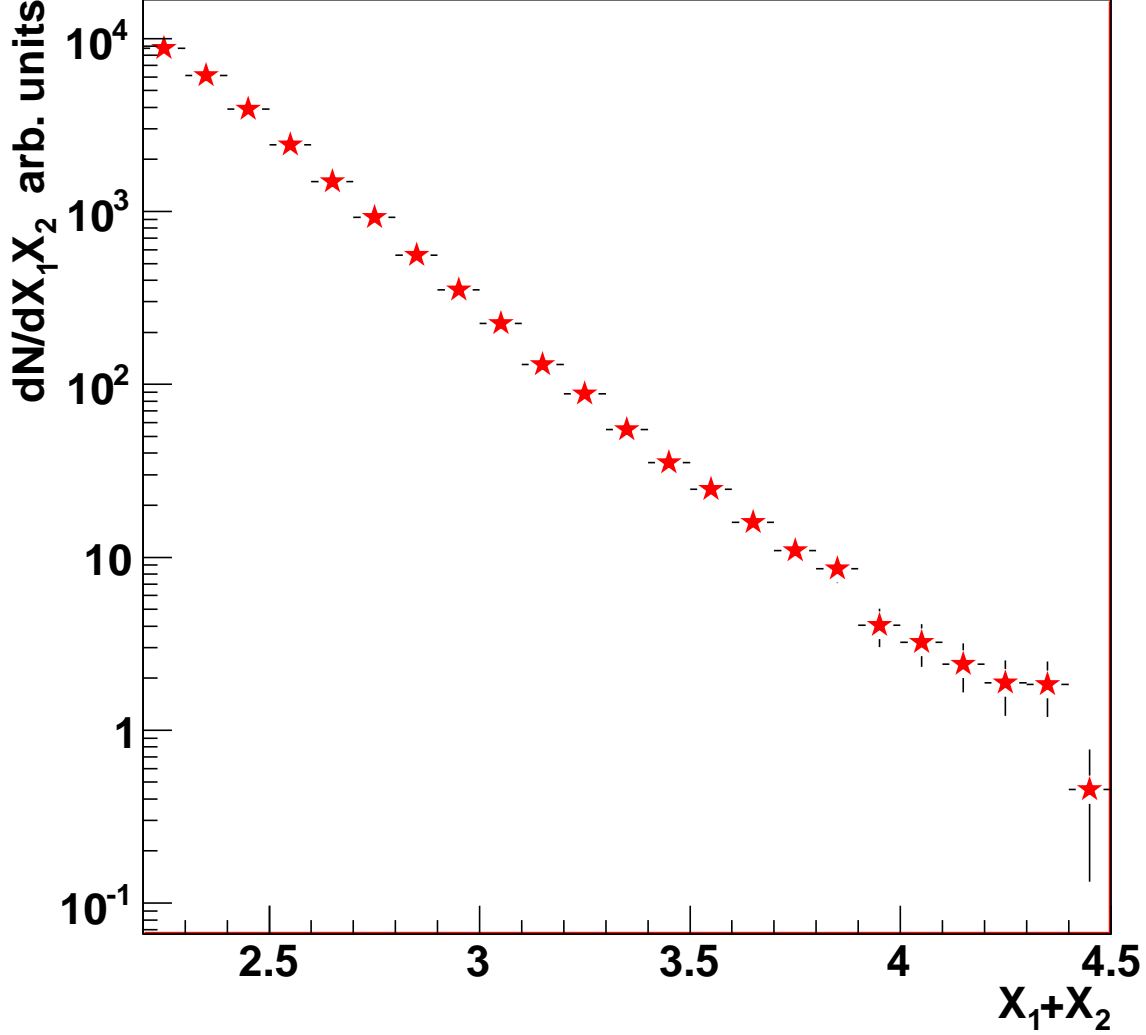


Figure 4: Photon spectrum measured by FLINT collaboration for Be(3.2AGeV)C interaction vs photon cumulative number.

3.1. Clusterization

One of the expected consequences of the proposed event selection is baryon clusterization in momentum space in the final state. We'll refer below phase space region where clusterization is expected as B2R3 (recoil baryon rich bubble region). The position of the B2R3 in the momentum space is model dependent (Fig.5). In quasi-binary model (see Fig. 5left) of flucton-flucton collision cluster momentum could be defined as $P_c \sim P_{f_1} + P_{f_2} - P_{trig}$, where P_{f_i} ($i=1,2$) is the momentum of flucton, and P_{trig} is the momentum of the triggered particle.

