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Aspects of matter-antimatter asymmetry and states for Astrophysics and Cosmology (and very high energy densities Physics)

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Matter-antimatter asymmetry observed in our Universe is discussed with attention to different effects which are (or may be) present in the phase diagram of matter. Some implications which can be eventually present in astrophysical objects are also discussed. They may not rely on non-equilibrium conditions. For this, spontaneous (or not) symmetry breakings expected and/or envisaged to occur in the phase diagram of matter are briefly discussed and different scenarios for particular periods of the early Universe are proposed which can also yield aspects of relevance for formation of large structures. Issues which can be of relevance also for the Hubble's Law are raised.

Keywords: Antimatter, cosmology, astrophysics, asymmetry, condensed vector field, classical vector field, symmetry breaking,inhomogeneities, Hubble's law, r.h.i.c.

1. Introduction

Dirac's interpretation for the positive and negative energy eingenvalues of relativistic free fermions as matter and antimatter solutions (in several ways this is a very "symmetric case") has been largely articulated over the decades [1,2]. Observational Astrophysics and Cosmology indicate a large baryon-antibaryon asymmetry in our Universe from cosmic background radiation (CBR) and cosmic rays observations [3,4]. Although the mechanisms which would have generated this asymmetry are based on nonequilibrium conditions of the early Universe, as proposed by Sakharov [6], most of these mechanisms do not seem to yield enough asymmetry to describe the observational data [3]. Estimations based on the standard Big Bang nucleosynthesis taking into acount CMBR fluctuations yield a ratio of the baryon density to the photon density to be around $\frac{\rho_B}{\rho_\gamma} \simeq (6.1 + .3 - .2) \times 10^{-10}$. The baryons would represent only nearly 5% of total energy density of the Universe while dark matter would correspond to at least 1/3 of this total energy density [3]. As discussed in this contribution "hidden" antimatter would be a suitable (although maybe partial) solution for this problem.

In the scope of the CPT theorem time reversal is expected to be broken since P and CP invariances are broken [2]. CP violation will not be discussed here although it is of its great relevance. Althought this provides a privileged time direction CPT theorem is strictly valid for local field theories in Minkowski spacetime and these conditions are not present in the early Universe and eventually in other astrophysical objects.

In this article the following issues will be addressed: (1) whether there can exist at least part of the primordial antimatter as hidden antimatter; (2) eventual contributions of antimatter components in astrophysical objects such as dense stars [7]; (3) issues of relevance also for the Hubble's law and eventually rhic. For these issues, aspects of the phase diagram of strong interactions with (spontaneous) symmetry breakings expected and/or envisaged to occur are briefly discussed. This subject has relevance for other questions such as where, when, how and at which level time arrow appears such that (our) "thermodynamical" Universe emerges. In the preparation of this work I became aware that "islands" of anti-matter had been proposed to be present in our 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. With experimental relativistic heavy ion collisions in BNL, GSI and CERN the investigation of matter and antimatter production rates at high energy densities has been largely favored [8].

2. General remarks

A general field theory with fermions, gauge, scalar and vector fields (ϕ_i, V_μ with 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 [9]:

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

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, $R(\mathrm{x})$ is the Ricci scalar, and the various Lagrangian densities are denoted simply by $\mathcal{L}$. In most part of this work it is assumed that at least one vector field condenses, being eventually associated to a spontaneous symmetry breaking. This can be considered for different phases of the early Universe. The non minimal coupling of gauge fields to gravity yields a sort of "effective mass" to it in strong gravitational fields which may help them to condense. In such conditions spatial anysotropies can be favored which could manifest themselves in the CMBR and large structures.

The eigenvalues of the Dirac equation for fermions and antifermions considering only the temporal component of a classical vector field (or vector meson field), with a chemical potential μ, are given by $E^{\pm} = g_V V_0 + \mu \pm \sqrt{\mathrm{p} + M^*}$, where M^* takes into account terms which modify the (anti)fermionic mass. The classical field V_0 can be redefined and from here on it will be denoted shortly $g_V V_0 + \mu \to V_0$. These solutions do not have the symmetry of the matter-antimatter in the vacuum. Should the vector field component V_0 become negative in the vacuum the eingenvalues associated to antimatter can be favored but at finite densities things are more subtle.

