PROSPECTS FOR CONSTITUENT(COLOR) QUARK CONDENSATE OF NUCLEAR MATTER STUDY AT NUCLOTRON AND ...

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Abstract

In this report will discuss a physical programm to study Constituent(Color) Quark Condensate(CQC) -the state of cold high density nuclear matter. Characteristics of CQC determines properties of matter inside massive stars and nevertheless can be probed in the laboratory experiments. Nowadays studies (cumulative processes and processes in region with $x_T \simeq 1$) have allowed to determine some characteristic properties of CQC. The offered program can advance considerably our understanding of properties of the superdense cold nuclear matter. We are stressing importance to carry out investigations with polarized beams of the lightest nuclei.

1 Introduction

A relativistic nuclei Nuclotron accelerator [1] operates and is continuously improved upon at the Veksler and Baldin Laboratory of High Energy Physics (VBLHEP). After the synchrophasotron was taken out of operation in 2003, Nuclotron is the basic accelerator for investigations in the field of relativistic nuclear physics and particle physics at JINR. The accelerator uses magnets with superconducting windings developed at the Laboratory of High Energies; it is capable of accelerating proton beams up to an energy of 12 GeV and nuclear beams up to 6 GeV/nucleon (currently, nuclei up to Kr are accelerated at Nuclotron). One specific feature of the accelerator complex of the Laboratory of High Energy Physics is the capability of investigating spin characteristics of interaction and spin structure of hadronic (nuclear) matter – polarization studies.

The possibility of creation of a collider at the Joint Institute for Nuclear Research (JINR) with energy up to $\sqrt{s_{NN}} \sim 10\ GeV$ is under discussion currently. The proposed physical program can be realized on the collider which will have some advantages. The presence of a wide set of polarized beams and targets makes the accelerator complex of the VBLHEP an ideal place for unique studies of the spin and quark - gluon structure of nucleons and the lightest nuclei.

The studies at the Laboratory of High Energy Physics (VBLHEP) of the Joint Institute for Nuclear Research focused on the investigation of hadronic (nuclear) matter at high densities and different temperatures when the degrees of freedom of quark and gluon, rather than of nucleon, begin to play the main role.

The last thirty years bring drastic changes in our knowledge about states of nuclear matter for different temperature and density [2]. Fig.1 from [2] shows the phase diagram (T(temperature)-μ_B(baryon number density))as a function of time. The solid lines indicate a first-order phase transition where could wait some jumps of physical parameters. The dashed line a rapid crossover region of where there is no some jumps. The nowadays (t∼2000) diagram shows that we deal with not only Quark - Gluon Plasma (QGP) but for the cold high density state we have some number of variants [3].

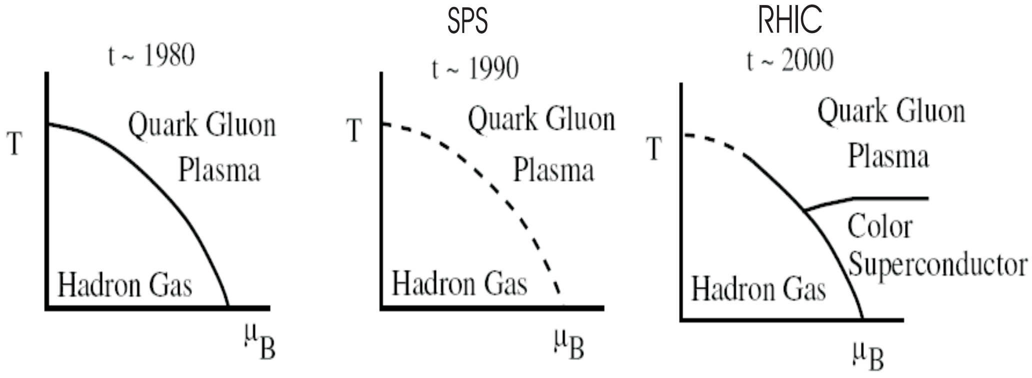

Figure 1: A phase diagram for QCD collisions. The Evolving QCD Phase Transition.

