Could Dense Quark Matter be a Source of Super High Energy Cosmic Rays?

Mais Suleymanov

COMSATS Institute of Information Technology, Islamabad, Pakistan

We propose that the dense quark matter could be a source of the high-energy secondary hadrons. These particles can be created from hadronization of the parton(s), which possess the energy of grouped partons from coherent interactions as a result of their collective behavior in high dense medium. The medium might be formed in the center of some massive stars, and it could be a source of the super high-energy cosmic rays. In this work we consider some experimental results as an evidence on collective phenomenon, that can lead to coherent interactions in high dense medium and production of the high-energy secondary hadrons.

§1. Introduction

Cosmic rays can provide us an important information on appearance and evolution of the Universe. Since super high energy particle beams (greater than $10^{17-18} \text{eV}$) are not available in ground-based laboratories, super high energy cosmic rays are the only resource to study interactions of the particles in this energy domain. The source of super high energy cosmic are still unknown. The electromagnetic fields generated by some massive stars are considered as plausible sources for the super high energy cosmic rays, however, some theoretical predictions show that these fields could be too weak to accelerate particles to energies of order $10^{15} \text{eV}$. In conclusion, we see that it is necessary to look for a new source mechanism of super high energy cosmic rays, that doesn’t involve acceleration.

§2. Conditions

The dense quark matter can be a source of the super high energy particles under following 3 conditions satisfied simultaneously:

1. Dense and/or hot quark matter with density $\rho >> \rho_0$, and/or with temperature $T >> T_0$ ($\rho_0$ and $T_0$ are the values of the density and the temperature of the normal nuclear matter);

2. Collective behavior of partons in the medium and formation of coherent parton group;

3. Coherent interaction in the system.

In these conditions the maximum energy of the produced partons are limited only by the values of the total energy of the system, where the values of energy will depend on the parameters of the system.
§3. What did we have until now?

3.1. First Condition - Dense and/or Hot Quark Matter

It is widely discussed that the dense and/or hot quark matter can be formed in the center of some massive stars, for example as a result of supernova explosion, and could lead to the neutron stars formation.

3.2. Second Condition - Collective Behaviour

3.2.1. JINR Cumulative Effect

At relativistic energies we had the first signal on collective behavior - JINR Cumulative effect. It lead to the notion of production of particles with energies beyond the kinematic limit of free nucleon collisions. The effect was deeply discussed in the paper and below you can see some ideas from it. Few interesting points:

- observation of the pions with energies $\simeq 8\text{ GeV}$ in $D + A$ reactions at $5\text{ A GeV}$;
- in the $B + A \rightarrow C + X$ reactions the particles $C$ were produced with $x > 1$.

The values of the $x$ can be defined as $x = \frac{u}{s} \simeq \frac{(\varepsilon - p\cos\theta)}{m}$, here $u$ and $s$ are the Mandelstam invariants, $m, \varepsilon, p$ and $\theta$ are the mass of nucleon, the total energies, the 3 momentum and the emission angle for the $C$ particles respectively, in the lab frame. For free nucleon collisions the values of $x$ must be limited by 1. But as we can see from Fig. for hadron-nuclear interactions at JINR energies particles were emitted with $x > 1$.

![Fig. 1.](image1.png) ![Fig. 2.](image2.png)

The JINR cumulative effect has very peculiar properties, some of them are listed below:

1. It has been observed for photon-nuclear; lepton-nuclear; hadron-nuclear and nuclear-nuclear interactions.

2. The strong $A$-dependences were indicated for the invariant inclusive cross sections of the cumulative particles ($f(p) = \varepsilon \frac{dN}{dp}$).

3. The inverse of the slope for $\varepsilon \frac{dN}{dp}$ behavior as a function of $x$ has a universal value $< x > \simeq 0.16$.

The theoretical interpretation of the effect proposed that it is a result of nucleon collective phenomena and the cumulative particles could be produced from the system of collected nucleons- coherent groups of nucleons. The latter could be formed as a result of fluctuations of nuclear density, the interaction of the projectile with target nucleons, and nucleon percolation. So we can say that JINR cumulative effect can be considered as a phenomenon with nucleons collective behavior and...
coherent interactions.

3.2.2. CERN EMC Effect

European Muon Collaboration (EMC) investigated the muon deep inelastic scattering on iron and deuterium. They found the big disagreement between experimental result and theoretical expectations. The experimental result shown that the $F_2$ and hence the quark and gluon distributions of a nucleon bound in a nucleus differ from those of a free nucleon. None of the popular models suggested to explain the EMC effect seem satisfactory and present a new point of view on the effect as a simple relativistic phenomenon. The effect can also be considered as a result of nucleon collective phenomena.

