Aspects of matter-antimatter asymmetries in Astrophysics and relativistic heavy ion collisions

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Matter-anti-matter asymmetry, expected to be very large in the Universe, is rediscussed considering effects which might not have been considered entirely before and which can also be relevant for (high energy densities) relativistic heavy ion collisions Effects from the phase diagram of strong interactions are raised for that.

I. INTRODUCTION

The idea of antimatter as a negative energy solution of relativistic free fermion equation as given by Dirac raises the issue of why the (observed) Universe is apparently constituted by matter whereas fundamental theories of elementary particle indicates the same laws for (creating) matter and antimatter [1, 2, 3, 4, 5]. In fact, observational Astrophysics and Cosmology indicate a large baryon-antibaryon asymmetry in our Universe from cosmic background radiation (CBR) and cosmic rays observations [2, 4, 5]. The most successful mechanisms which can generated this asymmetry are based on nonequilibrium conditions (together with non conservation of baryonic number, CP violation) of the early Universe, as proposed by Sakharov [6], although most of them do not seem to be sufficient [2]. The existence of "hidden" antimatter could provide a reasonable solution for this problem although antimatter in cosmic rays data and other experimental data analysed in some situations such as to yield domains ("islands") do not provide basis to believe that galaxies/stars of antimatter could be present neither in the closer clusters of galaxies nor in distances smaller than the size of the observed Universe [4]. Photons resulting from matter-antimatter annihilation in the borders of the islands would be present in cosmic rays/CMBR and their absence can be indication of no antimatter islands for regions smaller than nearly 20 Mpc. Other absent observational evidences for the discredit of the existence of antimatter islands are [5]: the missing of (very) light (primordial) anti-nuclei ($\overline{He}$) emitted from anti-stars in cosmic rays and finally the non-observation of antineutrinos from antisupernovae events - which would be a strong indication of the corresponding antimatter processes for realising energy in such objects [5]. It is our believe however that the general idea of "hidden antimatter" (making the Universe less baryonic-antibaryonic asymmetric, if not totally symmetric) cannot be completely discarded yet. There are still observations to complete the present knowledge: searching for light antinuclei in cosmic rays, investigating with more details the CMBR anysotropies and polarization (Planck mission) and eventually searching antimatter in other forms or places [5]. The breaking of CP symmetry is a relevant effect which would have allow for the baryogenesis. One possible effect which can be responsible for CP violation is briefly reminded, namely, the formation of a pseudoscalar condensate, being amplified in a dense medium as observed in experimental reactions. This mechanism of CP violation is not really completely forbidden by fundamental theorems [7, 8, 9]. CPT symmetry might also have been broken and, in this case, astrophysical matter - antimatter asymmetry would have to be reanalysed. In this sense it is worth to remind that CPT theorem is strictly valid for local gauge field theories in Minkowski spacetime, making more certain its behavior in the early Universe and eventually in certain astrophysical objects. However, in this communication, different scenarios for the existence of (primordial) antimatter are still considered [8].

In this article the following issues are addressed (based in [8, 10, 11]): aspects of antimatter components in Astrophysics, eventually considering primordial antimatter as hidden antimatter, which could yield small corrections to the Hubble's law; associated issues of relevance for relativistic heavy ion collisions. With experiments in (relativistic and high energy) heavy ion collisions in BNL and CERN the investigation of matter and antimatter production rates at high energy densities has been largely favored [12]. For these subjects, aspects of the phase diagram of strong interactions with (spontaneous) symmetry breakings expected and/or envisaged to occur are briefly discussed.

II. GENERAL ASPECTS

A general field theory with fermions, vector (gauge), and spin zero fields (ϕ_i, including interacting terms $V[\phi_i]$), in curved space time with non minimal coupling of gauge and scalar fields to the gravitational field can be given by [13]:

$$S = \int d^4x \sqrt{-g} \left\{ \frac{i}{2} \bar{\psi} \left(\gamma_\mu \mathcal{D}^\mu - m - a_1 \Gamma_i \phi^i \right) \psi + \mathcal{L}_{\phi_i, A_\mu, R(\mathbf{x})} \right\}, \tag{1}$$

where $\sqrt{-g}$ is the square root of the determinant of the metric, $\mathcal{D}^{\mu}$ is a covariant derivative with gauge and vector fields, $R(\mathbf{x})$ is the Ricci scalar, and the various Lagrangian densities are denoted simply by $\mathcal{L}_k$. In most part of this work it is assumed that at least one vector field can be treated classically - being eventually associated to a spontaneous symmetry breaking, as a "condensed" field. This can be considered for different phases of the early Universe. The non minimal coupling of vector (gauge?) fields to gravity yields a sort of "effective mass" to them in strong gravitational fields which may help condensation. In such conditions spatial anysotropies can occur [9], given that the vector fields usually are associated to gauge symmetries. The respective inhomogeneities could manifest and have constraints due to the measured CMBR and formation of large structures.

In the limit of flat space time the eigenvalues of the Dirac equation for fermions and antifermions coupled to a classical vector field are given by $E^{\pm} = g_V V_0 \pm \sqrt{(\mathbf{p}+\mathbf{V})^2 + (M^*)^2}$, where M^* takes into account terms which modify the (anti)fermionic mass. These solutions do not have the symmetry of the matter-antimatter in the vacuum. Should the vector field component V_0 become negative at zero density the eingenvalues associated to antimatter are more relevant but at finite densities things are more subtle. This component of the classical vector field might also be due to certain gluonic degrees of freedom in the deconfined phase of QCD at high temperatures/energy densities [9, 14].

