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ASPECTS OF MATTER-ANTIMATTER ASYMMETRIES IN  
RELATIVISTIC HEAVY IONS COLLISIONS AND  
ASTROPARTICLE PHYSICS

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# Aspects of matter-antimatter asymmetries in relativistic heavy ions collisions and Astroparticle Physics

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Matter-antimatter asymmetries observed in high energy / relativistic heavy ion collisions and, differently, in the Early Universe are discussed considering ideas from the phase diagram of strong interactions with assumptions that do not necessarily rely on non-equilibrium conditions, and that are based in effects such as spontaneous symmetry breaking.

## Introduction

Matter-antimatter asymmetry has been observed in the Universe and has become a relevant aspect, in another level of knowledge, for the understanding of the phase diagram of matter and the dynamics of the heavy ions collisions done for investigating strong interactions and beyond. From the cosmological point of view, although there are several indications that the Universe is constituted rather by matter [1] there still are (theoretical and experimental) investigations about the possibility of existing hidden antimatter [2]. On the other hand, relativistic (and high energy density) heavy ions collisions (r.h.i.c.) provide an appropriate system for investigating aspects related to matter-antimatter production although at an energy scale far smaller than that which is (usually) considered to have generated the eventual matter-antimatter asymmetry of the Universe. In fact it is observed that, rising the collision energy in, for example, AGS, RHIC and SPS (expected to occur in LHC), the ratio of (each kind) anti-hadrons to hadrons increase and seemingly goes to a value close to 1 already at RHIC energies. In these energies the deconfinement and chiral phase transition are expected to occur. In this communication some effects expected (or proposed) to be in the phase diagram of strong interactions, which can be of relevance for these two very different systems, are discussed.

## Chiral symmetry restoration and antimatter in relativistic heavy ion collisions

There are some mechanisms to explain and predict the ratio of matter to antimatter in (relativistic) heavy ions collisions and thermal models are known to reproduce most of the observed ratio [3, 4]. Whereas the sum of the baryon and antibaryon is nearly constant over a wide range of energy collision (from SIS up to RHIC experiments) their difference ( $\rho_B - \rho_{\bar{B}}$ ) has a minimum for energies between those of the AGS and SPS collisions. From these it is obtained that the volume of the region occupied by the fireball and then the hadrons until chemical freeze-out should increase with the energy of the collision besides the appearance of other effects for the dilepton emission [5].

However it is fair to ask the following question [6, 7]: can this antimatter production be associated to the chiral symmetry restoration? It will be considered that this would correspond to "breaking" or evaporating the QCD scalar quark-antiquark condensate into real quarks and antiquarks which are then bound (confined) very quickly in the expanding environment. On the other hand, it is also possible to consider that the scalar condensate is pushed away from the region where deconfinement occurs [6]. These would be two competing mechanisms and to what extent each of them would contribute to the dynamics will not be really addressed here. Different contributions for the profiles for the energy density in the coordinate space would arise [6].

The injection of energy in the vacuum which is expected to contain this condensed state can excite it and produce non condensed particles. Suppose that, inside the region of the fireball, quarks and gluons are deconfined and chiral symmetry - whose order parameter is assumed to be the quark-antiquark scalar condensate - is restored. For this, it can be also assumed that the infinite volume reservoir of scalar condensate in the Universe will quickly occupy this small region as the temperature or energy density lowers with time and hadronization takes place.

A naive estimate with the volume of the fireball before hadronization at the energies of RHIC up to LHC can be obtained as a fraction of estimated volumes for the chemical freeze out. This can provide roughly  $V = 1,500 fm^{-3}$  at RHIC energies [8, 9]. For the QCD scalar condensate will be considered as a density of quarks-antiquarks, from lattice QCD:  $\langle (\bar{q}_R q_L + \bar{q}_L q_R) \rangle \simeq (250 MeV)^3$ . The total number of quarks and antiquarks would be of nearly 1,500, for 100% of restoration of chiral symmetry inside this volume. This can be a considerable part of the total hadron multiplicity in most central events at RHIC (for example Au-Au at  $\sqrt{s_{NN}} = 200 GeV$ ) equal to nearly 7,000 [4]. However the relation between the value of the scalar condensate and the number of quarks which can be obtained from it can be more complicated. Without further considerations about the energy of the reaction, the colliding nuclei and other effects present in the dynamics and hadron structure, this number could produce up to nearly 750 (light) mesons or 375 baryons and 375 antibaryons. Eventually there can have production of

a particular species of hadron (baryons/antibaryons or mesons) favored from this effect.

