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Dense Cold Matter

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Abstract. Possible way to create dense cold baryonic matter in the laboratory is discussed. The density of this matter is comparable or even larger than the density of neutron star core. The properties of this matter can be controlled by trigger conditions. Experimental program for the study of properties of dense cold matter for light and heavy ion collisions at initial energy range $\sqrt{s_{NN}}$~2-3GeV is proposed.

1 Motivation and main idea

To the present time there is large uncertainty in theoretical predictions of nuclear matter's Equation of State in the region of low temperatures and high densities. There is a large number of theoretical models pretending to describe the properties of this state of nuclear matter. The special interest focused on cold superdense state of the nuclear matter is because the properties of this state govern the behavior of matter in center of heavy stars and regulate its evolution. Up to now there is no experimental data obtained in laboratory experiments on properties of such state.

It is well known that ordinary nuclear matter has a multinucleon component in the form of local($r \sim r_N$[1]) fluctuation (SRC or fluctons)[2,3]. Let's consider the kinematic of the process $A_1+A_2 \rightarrow a+X$, where particle a – meson at central rapidity region with very high p_t , close to kinematical limit for the interaction between nucleus A_1 and A_2. It is clear that for heavy nucleus A_1 and A_2 and for high energy collisions the probabitity of such a process is negligible. But for He at E_0~1-3GeV/nucleon is not so hopelessly, as it will be shown below. Below we will talk only about He+He collisions. So, 3-4 nucleons from each colliding nucleus in the form of local multinucleon fluctons interact with each others and produce particle a in the high p_t kinematical region close to kinematical boundary for HeHe collision. He is relatively compact nucleus (r_{rms}~1.4fm). Even most conservative estimate for the density of the matter in such a collision leads us to the value of $\rho > 2\rho_0$.

The set of particles forming the system X depends on trigger particle quantum numbers[4]. The system X will tend to have minimum internal energy when the trigger particle approaches kinematical limit. It means that we will have not only dense but also cold system X in the final state. If the size of the system X is of the order of nucleon size it can be considered as a droplet of dense and cold matter in case of nucleon relative momenta $\delta p < 0.3$GeV and, correspondingly, $T_0 < 50$MeV. Price to be payed for the access into new phase diagram domain is a relatively small size of the droplet and small (but measurable) cross cection of the process. As for the size of the droplet, one should take into account that the criterion of a medium is l>>r, where l-mean length of free path and r-the size of the system. For the ordinary nuclear matter l~1-2 fm and nucleus heavier than carbon is usually considered as droplet of nuclear matter. The larger the density the smaller mean length of free path. 6-8 nucleons in the volume of the order of one nucleon volume correspond to the density tens times larger then ρ_0, and one can expect l<<1fm. It means one can expect the properties of cold and dense nuclear matter even for droplet size of the order of 1fm.

To understand what properties of the matter we expect to see in the produced droplet let us take into account the deficit of free energy in the produced system and Pauli principle. The solution

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acceptable for neutron star- the increase of Fermi momentum of nucleons - not exeptable because of the free energy deficit. Spin and izospin degrees of freedom are expected to be used as far as possible. Extra nucleons must be transformed into other states without significant increase of the effective mass of the droplet. Low mass dibaryons or(and) pentaquarks, if exist, could provide acceptable solution.

"Cold baryonic droplet" experimentally means a bump in the nucleon-trigger correlation function with relatively small nucleon-nucleon mean relative momentum within this bump. The density of the droplet depends on space – time interval between its constituents. The latter is usually measured by Kopylov-Podgoretsky method, now frequently called as femtoscopy due to characteristic scale of measured size ~1-10fm. Starting from femtoscopy, which is only passive test for space-time parameters of the object under investigation, we achieve in our study the active control of the of the process on the space scale of the order of fm.

The choice of trigger particle specie determine minimal configuration of baryonic droplet. One need K^- trigger to search for $\Theta+$ because of such a trigger provides minimum droplet configuration with one strange antiquark, while pion or photon trigger would be more preferable to search for di-baryon d'. For the same reasons K^+ trigger would be a good choice to search for multistrange hyperonic system. More common statement that the choice of trigger particle specie controls quantum numbers of produced baryonic droplet.

On the other side, the trigger particle momentum variation change the minimum number of nucleons within droplet, and, consequently, the initial density of the droplet. The density variation provides transition from one phase diagram domain to another and, consequently, provides access to new state of matter through the phase transitions.

All these processes proceed at the space-time scale of the order of 1-10 fm, and one can say about an embryo of future femtotechnologies in such experiments

The whole spectrum of theoretically predicted properties of dense matter in new, absolutely unstudied sector of phase diagram should be experimentally evaluated. This makes the proposed physical program potentially comparable by means of volume with the program of biggest experiments working or planned in the field of relativistic nuclear physics. The list of these properties will be refined in future.