3.2.3. Azimuthal Anisotropy at RHIC and LHC

Azimuthal anisotropy observed experimentally at RHIC and LHC shows a collective behavior, which is likely to be formed at an early, parton, stage of the space-time evolution of the produced hot and dense matter. The anisotropy indicates that matter under extreme conditions behaves as a nearly ideal liquid rather than an ideal gas of quarks and gluons. Scaling behavior of $v_2$ vs $p_T$ gives a possibility to assume that the collective behavior of the partons defines the dynamics of the expansion in the longitudinal plane namely (see Fig.2)

The first measurement of elliptic flow of charged particles in $Pb-Pb$ collisions at the center of mass energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ A GeV, with the ALICE detector, demonstrated that the $v_2(p_t)$ does not change within uncertainties from the $\sqrt{s_{NN}} = 200$ GeV to 2.76 TeV. ALICE LHC data demonstrated that values of the $v_2$ increase with energy.

3.3. Third Condition - Coherent Interactions

We have not had any experimental signal on coherent parton interactions. But we had the Coherent "Tube" Model (CTM) which can give us even a clearer explanation for the energetic (cumulative) particle production. Here the interaction of a hadron with a target nucleus results from its simultaneous collision with the tube of nucleons of cross section $\sigma$ that lie along its path to the target nucleus. For the interaction of projectile with momentum $p_{lab}$ the cumulative square of the center-of-mass energy is $s_i \approx 2imp_{lab}$ ($i$ is a number of nucleons, $m$ - a nucleon mass). The paper quantitatively described unusually strong $A$ dependence (stronger than the commonly assumed $A$ or $A^{2/3}$) of the cross section for $p + A \rightarrow J/\Psi + X$ reaction at incident energies below 30 GeV, using cumulative effects (via energy rescaling). Ref discusses the CTM for high energy nucleus-nucleus collisions. In this case two tubes are considered: $i_1$ nucleons in incident tube and $i_2$ nucleons in the target tube. The c.m. energy squared for this tube-tube collision is approximately given by $s_{i_1i_2} \approx 2i_1i_2mp_{lab}$.

§4. Physical Picture

So we could say that:
1. In the high density (and/or high temperature) nuclear matter the collective
behaviour of partons could lead to formation of the coherent groups of partons.

2. As a result of the coherent interactions the parton(s) could be produced with limited large values of $x \rightarrow 1$ and hardonize to super high-energy particle(s), since in this case the resulting energy will also depend on the parameters of the system, so the energy of energetic particle can only be limited by values of the total energy of the system.

3. The coherent interactions and formation of the super high energy parton(s) can change the $x$ distribution of the partons.

4. A medium with high density (and/or high temperature) close to the QCD critical one could be a source of cosmic particles with super high energies, and could be created in the center of some massive star. The parton(s) with large values of $x$ or energy can be formed in this system as a result of collective phenomenon and coherent interactions, hadronize and appear as super high-energy cosmic particles. Their energies can only be limited by the values of total energy of the grouped partons.

This physical picture assumes the existence of two strong correlations in the hot and dense matter: between the partons with limited small values of $x \rightarrow 0$; between partons with limited large values of $x \rightarrow 1$ and limited small values of $x \rightarrow 0$. It means in hot and dense matter the $x$ distribution of partons can vary and can get the structure with two additional maxima at $x \rightarrow 1$ and $x \rightarrow 0$.

The observation of super high energy particles could be a signal on the hot and dense states of strongly interacting matter, as well as on the Quark Gluon Plasma formation.

References

1) V.L. Ginzburg, Phys. Usp. 36, 7 (1993) 587.
2) K.V. Ptitsina and S.V. Troitsky, Phys. Usp. 187, 7 (2010) 587.
3) A. G. Lyne and F. G. Smith, Pulsar Astronomy (Cambridge University Press, 1990).
4) A.M. Baldin et al., Sov.J.Nucl.Phys. 18, (1973) 41; Journal of PEPAN, 8, (1977) 429
5) A.V. Efremov, PEPAN, 13, (1982) 613
6) V.S. Stavinski, Journal of PEPAN, 10 (1979) 949
7) D.I. Blokhintsev, JETP 32 (1957) 1295
8) H. Satz, hep-ph/0212046 Janusz Brychczyk, nucl-th/0407008 C. Pajares, hep-ph/0501125
9) J.J. Aubert et al., Phys. Lett. 123B, (1983) 275
10) A. V. Efremov, Phys. Lett. 174B, (1986) 219
11) V. A. Okorokov, Physics of Atomic Nuclei, 72, 1 (2009) 147
12) J. Adams et al., Phys.Rev.Lett. 95, (2005) 122301
13) A. Adare et al., Phys.Rev.Lett. 98, (2007) 162301
14) K. Aadodt et al., arXiv:1011.3914
15) G. Berlad, A. Dar and G. Eilam, Phys. Rev. D 13 (1976) 161; S. Frederiksson, Nucl.Phys.B 111 (1976) 167; L. Bergstrom, S. Frederiksson, Phys. Lett.B 68, (1977) 177; Y. Afsk et al., Technion Hifa preprint TECHNION-PH-7722,1978; Y. Afsk, G. Berlad, G. Eilam and A. Dar, Technion Report No. PH-76-12
16) Y. Afsk, G Berlad , G. Eilam and A. Darf Phys. Rev.Lett. 37 (1976) 947
17) Y. Afsk, G. Berlad, A. Dar and G. Eilam, Technion No.PH-76-87