The cluster momentum is close zero (in c.m. system of colliding nuclei) in the model where one of the partons (quarks) carries most of the flucton momentum and triggered particle is produced in the hard interaction of two partons (see Fig. 5right).

It is expected that the B2R3 will be at mid-rapidity region in both model, but the momentum of cluster will be different. The other models which describe two nucleus collision are possible, but we restrict our considerations with these models. One can expect much more narrow relative momentum distribution (in final state) of baryons which were involved in the selected flucton-flucton interaction in comparison with relative momentum distribution of other baryons (spectators) produced in light ion collision. For heavier than HeHe colliding system (*e.g.* CC), one can expect a gap in baryon-relative-momentum distribution. This gap separates baryon pairs participating in dense and cold baryon system from other pairs. Spectators of colliding nuclei (which clusterization is trivial) should be excluded from analysis. Thus to see the expected clusterization effect one should identify and measure baryon momenta at mid-rapidity region ($y \sim 0$) and transverse momentum region upto momentum of triggered particle ($0 < P_t < P_{trig}$). The momentum measurement accuracy should be better than typical Fermi momentum ($\Delta p \lesssim P_F$).

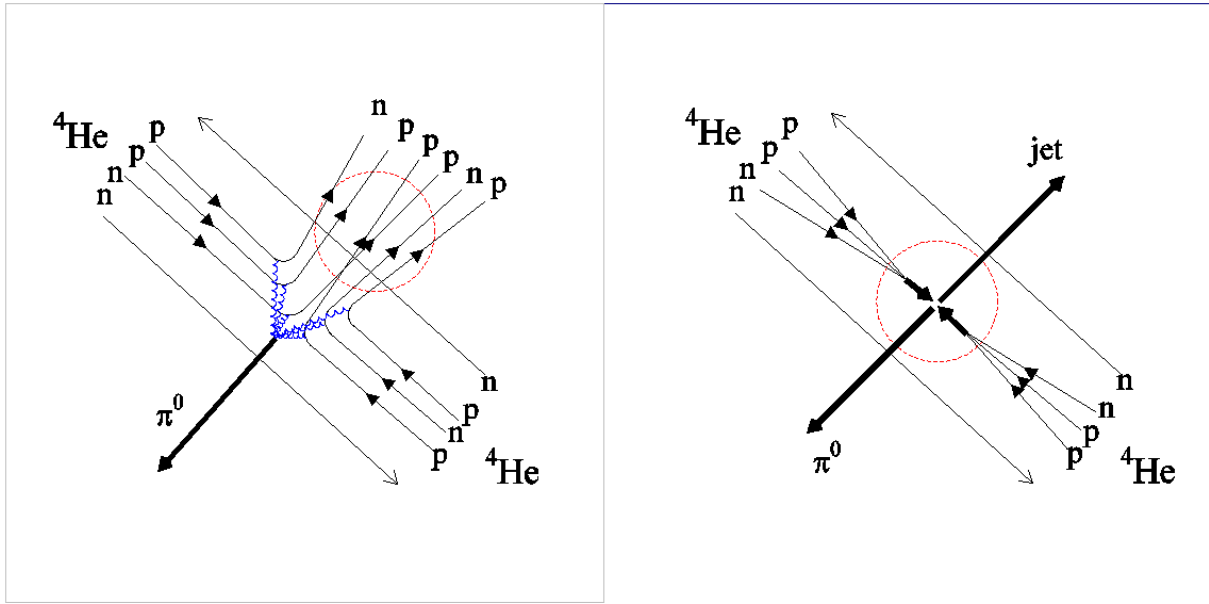


Figure 5: Possible scenario for the cumulative process $3N + 3N \rightarrow \pi^0 + X$ at HeHe interaction.

3.2. Femtoscopy

One can expect also a clusterisation of baryons (which was involved in selected flucton-flucton interactions) in the coordinate space and the increase of cluster throwout time in comparison with throwout time of particles which are not in the same cluster. These predictions could be experimentally tested using correlation method (femtoscopy). The femtoscopy method based on the pair correlation function analysis at small relative momenta for different particle types [11]. Correlation functions can give information about size and possibly about form of source. The method is widely used in heavy ion collisions.