2.1. *Finite densities in Minkowski space*

Consider a general finite density environment in the Minkowski space [10]. The leading terms of the expression of fermionic and antifermionic energy densities $\rho_f^{M,\bar{M}}$(basically irrespectively to the fermion under consideration) AND the fermionic and antifermionic densities $\rho_B^{M,\bar{M}}$(measuring their number per volume), with normalized spin and internal spaces wavefunctions $\varphi^{+,-}$ are given respectively by:

$$\begin{aligned}
\rho_f^{(M,\bar{M})} &\simeq \frac{\gamma}{(2\pi)^3}\int^{k_F^i} d^3k \left(\frac{2E^i_{(+,-)}(M_i^* + E^i_{(+,-)}) + V_0(V_0 - 2E^i_{(+,-)})}{2(M_i^* + E^i_{(+,-)})}\right)|\varphi^{(+,-)}|^2 + ...; \\
\rho_B^{(M,\bar{M})} &\simeq \frac{\gamma}{(2\pi)^3}\int^{k_F^i} d^3k \left(\frac{(M_i^* + E^i_{(+,-)})^2 - \mathbf{k}^2}{2M_i^*(M_i^* + E^i_{(+,-)})}\right)|\varphi^{(+,-)}|^2 + ...
\end{aligned} \tag{2}$$

Where k_F^i are the momenta at the respective Fermi surface and M_i^* the effective masses. There still are other less relevant terms which are composed by fermion-antifermion mixed states and depend on the relative momenta. These expressions are not the same of those for Fermi liquids.

In Figure 1 the fermionic and the antifermionic (with signal minus) energy densities (respectively ρ_f^M and $-\rho_f^{\bar{M}}$) are plotted as functions of the classical expected value of the field V_0 as defined above encompassing a chemical potential. It is seen

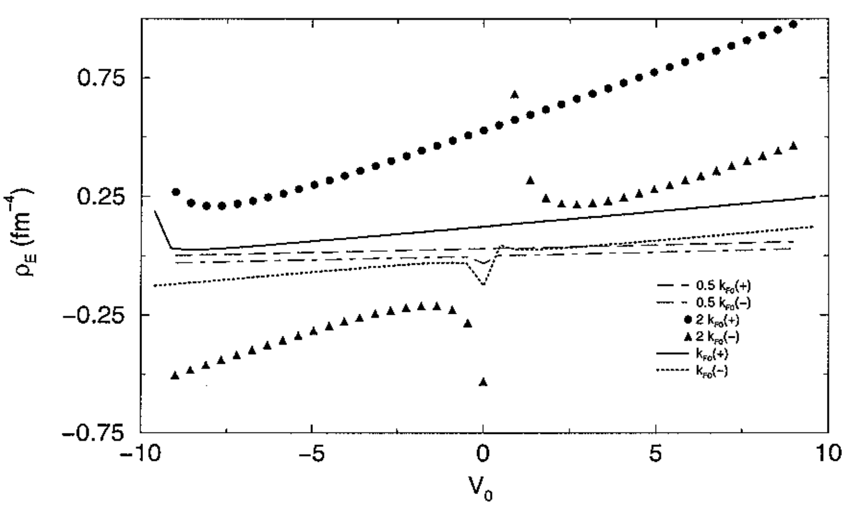

Fig. 1. Fermionic and (minus) antifermionic energy densities (ρ_f^M and $-\rho_f^{\bar{M}}$) as functions of the (effective) classical component of vector field V_0 for different Fermi momenta (i.e. several $\rho_B^{M,\bar{M}}$).

that matter or antimatter configurations are favored for different values of V_0 at different Fermi surfaces (k_F). There is a singularity in $\rho_f^{a.m.}$ at $V_0 = 0$ suggesting no stable antifermionic bound state. It still is possible to consider $M^* \neq M^*_{\bar{M}}$ for the effective masses, for example if CPT is broken [2].

The coefficient which measures the ratio of these components, in a static environment as a first approach to the problem, provided they do not annihilate, can be defined as: $\omega = (\rho_{\bar{B}} - \rho_B)/(\rho_{\bar{B}} + \rho_B) \propto V_0$. The negative values may be associated to unstable or time-varying states. Therefore considering the above expressions, for equal values of effective masses and Fermi momenta, the antimatter density is privileged, for example, when $K_F > \sqrt{V_0(2M^* + V_0)} artanh \frac{K_F}{\sqrt{V_0(2M^*+V_0)}}$ or when $V_0.(2M^*_{a.m.} + V_0) > 0$ for very large absolute value of $V_0 < 0$. The conditions under which this kind of strong classical vector field would develop are not investigated here, although at very high densities this can be expected at least for massive spin one fields [11]. The asymmetry disappears in several cases, such as: $V_0 = 0$, as it should, $V_0 = -M^* = -M^*_{\bar{M}}$, and few other values of the parameters. These expressions can be nearly valid for a variety of situations of different fermions.

