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**ROCHELLE SALT:
A PROTOTYPE OF PARTICLE PHYSICS¹**

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Abstract

Rochelle salt has a remarkable characteristic of becoming more ordered for a range of high temperatures before melting. In the particle physics language this means more symmetry breaking for high T . In many realistic field theories this is a perfectly consistent scenario which has profound consequences in the early universe. In particular, it implies that there may be no domain wall and monopole problems, and it may also play an important role in baryogenesis if CP and P are broken spontaneously. In the case of the monopole problem this may require a large background charge of the universe. The natural candidates for this background charge are a possible lepton number in the neutrino sea or global continuous R-charges in supersymmetric theories.

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1 Introduction

Intuition and experience tell us that with increasing temperature physical systems become less ordered. It is appealing to believe that this is a universal physical law, but surprisingly enough there are exceptions. The well known counterexample is a Rochelle salt which, when heated up crystalizes more, at least for a range of temperatures, until it eventually melts[?]. This is a remarkable phenomenon and one would like to know how general it is. It turns out to be a natural possibility in many realistic particle physics theories. We can divide its source in two different categories:

a) *microscopic properties of the theory*. Here we have a range of parameters in the Lagrangian which allows for nonvanishing vevs at high temperature[?, ?, ?, ?]. The theory in question must have at least two Higgs multiplets, a natural feature of any extension of the standard model (SM).

b) *macroscopic external conditions*. It is exemplified by a large background charge density of the universe and has nothing to do with the underlying microscopic theory. In this case, for large enough charge density, symmetries get broken at high T in all of the parameter space [?, ?]. The natural candidates for such charges are lepton number in SM [?, ?, ?] and continuous global R-charges in supersymmetry [?, ?].

Both scenarios are very appealing; however, they are far from being automatic. The questions are:

i) why should we live in the parameter space that allows for high T symmetry breaking in case a)? ; and ii) what could have created large background charge in case b)? We have no answers yet to these questions. However, the consequences of this phenomenon are striking, and worth discussing. First of all, if at high T symmetries do not get restored, there may be no domain wall [?, ?]and monopole problems [?, ?]. It has been known for a long time that during phase transitions from the unbroken to the broken phase topological defects get formed [?]. In the case of discrete symmetries the resulting defects, the domain walls, are a cosmological catastrophe, since a single large wall carries far too much energy density [?]. The monopole problem is rather different: a single monopole poses no problem at all, but during the GUT phase transition we get too many of them [?]. If, on the other hand, there is no phase transition, these problems would simply disappear. This is similiar to inflation, and should be not viewed as an alternative to it, but rather as a complementary phenomenon. As we discuss below, inflation better take place (after all, it is the solution to the horizon problem). However, it does not have to take place at lower temperatures. This may be of great help in model building.

Second, symmetry breaking at high T may play an important role in baryogenesis, if it takes place at temperatures much above the weak scale and if CP and P are spontaneously broken at lower scales. Spontaneous breaking of P and T symmetries provides an alternative to the axion as the solution of the strong CP problem [?, ?, ?]. Thus, if symmetries are not restored

at high temperature, parity and time-reversal symmetries would remain broken as to allow for a nonvanishing baryon density [?].

2 Symmetry breaking at high temperature

We now discuss the possibility of our particle theories mimicking Rochelle salt. We wish to achieve symmetry breaking at high T, i.e. we wish to have a scalar field ϕ possessing a nonvanishing VEV for $T \gg m$, where m is the relevant physical scale. Since in such a case T becomes the only scale of the theory, one expects for $T \gg m$

$$\langle \phi(T) \rangle \simeq T \tag{1}$$

and thus we would have more order with increasing temperature. In other words the effective mass term for ϕ at high T needs to be negative. We have already said that the sources of this may be either microscopic or macroscopic, which we now discuss.