Consider, for example, that the total yield of protons and antiprotons obtained in hadronization phase of r.h.i.c. for nuclei-nuclei with  $Z = \alpha A_t$  (fraction of the mass number, gold  $A_t = 198, \alpha = .40$ ) are given respectively by:  $N_p = \alpha A_t + N_p^{cr}$ ,  $N_{\bar{p}} = x_e N_p = y_e N_p^{cr}$ , where  $N_p, N_{\bar{p}}$  are respectively the number of protons and antiprotons in the final state and  $N_p^{cr}, N_{\bar{p}}^{cr}$  are the number of protons and antiprotons created in the collision.  $x_e = x_e(\sqrt{s_{NN}}, \mu_B, T)$  is a coefficient dependent on the energy of the energy, chemical potential and temperature. The coefficient  $y_e$  is equal to 1 when the baryonic number is conserved (equal amount of baryons and antibaryons are created), and it can depend on the energy at the early Universe cosmological scales. Manipulating these expressions the following expression for the number of protons and antiprotons created during the collision at an energy  $e$  is obtained:

$$N_p^{cr} = \frac{\alpha x_e A_t}{y_e - x_e}, \quad N_{\bar{p}}^{cr} = \frac{y_e \alpha x_e A_t}{y_e - x_e}. \quad (1)$$

The same reasoning can be applied to the other baryons/antibaryons although it does not necessarily take into account inelastic in medium effects after hadronization. For  $x_e^i \simeq \sqrt{s_{NN}}/(a_i + b_i \sqrt{s_{NN}})$  as a parametrization for each of the hadron ( $i$ ) created (and its yields), it can be written that:  $p_{cr}^i \simeq \sqrt{s_{NN}}/(a_i y_e + (b_i y_e - 1)\sqrt{s_{NN}})$ , which can be good as long as  $b > 1$  [3].

### Finite density and Temperature

Consider a general finite density system in the Minkowski space. In curved space time the corresponding formalism is much more involved making difficult, for example, the interpretation of particle number besides other aspects [10]. The temporal component of the vector field will be considered to be a dynamical degree of freedom which can develop a sort of classical component (which can be an effective component) [11]. They modify the solutions of the fermion fields and the corresponding densities and may not be just a shift to the chemical potential.

At zero temperature the leading terms of the expressions of fermion and antifermion (number) densities calculated from the solution of the associated Dirac equation coupled to  $A_\mu$  or  $A_0$ . The density of fermions and antifermions ( $\rho_{M, \bar{M}}$ ) are given by:  $\rho_{M, \bar{M}} = \int_0^{k_F} \bar{\psi} \gamma_0 [k, A_0] \psi [k, A_0] d^3 k$ , they were exhibited in [13] without the corresponding thermal contribution. These expressions are different from those for Fermi liquids. Different contributions emerge for other densities (scalar, pseudoscalar) which can trigger other kinds of condensation [13, 14]. A coefficient measuring the asymmetry of the components is proportional to  $A_0$  (or  $A_0^2$ ).

The conditions under which classical vector field would develop are not investigated here [11, 15]. Considering an inhomogeneous classical vector field with components  $A_0 = A_0(\mathbf{r}, t)$  and  $A_i = A_i(\mathbf{r}, t)$ , inhomogeneities in the fermionic densities can emerge naturally. This can produce non trivial contributions for the dynamics of matter-antimatter including their "chemical equilibrium".