2.2. *Some speculative scenarios*

More realistic cases seem to appear when V_0 is not an homogeneous quantity, i.e., when $V_0 = V_0(\mathbf{r})$, modifying the above equations with $V_0(\mathbf{r}) \to \tilde{V}_0(\mathbf{k})$. Different scenarios for the matter-antimatter inhomogeneous configurations can be formulated for different matter-antimatter asymmetries. The geommetry at this time is determinant in several ways. The Dirac equation for a fermionic and an antifermionic fields are given by:

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

where the Dirac matrices depend on the geommetry. The particle number in curved space time has intrinsic subtleties [9] which will not be addressed here. Suppose that for the $\vec{\nabla}\psi \simeq (\vec{F} - i.\vec{k})\psi$ 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 nonhomogeneous configuration. This can be obtained, for example, within a non local theory, which by the way, does not necessarily garantees the CPT theorem. In this case $\phi[F, G]$.

One resulting possibility for the above ideas, already mentioned, was called "antimatter islands" [4]. Another one is that, by the violation of CPT theorem or not, gravitational interactions for matter and antimatter would have been large enough as to provide different expansions rates. Even if $m_m \neq m_{\bar{m}}$ for some small time interval this may be enough to somehow decouple part of the expansions rate of matter and antimatter in the early Universe. This would eventually prevent them to annihilate each other. Furthermore the time in which these domains would have been formed is relevant for defining the resulting scenario even because inflation mechanism would cause further implications. **(i)** Stronger antimatter (gravitational) attraction (for example by means of larger antiparticle masses) would yield tendence to faster collapses either in "islands of antimatter" and/or eventually anti-black-hole-kind objects, primordial ones akin to those discussed by Horvath and Stocker in this meeting for different energy scales. **(ii)** Consider that, in a (nearly) isotropic situation, most of matter is created in a radial direction against the direction of expansion while antimatter in the opposite way, coherently as to say. This can function mainly for the case of nonlocal particle creation. While matter could have been created, for example, inwards the antimatter would be ejected outwards expanding faster than matter. Mutual annihilation can be avoided. keeping antimatter towards the edges of our Universe. All these events are to be thought mainly in "average" because it can require to think about a center in the Universe [12]. The actual expansion could have to do with effects between the inner matter dominated region and the outer one dominated by antimatter. This could yield eventually strong and catastrophic events in the edges depending on the actual expansion rates variation.

Some aspects of this work can be partially considered for the relativistic heavy ion collisions providing information about quantum chromodynamics, electroweak and other unification theories [8]. In particular the ratio of antimatter to matter is increased with respect to low energy [8]. In another work I argue that it can be related to the restoration of chiral symmetry [13].

Different topologies for the Universe could also account for the unobserved antimatter which would be present in a different sector of the Universe, inaccessible to observations, such as in a (single or double) "Moebius belt hypersurface" configuration.

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 [7]. These classical fields can favor the appearance of condensates of di-antifermions $< \overline{q}\overline{q} >$ besides the usual di-fermions (di-quarks) condensates $< qq >$ in color superconductivity in a way similar to that showed above for finite density fermions. The possility of coexistence in dense stars is an opened issue.

3. Raising issues on Hubble's law

In some cases discussed above the isotropy or homogeneity of the system were broken. When a vector field condenses and when matter and antimatter are created in different domains. For large scale structures were created from fluctuations (decoupled from CMBR fluctuations, appearing in the different eras) it is fair to ask whether Hubble's law [14] has anisotropic corrections.

The anysotropic fluctuations in the CMBR observed by COBE and HUBBLE telescopes can indicate that the anysotropies in the large structure formation can eventually be tested by mapping appropriatedly the receding galaxies. The Hubble's law could then be written nearly as:

$$\frac{\dot{R}}{R} = H_0 \left\{ (1 + f(\theta, \varphi)) - q_0(1 + g(\theta, \varphi))(t - t_0) \right\}, \tag{4}$$

where θ, φ are spherical coordinates, H_0 is the Hubble constant, q_0 is the decelerating parameter (it may depend on a cosmological constant, if it exists). f, g ccan be decomposed in multipolar modes and may be related to the CMBR.

4. Concluding Remarks

In this article several scenarios were discussed where the matter-antimatter asymmetry of the visible Universe can be smaller than usually expected or even zero. Some issues relevant also for the Hubble's law were discussed.

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