2 Experimental status

There have been measured by CLAS [5] two and three nucleon SRC probability for He and C; these probabilities are shown in the table. To estimate 4N SRC probability one can take into account two facts. 3N SRC probability is several times smaller than 2N probability squared. Proton-proton SRC probability is at least one order of magnitude suppressed with respect to np SRC [6]. Since 4N SRC has at least 2 pairs of identical nucleons let us consider for estimate $a_{4N}\sim(a_{3N})^2/a_{2N}$(right column of table). Based on probabilities shown in the table one can estimate the fraction of flucton-flucton interactions in $^4He^4He$ collisions as $0.18*10^{-4}$, $0.46*10^{-6}$, $1.2*10^{-8}$ for the total number of nucleons involved into flucton-flucton collisions N_1+N_2=6,7,8 accordingly. Let us consider for the first estimate ideal detector with full particle ID in angular-momentum region. If He beam intensity would be $1.5*10^9$ sec^{-1}, He target efficiency 0.2 and exposition as long as $3*10^6$ sec, one can accumulates $2*10^{10}$, $5*10^8$ and 10^7 events for the total number of nucleons involved into flucton-flucton collisions N_1+N_2=6,7,8 accordingly. It is a large statistic, but for ideal detector.

Only small fraction of flucton-flucton interaction provides dense cold droplet in the final state. The main fraction is simple multinucleon system with secondary particles distributed over practically all available phase space of the reaction. This fraction depends strongly on the parameters of the droplet and can be estimated only roughly. It is clear that the larger initial energy the smaller the events fraction with dense cold droplet in the final state. On the other hand, the larger initial energy the larger droplet transverse momentum and, consequently, the background conditions. It seems that optimal initial energy range for the proposed measurements $T_0\sim$ 1-2GeV/nucleon.

Proposed in section 1 trigger not only selects flucton-flucton interactions, but also selects the final state with relatively small internal energy. The effect can be named as kinematical cooling. The physical reason for the kinematical cooling is the fast (exponential) decreasing of probability of cumulative process (in our case-production of the baryonic droplet) with the increasing of the minimum mass of fluctons ($m_0 \sim \exp\{-T_n/T_*\}$, where T_n.-kinetic energy of the nucleon in the droplet and T_* - the slope parameters ~ 60MeV). Absolute minimum in the flucton mass corresponds to the zero internal energy of the baryonic system and, and consequently, zero phase space of the reaction (for nonrelativistic system $dS=d^4p_1 \dots d^4p_n \delta(p_i^2-m_i^2)\delta^4(\sum_1^n p_i-P_n) \sim T_n^{(3n-5)/2}$). Maximum of $dS * m_0^2$ would be for nucleon kinetic energy of the order of $T \sim (3n-5)T^*/2n \rightarrow 3T^*/2 \sim 100$ MeV, which corresponds to nucleons relative momenta within the droplet $p \sim 0.45$ GeV/c.

The efficiency of proposed trigger can be estimated from data accumulated by FLINT collaboration [7]. FLINT obtained ~ 10^3 events at $Q_1+Q_2>4$ with photon trigger. From simulations we know that effective number of nucleons in the droplet exceeds the minimum one for the value about 0.5-1.0. In case of photon trigger there is additional uncertainty because of unknown mechanism of photon production. Photon can be direct one or from pion decay. In the last case the second photon carry on a small, but not negligible fraction of pion energy. For that reason effective value N_1+N_2 for this experimental data can be estimated as large as ~5-6. It was done during ~50 hours exposition with detector acceptance $\sim 10^{-2} * 4\pi$ and CBe interaction rate $\sim 2*10^6$ sec^{-1}. It looks quite real to obtain data for 1000 hours exposition with interaction rate $\sim 2*10^8$ sec^{-1} with ten times larger detector acceptance and different types of triggers ($\gamma,\pi^{\pm},K^{\pm}$). Even for HeHe interactions (~0.1 supresion with respect to CBe) it provides estimated number of accumulated events $\sim 2*10^8$ for $N_1+N_2 \sim 6$ at initial energy 2 GeV/nucleon. Total numbers of flucton-flucton interactions at the same conditions two order of magnitude larger($2*10^{10}$-section 3).

To summarize this section one can conclude:

1) When applicable, such trigger suppresses statistics by two order of magnitude and then makes off-line analysis much more easy.

2) Kinematical cooling provides relative momenta scale within droplet (~0.45GeV/c) comparable and not smaller than estimated relative momentum in the dense cold matter droplet (~0.3GeV/c). It means that trigger does not significantly suppresses events under study.

3) It is really possible to get information for droplets with $N_1+N_2 \sim 6$-7.

3 Detector for DCM study

For the realization of the program the specialized wide aperture experimental setup are proposed. The setup shall contain solid-state and cryogenic nuclear targets, vertex detectors, magnets, tracking systems, TOF, electromagnetic calorimeters, neutron detectors, threshold detector systems(see figure).

The trigger on a direct (double)cumulative photon or a neutral pion can be realized using and electromagnetic calorimeter. At beam energies of 2-6 GeV/nucleon the optimal polar angle of trigger arm is ~35-50 degrees, but small deviations are not critical.