We know from the Rutherford time (and quantum theory) to find a state of nuclear matter having a small size and high density it is necessary to investigate processes with extremely high momentum transfers. Such processes are studying very intensively in VBLHEP(Dubna), ITEP(Moscow) and other places from the beginning of 1970s. The processes in kinematic region beyond the kinematical limits for interacting with free nucleons (named as **a cumulative processes**) gave us may be the main bulk of our knowledge about the superdense cold nuclear matter. These studies are using as target different nuclei and different particles and nuclei as projectiles. Last years many results came from JLAB from intensive electron beams. From the foregoing investigations we have well enough optimism to say that the superdense cold nuclear matter could be and should be detailly investigated in the laboratories.

2 Hadron and nuclear probes

First of all we must say about processes with high p_T. Investigations of pp - elastic scattering with polarized and unpolarized protons in the region $x_T = 1$ have shown that for $p_T \sim 2GeV/c$ can see (not explained up to now) deviation from theoretical models both for cross sections and for polarization characteristics [4]. Investigations with nuclei have yielded also unusual results. In the same place ($p_T \sim 2GeV/c$) were found the resonance deviations of the color(nuclear) transparency (CT)[5] and the R_{AA} at RHIC. The explanation for all these effects could be found in occurrence of multiquark configurations inside nucleons and nuclei. Discovered phenomenons can be explain as manifestation of transition from the multi scattering effects to the scattering on the multiquark configurations. There are many models which introduce the different multiquark configuration. The most popular models deal with the diquarks or the multiquark bags. Very attractive hypothesis is the color transparency [6] which says about occurrence of the small-size color-singlet configurations of the hadron which can thus propagate through the nuclear medium with minimal hadronic interactions. In other words there are configurations of white color hadrons which dimension is very small - the point like configurations of hadrons. A little bit later we will attract attention to very close relation between CT hypotheses and the Short Range Correlation (SRC) model.

In 1957 D.I. Blokhintsev has published the article [7] with hypothesis that a large momentum can be transferred to a complex system of nucleons as a whole when some nucleons are inside small volume. A multi-nucleon formation of this type has been called as a "flucton". Modern development of this hypothesis was stimulated by the experimental investigations of the cumulative processes [8].

The birth day of the cumulative processes was 1971 when this phenomena had been predicted by A.M. Baldin [9] and short time later was discovered by team of V.S. Stavinsky [10]. At JINR were concentrated mainly on the cumulative meson production. Before that time at ITEP (Moscow) team headed by G.A. Leksin has been continuing the studies of the Deep Inelastic Nuclear Reactions (DINR) where mainly the cumulative nucleons had been detected [11]. The bulk of experimental data of cumulative processes have been obtained by the inclusive setups in fragmentation regions of beams or targets. There are some very important features which have been discovered :

1) **The slope** cumulative particle spectra (the value of T_0 if inclusive cross section is approximated as $f = E\frac{d^3\sigma}{dp^3} = C \cdot exp(-\frac{T}{T_0})$) **is independent on type and energy of incident particle and atomic weight A of target nucleus**;

2) The isosymmetrization - **the ratios of hadron yields** (neutron to proton and π^+ to π^-) from the nonsymmetric heavy nuclei **approaches to 1** if energy of secondary hadrons increases;

3) The inclusive spectra of secondary particles as a function of the light cone variable $\alpha = \frac{E-p_L}{m_N}$ are similar at $\alpha > 1$ and **the cross section decrease with increasing number of constituent sea quarks (non u or d quarks) in the cumulative hadrons**.

From the first item we can make conclusion that cumulative particles haven't produced during compression but should be produced by "fluctons" which exist in ordinary nuclear matter before collisions as some fluctuation of nuclear density.Second item says that "flucton" is an isotopic singlet state with identical numbers of u and d quarks. Third item indicates that the sea components at "flucton" are suppressed. It means that inside ordinary nuclear matter there are blobs of the cold high density state which constituents are u and d quarks only - Constituent(Color) Quark Condensate (CQC).

In 1993 A.A. Baldin has shown that using scaling variables proposed by V.S. Stavinsky [12] there is possibility to describe data for cumulative and subthreshold processes using the same function for parametrization. In common case Stavinsky's variables describe nuclear-nuclear collisions of nuclei with atomic weights A_I and A_{II}. Four-momentums for these nuclei are P_I and P_{II}. For cumulative processes we can subtract subprocesses which characterized by the invariant value $s_{cumulat}$ which defines as

$$s_{cumulat} = (X_I \cdot \frac{P_I}{A_I} + X_{II} \cdot \frac{P_{II}}{A_{II}})^2.$$

The $s_{cumulat}$ need to compare with the invariant value s_0 defines as

$$s_0 = (\frac{P_I}{A_I} + \frac{P_{II}}{A_{II}})^2$$

which characterized free nucleon-nucleon interactions. Processes with $s_{cumulat} > s_0$ are forbidding for free nucleon-nucleon interactions.