### Condensed diantiquarks in high energy density

It has been shown that diantiquarks can condense depending on external classical vector fields with nearly the same interactions that make diquark to condense in high density color superconductivity [16]. Gluons, besides other vector fields in strong interactions, can assume many different configurations including some which are treated like classical parts, including with topological properties [11, 15]. Besides the usual infinite color superconductor which can be present in the core of dense stars (and correspondingly the "infinite" medium di-antiquark superconductor) it has been shown that it is possible to produce diquark condensation in finite size system [17]. Suppose that there can have particular gluonic configurations which can mimic a classical vector field inside the hadrons such that (in the range of values and configurations) a di-antiquark condensation occurs inside hadrons where the quarks move almost freely [16]. The energy density inside a baryon is already quite high and this condensate would shift the total quark masses.....

On the other hand, this could provide a possible explanation for the baryon-antibaryon asymmetry in the Universe because, if (most of the) quarks became confined into baryons, the antiquarks would have been condensed at the time of the early confinement phase transition being trapped inside hadrons. However the number of antiquarks needed to make this kind of condensation (inside a baryon for instance) could easily be greater than the number of quarks in the baryon structure ( $N=3$ ).

### Cosmological scenarios

Besides being relevant for the "microscopic" dynamics of relativistic heavy ions collisions these effects discussed above could have cosmological consequences in the Early Universe providing eventually another way of producing domains of matter and antimatter [1, 2, 13].

Below the confinement phase transition ( $T_c \simeq 170$  MeV) there should have a configuration and energy density that allowed for quarks and antiquarks which eventually were confined into baryons/antibaryons and mesons and also which have formed the QCD scalar condensate. The total amount of quarks and antiquarks would have been used to form hadrons and the scalar condensate although there might have been other kinds of ("exotic")

objects, for example in [4]. Several scenarios for considering a more "symmetric" matter-antimatter Universe have been considered along the years. Ideas like "antimatter islands" in the observed Universe with anti-stars and even anti-galaxies have been searched without success due mainly to the absence of antimatter in cosmic rays, to the most probable consequences for Cosmic Microwave Background Radiation (CMBR) and absence of antineutrinos from (anti)Supernovae although in some of this ideas further investigations are done [1, 2, 13]. In particular diffuse anti-world and a outer antimatter region of the Universe still seem to be plausible [1, 13].

The violation of CPT [12] in the early high energy density Universe could also introduce different gravitational interactions for matter and antimatter large enough as to provide different expansions rates. If  $m_m \neq m_{\bar{m}}$ , just for some small time interval, this might have been enough to somewhat decouple part of the expansions rate of matter and antimatter hindering complete mutual annihilation. Furthermore the time in which these domains would have been formed is relevant for defining the resulting scenario. Besides that, stronger antimatter gravitational attraction could have been responsible to collapses yielding, eventually, antimatter blackholes (ABH) or objects akin to early blackholes [18]. At LHC energies mini black holes are expected to appear [19] and the eventual formation of ABH as well as whether they are distinguishable from matter blackholes could be tested.

The corresponding quark-antiquark equations in an expanding environment, considering two kinds of CPT violating terms, could read:

$$\begin{aligned} (i\gamma_\mu(\nabla^\mu - gA^\mu(x)) + m_p - a_1\phi(\mathbf{x}))\psi(\mathbf{x}) &= 0, \\ (i\gamma_\mu(\tilde{\nabla}^\mu - gA^\mu(x)) - m_{\bar{p}} + a_1\phi(\mathbf{x}))\bar{\psi}(\mathbf{x}) &= 0, \end{aligned} \quad (2)$$

Solutions with relevant effects will be shown elsewhere.

Considering the above scenarios it is interesting to rise questions about the spatial distribution of baryons/anti-baryons (and hadrons/anti-hadrons in general) produced in AGS/RHIC/SPS/LHC. Besides the possibility of forming (anti) black-holes at the LHC energies the spatial localization of quarks-antiquarks in the hadronization stage could provide information about mechanisms relevant in this phase.

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