To discover and localize in momentum space the baryonic system generated at flucton-flucton interaction it is proposed to study the reaction

$$A+A \rightarrow \gamma+N+(+N)+X,$$

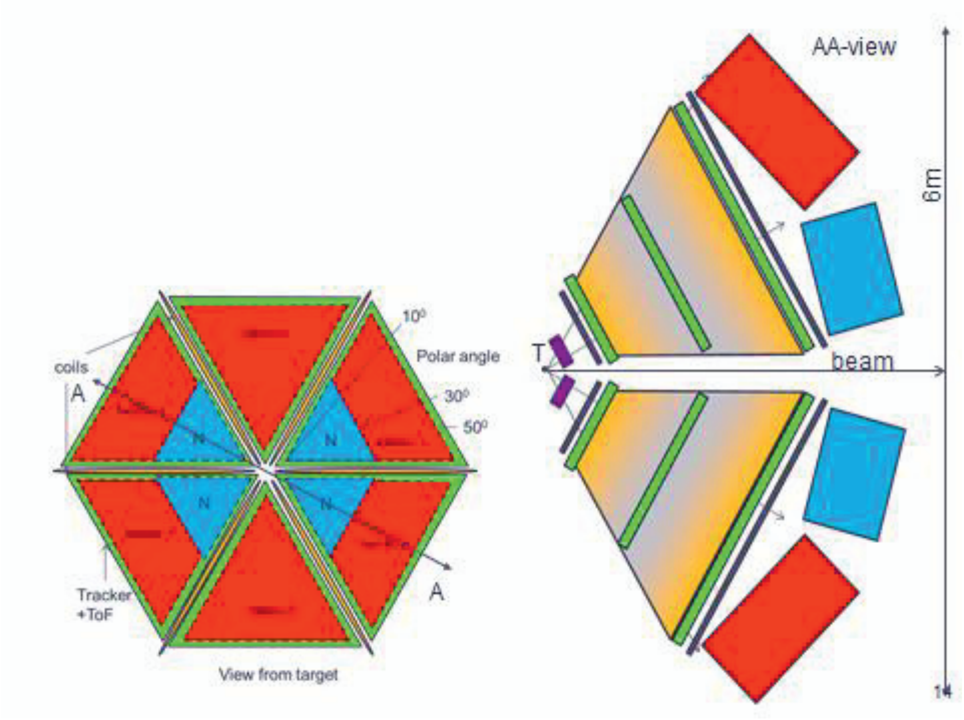

Figure . Current version of detector setup for the study of dense cold matter.

where N – nucleon (proton or neutron). It is assumed that the response on trigger photon will be localized at midrapidity at comparatively small transverse momenta $p_{tN} \leq p_{t\gamma}/(Q_1+Q_2)$, which will lead to increase of correlation function of photon and nucleon. The task of nucleons (protons) identification and measurement will be solved by using standard set of detectors: several slices of coordinate detectors (chambers) before and after the magnet and TOF system. Since the momenta of protons are comparatively small (0.3-1.2 GeV/c), but the multiplicity of secondary charged particles at these collision energies is comparatively small (~10-20), it is not needed to have record parameters of magnet, cameras and TOF system. Since the task of proton's momentum measurement is being solved by the tracking system and TOF is used for proton identification with $\beta<0.7$ on the base of $l>1$m, than the TOF system's precision required (~ 0.3 nsec) is not a big problem. Nevertheless, building of such arm using modern and reliable equipment is a serious task.

The discovery, localization and measurement of superdense cold matter temperature is possible using the charged particles detectors only, without taking into account the information about the neutral particles. The neutron detector is needed first of all to study the isotopic properties of superdense cold matter and the features of its space structure, particularly to measure the difference of proton-proton (neutron-neutron) and neutron-proton femtoscopical sizes. Since in dense and cold fermionic system, due to Pauli principle, the degrees of freedom should be maximally involved, the izosymmetrization of the droplet and decrease of neutron-proton femtoscopic radii compared to the proton-proton (neutron-proton) is expected. The measurement of the time when the signal comes with accuracy of ~0.2-0.3nsec is needed because the time-of-flight method for neutrons is used not only for identification, but also for momentum measurement.

The complementary opportunities for study of creation conditions and properties of superdense cold matter are proposed to be created by use of alternative forms of trigger with different izospin projections ($\pi^{\pm}$, π^0) or strangeness (K^0-π^0). It is expected that at the same kinematical conditions the cross sections of triggers will be different ($\sigma(K^0)>\sigma(\pi^0)$), and for izosymmetric colliding nuclei $\sigma(\pi^0)>\sigma(\pi^{\pm})$. For the fast identification of neutral kaons and improved identification of hyperons it is proposed to incorporate into the arm the vertex detector.

4 Conclusion

The way to create and to investigate a dense cold matter droplets in the laboratory is proposed. The reality of this approach are argued. Estimated possible statistic is large enough for detail study of the properties of such a matter. Detector configuration suitable for the proposed study are discussed.

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