Stavinsky's variables have differs compare with x variables for the quark-parton model. In the quark-parton model x did not fix and we need to integrate over the full range of x. The additional condition which fix variables have been introduced by Stavinsky. We need to take X_I and X_{II} only which give us the minimal value $min(s^{1/2}_{cumulat})$. Combination with the four-momentum conservation laws give us possibility for unique determination of variables. Thus defined X_I, X_{II} and $min(s^{1/2}_{cumulat})$ can use for uniform description of cumulative and subthreshold processes by phenomenological equation

$$E \cdot \frac{d^3\sigma}{dp^3} = C_1 \cdot A_I^{\frac{1}{3}+\frac{X_I}{3}} \cdot A_{II}^{\frac{1}{3}+\frac{X_{II}}{3}} \cdot exp(-\frac{\Pi}{C_2}),$$

where C_1 and C_2 are constants and

$$\Pi = \frac{1}{2 \cdot m_{nucleon}} \cdot min(s_{cumulat}^{1/2}),$$

where $m_{nucleon}$ is the nucleon mass.

Other proof can be received using the "flucton" model. In the frame of "flucton" model the cumulative cross section for $pA \rightarrow h + X$ reactions can be describe by

$$\sigma \sim P_K \cdot G_{h/K}(K),$$

where P_K is a probability to find the "flucton" consisting of K nucleons inside the nucleus. The $G_{h/K}(K)$ gives probability to produce hadron h by this "flucton". Main features of these models are existence of the "fluctons" with some probability and universal function which describe fragmentation "fluctons" into hadrons. Deep subthreshold particle production can be described by "flucton" - "flucton" — interactions in reactions $AA \rightarrow h + X$. If it so the cross section is

$$\sigma \sim G_{h/K}^2(K).$$

The parametrization from the item 1) give possibility direct estimation the slope of subthreshold particle production from the cumulative slope

$$T_0^{subthreshold} \approx \frac{T_0^{cumulative}}{2}. \qquad (1)$$

Comparison of the slopes for the cumulative pions [13] (at energy greater 4 GeV, $T_0^{cumulative} \simeq 60MeV$) and the subthreshold pions [14] (at energy less 40 MeV/u, $T_0^{subthreshold} \simeq 27MeV$) shows very nice coincidence with relation (1).

Other model which try to describe the cumulative processes says about nucleons with a very high momentum inside nuclei has been named short-range correlation(SRC)[15]. It is a some development the Fermi motion. Main features of SRC that there are nucleons with very high momentums($\bar{k}$) inside nuclei. The particle with sea quarks are produced in the nucleon-nucleon interactions. The reaction $pA \rightarrow p, n, ... + X$ can be describe by

$$\sigma \sim n(\bar{k}) \cdot \sigma_0,$$

where $n(\bar{k})$ is a probability to find the nuclear fragment with three-momentum $\bar{k}$ inside the nucleus. The particle with sea quarks from reaction $pA \rightarrow \pi, K, \bar{p}... + X$ will be describe by

$$\sigma \sim n(\bar{k}) \cdot \sigma(NN \rightarrow \pi, K, \bar{p}... + X),$$

where $n(\bar{k})$ is a probability to find nucleon with three-momentum $\bar{k}$ inside the nucleus. This model have dealing with nucleons with very high momentum which haven't lost the individuality on distances less the nucleon radius. Here we should remember about CT model which says about the point like configurations of hadrons too but without any correlation with other ones.

The programm how to resolve the main question about validity of "flucton" or SRC was proposed in [16]. We need more complete studies in region of maximal p_T in semi-exclusive and exclusive experiments to understand the nature of cumulative processes. It will need to investigate:

- average number of baryons accompanied high p_T cumulative particle production and its $s_{cumulat}$ or $< X >$ dependances;

- average multiplicity accompanied high p_T cumulative particle production and its $s_{cumulat}$ or $< X >$ dependances;

- $s_{cumulat}$ dependence of polarization characteristics (analyse power, asymmetry and so on), for SRC mechanism will be scaling repeating effects for free nucleon-nucleon interactions.