Considering that due to the curved metric and/or to in medium effects the fermions have their wave function such that: $\vec{\nabla}\psi \simeq (\vec{F} - i.\vec{k})\psi$ and $\vec{\nabla}\bar{\psi} \simeq (\vec{G} + i.\vec{k})\bar{\psi}$ where F and G can be constants or functions of momenta such that it is possible to define (different) effective masses for fermions and antifermions in a non-homogeneous configuration.

However the geometry at the scale of the Universe is determinant in several ways. The Dirac equation for a fermionic and an antifermionic fields in a Friedmann-Robertson-Walker metric are given by:

$$(i\gamma_\mu(\nabla^\mu - g_v V^\mu) + m_\psi - a_1\phi(\mathbf{x}))\psi(\mathbf{x}) = 0, \qquad (2)$$

$$(i\gamma_\mu(\nabla^\mu - g_v V^\mu) - m_{\bar{\psi}} + a_1\phi(\mathbf{x}))\bar{\psi}(\mathbf{x}) = 0, \qquad (3)$$

where both the differential operator and the Dirac matrices depend on the geommetry. Besides that the masses were consider to incorporate eventual effects from CPT breakdown. The particle number in curved space time has intrinsic subtleties [13] which will not be addressed here.

The usual scenario for describing the observed Universe with (nearly) equal quantities of matter and antimatter (constituted by islands / domains of matter and antimatter) considers that inflation would have kept these domains apart hindering mutual annihilation [4, 5]. However considering that most (if not all) matter (antimatter) from the early Universe was created just after inflation it is reasonable to think about domains of matter and antimatter which could have been kept apart due to particular mechanisms [5, 9] reducing the flow of particles towards the annihilation zone [4].

A. Finite densities in Minkowski space

Asymmetries between fermions and anti-fermions at finite density (chemical potential) could have had different configurations and dynamics in the early Universe, as well as they seem to exhibit in relativistic heavy ions collisions, and some other examples and cases are considered elsewhere [8, 9, 11].

B. Some speculative scenarios

Different scenarios for the matter-antimatter (inhomogeneous) configurations can be formulated for different matter-antimatter asymmetries.

One of the most investigated possibilities for the problem of antimatter in Cosmology was called "antimatter islands" as discussed above [4]. Different ways of explaning why the observations discussed above do not provide evidences for these islands is proposed in the following.

Even if the existence of stars/galaxies of antimatter would be ruled out in the future cosmic rays investigations [5], other possibilities remain open. For instance, these light nuclei could have been suppressed in collisions before reaching Earth.

However if CPT had been broken in the Early Universe in such a way as to make antimatter domains to collapse faster than matter "antimatter made black holes" (such the Primordial Black Holes) there would have been formed. These "anti-black holes" could eventually be responsible for a considerable amount of (hidden) antimatter. They could be even present in very energetic places such as the center of the Galaxy [17]. Effects in the dynamics of black holes and anti black holes may not be observed however.

Finally consider the dynamics of relativistic heavy ion collisions in particular associated to the antiparticle-particle ratios (which increase with the increase of energy densities) created at finite energy density [12]. Besides the possible contribution of (nonhomogeneous) vector fields (classical or not) as discussed above for the case of particle-antiparticle ratios and configurations it is also argued in [9, 11] that the different ratios in the yields of baryons and antibaryons in relativistic heavy ions collisions may be a signature of the restoration of the spontaneously breakdown of chiral symmetry.

C. Other developments

Antimatter in dense stars: di-antiquarks condensation. Some partial effects of classical tensor and vector fields, eventually associated to classical gluonic configurations, were considered to the formation of superconductive states at very high densities in a schematic model. These classical fields can favor the appearance of condensates of di-antifermions $< \overline{qq} >$ besides the usual di-fermions (di-quarks) condensates $< qq >$ in color superconductivity in a way similar to that showed above for finite density fermions [15]. There is the possility of coexistence in dense stars.

Raising issues on Hubble's law Deviations from the Hubble's law expansion (eventually to be coped with ideas related to the so called "quintessence" [1]) can be suggested by: (i) the observation of very far Supernova type I in the edges of the observed Universe, (ii) the small fluctuations in different scales of distance-speed of recession of galaxies. The formation of large scale structures from fluctuations still allows to ask whether Hubble's law [16] has anisotropic corrections compatible with observations [1, 8]. In relativistic heavy ions collisions the flow of particles usually follow a quite well defined Hubble's flow. However there still are hints of deviations [14].

III. CONCLUDING REMARKS

In this article several scenarios were discussed for the matter-antimatter asymmetry of the visible Universe. Some of the aspects can be eventually useful for the investigation of antimatter present in relativistic heavy ions collisions. Some issues relevant also for the Hubble's law (and eventually for the corresponding Hubble's flow in relativistic heavy ions collisions) were also briefly discussed. It was pointed out that CPT invariance might have been broken (more probably in the past), besides the usual breakdown of T reversal (and the corresponding CP invariance) which is observed in strong and weak processes, contributing either to the stronger baryogenesis or the different scenarios in which the baryon-antibaryon asymmetry is smaller than observed nowadays in Astrophysics. This issue can have also relevance for the understanding of other deep questions such as: where, when, how and at which level does time arrow appear such that (our) "thermodynamical" Universe emerges? would an "antimatter thermodynamical domain of Universe" have the same behavior and laws of our matter dominated domain (if it is really a domain) In this sense it seems to be fair to ask whether light antinuclei (He) from anti-stars could be expected to be as abundant as the light nuclei from stars ?

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