Dividing secondary baryons into groups: participants of dense cluster which was formed in the flucton-flucton interaction (N_c) and other participants (N_p) (spectators

are not in the consideration) one can expect hierarchy of sizes $r(N_{c1}, N_{c2}) < r(N_p, N_p) < r(N_c, N_p)$. Such measurements is needed to control the density and the lifetime of the baryonic system. The example of two proton correlation functions ($R_{pp}(q)$, where $\vec{q} = \vec{p}_1 - \vec{p}_2$, \vec{p}_1 and \vec{p}_2 are the individual proton momenta in the pair rest frame) calculated for expected source size values (r_{RMS} is the root means square of the source which the protons are emitted) is shown in Fig. 6. The interference of identical particles, as well as Coulomb and strong final-state interactions, were taken into account. Strong final-state interactions are dominant, causing an increase of the pair production cross section near $q \sim 0.04$ GeV/c. The intensity of this effect depends inversely on the source size parameter r_{RMS} .

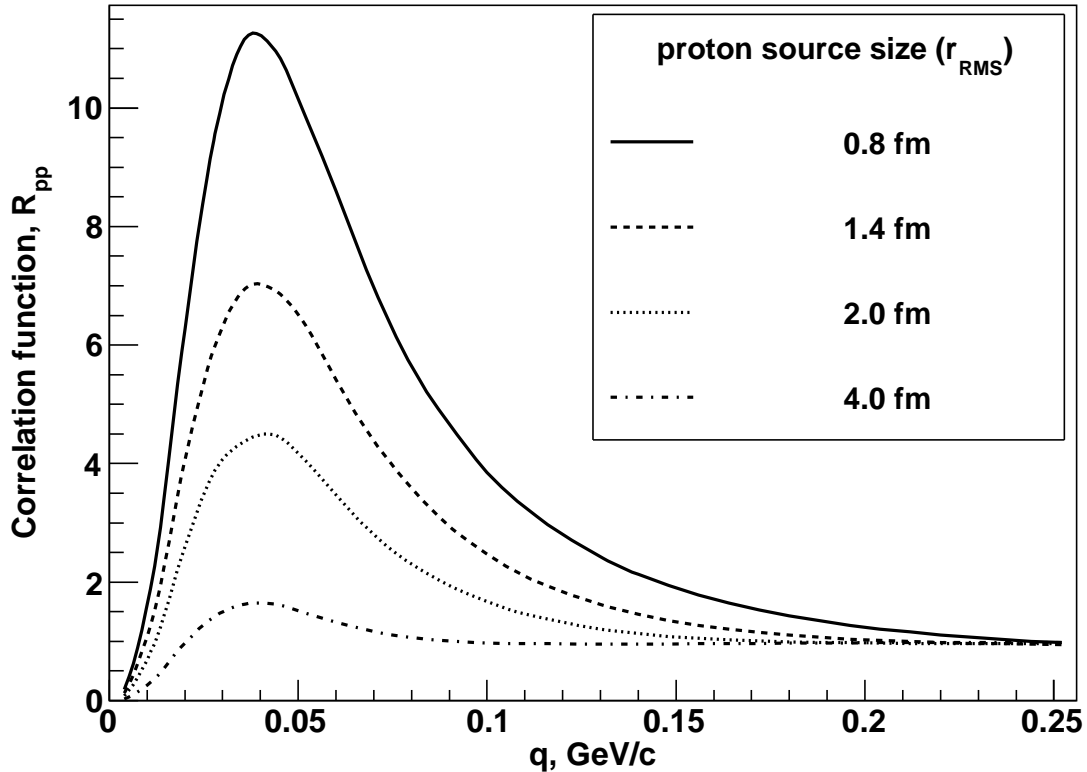


Figure 6: The two-proton correlation functions $R_{pp}(q)$ are calculated for different source size parameters (r_{RMS}). Solid curve corresponds to $r_{RMS} = 0.8$ fm. Dashed curve corresponds to $r_{RMS} = 1.4$ fm. Dotted curve corresponds to $r_{RMS} = 2.0$ fm. Dash-dotted corresponds to $r_{RMS} = 4.0$ fm.

Dense fermion-rich system should cause a decrease of the average distances between nonidentical baryons in comparison with identical ones. Such effect is interesting itself (see subsection 3.7 below). Secondary particle momentum-space region where correlations propose to study corresponds to the B2R3. The pp(np) correlations should be measured at relative momenta $q_0 < 0.2$ GeV/c with relative momentum resolution $\Delta q \ll q_0$.