These investigations will give us new important information to define real mechanisms which respond the processes with $x > 1$. We could receive proof about SRC or "flucton" structures inside nuclei (in the last case we will investigate the some features of "fluctons" too). We must stress that up to now we haven't quantitative predictions for these exclusive(quasi-exclusive) cumulative characteristics with high p_T from the theoretical side.

Studies with polarized beams [17] can open new unique capabilities for CQC investigations. The availability of polarized beams of the lightest nuclei at Nuclotron and in future at new collider allows one to solving a number of the most fundamental problems of the structure of nuclear (hadronic) mater as:

— investigate $pp, pd, dd, p^3He, d^3He,^3 He^3He$ collisions with polarized beams, which will allow one to solve the puzzles of the spin structure of nucleons and lightest nuclei and elucidate the specific features of the spin structure of interaction in the region of nonperturbative QCD; it is especially important that it will be possible for the first time to study the interaction of polarized nuclear matter whose properties may determine the structure of the core of massive stars with great magnetic fields;

— elucidate the nature of strong polarization effects in NN - interactions at $p_lab > 6\ GeV$ in the region of limiting large p_T, which has not been explained yet, and find out how these specific features are related to the change of behavior of valence quarks in this kinematic region; the availability of polarized nuclei at a collider will allow one to study the complete isotopic set of states of nucleonnucleon system (nn, pn, and pp) for the first time;

— study in detail the problems of P and T parity violation in NN - interactions;

— solve the problem of the nature of cumulative (subthreshold) processes;

— elucidate the nature of quark counting rules violation and determine the region of their applicability (including at interaction of lightest nuclei);

— solve the puzzle of resonance behavior of color transparency at $p_lab \sim 9.5\ GeV/c$ ($p_T \sim 2\ GeV/c$).

3 Conclusion

Is it possible to obtain the cold high density nuclear matter in a laboratory? Studies of cumulative (subthreshold) processes have shown that we observe the CQC state in which nuclear matter exist at low temperatures and densities which exceed the ordinary nuclear (hadron) density up to ten times [14]. The density three times greater then ordinary density has been observed in the processes of the deep inelastic scattering (DIS) of electrons on the nuclei in JLAB [18]. It has been shown that CQC with a certain probability exists in the ordinary nuclei (not be produced during the collision). It is clear that the probability of CQC state should be increased when outer pressure will grow and there is no energy gap for the transition to the CQC phase for whole nucleus and nuclei. Moreover it means that the diagram (t 2000) from Fig.1 not valid for the low temperature and high density region where has been predicted the first-order phase transition. In this region we can wait the crossover transition same as in the CGC region.

The properties this form of nuclear matter determine the physical properties of matter in the center of massive stars and, possibly, it is directly connected with the riddles of the explosions of supernovas. The discovered enormous magnetic fields in stars (up to $\sim 10^{17}$ T) can lead to the fact that the Constituent(Color)Quark Condensate (CQC) will be polarized. Therefore the polarization characteristics of super-dense nuclear matter not only are interesting by themselves, but they have important significance to developing the theory of evolution of massive stars.

This analysis allows one to make the following conclusions. In the region of the Nuclotron energies and in view of the future development of the accelerator complex of the Laboratory of High Energies of the Joint Institute for Nuclear Research, experiments with beams of polarized lightest nuclei in the energy region up to $\sqrt{s_{NN}} < 10\ GeV$ allow one to contribute in the solution of some of the most fundamental problems of the structure of lightest nuclei and nucleons in the valence quarks dominance region, the so called nonperturbative QCD region. In particular:

— there is a realistic possibility of solving the puzzle of the large polarization effects in elastic pp scattering at an angle of 90 in the center of mass system which has not been described theoretically yet;

— it is possible to elucidate the nature of the resonance form of energy dependence of color (nuclear) transparency; the topical character of this problem is related to the observation of the jet quenching effect in nuclearnuclear collisions at high energies which has a similar energy dependence at the range $p_T \sim 2\ GeV/c$;

— it is possible to determine the main mechanism of cumulative particles formation (and simultaneously the ways subthreshold particles are produced), which would answer the question of the possibility of the existence of mutliquark states at high densities of nuclear matter (these states of nuclear matter determine the scenarios of the evolution of massive stars).

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