3.3. Isosymmetrisation

If dense fermion rich system is created and selected with trigger (event selection) and this fact is ultimate (articles a, b) one can proceed with its properties study. All degrees of freedom in such system which populating is not much energy consuming should be brought into play. Therefore a ~~list of~~ broken symmetries should be tended to restore. Particularly, the cross section ratio of particle production when particles are components of the same isomultiplet should be close to unit [12]. This conclusion is trivial for isosymmetric nuclei collision and isosymmetric trigger, but it becomes non-trivial for $\text{He}^3 + \text{He}^3$ collisions and (or) asymmetric trigger (e.g. charged pion or kaon). The proposed measurements are p/n , π^+/π^- ratios for particles produced in selected flucton-flucton interactions within B2R3 and for particles outside this kinematical region as the reference measurements. While π^+/π^- ratio measurement is a routine task for tracking detector, the n/p ratio measurement needs special efforts. But ratio measurement for nucleons seems to be more informative. The “background” measurements of isosymmetric nuclei with isosymmetric trigger are needed to increase the measurement precision of isosymmetrisation effects and decrease of systematical errors. Also at high secondary particle multiplicity isosymmetrisation is trivial therefore total multiplicity should be controlled.

3.4. Strangeness

Another broken symmetry (SU(3)) also should be tended to restore in high baryon density conditions. This could cause the equalization of probabilities to produce different components of baryon octet. Since a strange baryon (e.g. Λ -baryon) production must be accompanied by production of additional kaon (strangeness conservation), it will result in noticeably increase produced mass in the process with free energy lack. At colliding nuclei energies of a few GeV/nucleon the energy lack could be regulated by varying of minimal target mass – cumulative number [13]. By separating mass increasing effect from other one the probability of strangeness production within dense baryonic system would be higher than the probability of non-strange particle production. Strangeness increase is also considered as one of the signatures of usual quark-gluon plasma, but the reason for that is quite different (processes like $gg \rightarrow ss$) [14].

The case when additional kaon makes cumulative number more than the sum of colliding nuclei mass is of special interest. In such a case the only visible way for Λ production is associative production with light pentaquarks e.g. ($qqqqqs$) or (and) dibaryons ($qqqqqqqs$), in case of the last one exists in the nature (see subsection 3.6 below).

3.5. Vector mesons

An increasing resonance production and high spin particles is expected in cumulative processes. In particular the vector to scalar meson ratio should increase with increasing of cumulative number (the effect is predicted in [15]). An interesting effects can be seen due to free energy lack in the process. Since kinematical restrictions become more important with increasing of the produced particle invariant mass, the shape and width of peaks which correspond to wide resonances production (like ρ and Δ) are expected to be distorted with respect to PDG values.

3.6. Exotic

When the possibilities to satisfy the requirements of Pauli principle using known degrees of freedom are exhausted then the dense baryon reach system has to find new forms of existence. The role of exotic states is expected to be increased in comparison with usual reactions in dense fermionic medium conditions. In particular diquark medium will help in dibaryonic resonances production. Exotic states produced in this processes cannot be too heavy due to kinematical limits. Light (below the threshold with pions production) pentaquarks like $(qqqqs)$ or (and) dibaryons like $(qqqqqqqs)$ will probably decay into nucleons and photons. Existing limits of exotic production c.s. [16] are to several orders magnitude higher than cross section of our proposed trigger hence there is no experimental exclusion for the exotics discussed in the subsection.

3.7. Multifermion effects

Multifermion effects could appear in dense medium. To get the first imagination on the expected effects one can take into account the effects for dense multiboson system, which was discussed, for example in [18]. While for rare systems the slope parameter of the momentum spectra and the size parameter for the width of the interference effect could be independent, this is not the case for dense matter. Equally populated [cells](#) in momentum and coordinate space can be considered as an additional signature of dense matter.

4. Concluding remarks

Some points proposed program already realized or have status “in progress” within FLINT experimental program at ITEP [10]. The whole proposed program can be realized in future facilities FAIR (even with SIS100) and (or) NICA (Nuclotron M). Authors would like to thank our colleagues and collaborators from ITEP FLINT, NICA MPD and FAIR CBM and especially thanks to A.A.Baldin, M.Chernodub, A.Kaidalov, D.Kharzeev, R.Lednicky, A.Litvinenko, L.Malinina, V.Nikitin, M.Polikarpov, Yu.Simonov, S.Shimansky and M.Tokarev for helpful discussions on related subjects. This work was done with financial support by Federal agency of Russia for atomic energy (Rosatom) and RFBF under grants N 08-02-00676-a and 08-02-92496-NCNIL-a.

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