2.1 Microscopic

This is purely a property of an underlying theory and it requires at least two scalar multiplets. Namely, the effective mass term for a field ϕ at high T has the form [?]

$$\mu^2(T) = (g^2 + |h|^2 + \lambda)T^2 \tag{2}$$

where g , $|h|$ and λ stand for the gauge, Yukawa and scalar contribution, respectively. Also, the equation is symbolic in a sense that the precise coefficients are omitted since they play no role in the qualitative picture we are discussing here. The first two terms are manifestly positive, and in the single field case so is the last one, since $\lambda > 0$ is the necessary condition for the boundedness of the potential. However, if there are more scalar fields, some of their couplings are allowed to be negative and the $\mu^2(T)$ need not necessarily be positive. There is a finite parameter space which corresponds to a negative high T mass term and a nonvanishing VEV [?, ?, ?]. However, for realistic values of gauge couplings this parameter space becomes very small, and next to the leading terms seem to invalidate this picture [?]. This is a crucial fact to keep in mind when we discuss the monopole problem below. On the other hand, in the case of global symmetries without large Yukawa couplings, the high T symmetry nonrestoration is a perfectly valid scenario [?, ?, ?, ?] and it plays an important role for the domain wall problem.

What happens in supersymmetric theories? The learned reader could have already noticed that the above mechanism of symmetry nonrestoration is not compatible with supersymmetry [?, ?], since supersymmetry relates Yukawa and scalar couplings and we have already argued that the Yukawa contribution to the mass term is always positive. It does not help to include the nonrenormalizable interactions [?, ?], although there has been some promise originally [?]. On the other hand, in theories with flat directions the idea of nonrestoration seems to work [?].

2.2 Macroscopic

This is the case of the nonvanishing background charge density of the universe. To illustrate the phenomenon, take a simple case of the complex scalar field ϕ with a global $U(1)$ symmetry

$$\phi \rightarrow e^{i\alpha} \phi \quad (3)$$

and let us assume a nonvanishing background charge density n corresponding to the charge Q : $Q = nV$, where V is the volume. Notice that if the charge Q is conserved during the expansion of the universe, the density grows with the temperature: $n \simeq T^3$, since $V \simeq T^{-3}$. The effective potential for the field ϕ at high T ($T \gg m$, where m is the $T = 0$ mass term) and high density $n \simeq T^3$ is readily found to be [?, ?]

$$V(n, t) = \frac{n^2}{2(|\phi|^2 + T^2/3)} + \frac{\lambda}{6} T^2 |\phi|^2 + \frac{\lambda}{4} |\phi|^4 \quad (4)$$

It is clear that the first term prefers ϕ to be nonvanishing, as opposed to the second high T mass term. For sufficiently large density n

$$n > n_C = \frac{1}{3} \sqrt{\frac{\lambda}{3}} T^3 \quad (5)$$

ϕ has a nonvanishing VEV and the symmetry is broken independently of what happens at $T = 0$ [?]. There is nothing mysterious about symmetry breaking in this case: for sufficiently large density it becomes more advantageous for the system to store the charge in the vacuum rather than in the thermal modes. This is what we meant by macroscopic: symmetry breaking at high T is due to the macroscopic conditions in the universe and has nothing to do with the space of the parameters of the microscopic theory. All that is needed is a sufficiently large background charge on the order of the entropy (actually even smaller), a rather natural condition. Of course, whether or not it is easy to achieve this condition is not so clear and requires more serious study.

A more interesting question for us is what charge can play this role. In the standard model we have a perfect candidate: lepton number. At low T , lepton number is a perfect symmetry, at least on cosmological time scales, and we have a neutrino sea in the universe with a density on the order of the photon density, i.e. on the order of entropy. If the neutrino sea were to carry a lepton number, the gauge symmetry of the SM would remain broken at high T . We shall discuss the consequences in the following section.

An important feature of this phenomenon is that it is equally operative in supersymmetric theories [?]. I discuss it here from the conceptual point of view; for computational and technical aspects see the talk of Borut Bajc at this conference [?]. Actually in supersymmetry there is another perfect candidate for the background charge. Many supersymmetric models possess global continuous R-charges, i.e. charges that do not commute with supersymmetry. In fact, in the supersymmetric standard model there is an automatic $U(1)$ R-symmetry, even if one allows all the gauge invariant terms in the superpotential, including those that break matter parity

(R-parity). If the universe had a large background R-charge in the early universe, the gauge symmetries of the MSSM would have been broken at high T. Of course, soft supersymmetry breaking terms also break the continuous R-symmetry and thus eventually wash out the original R-charge. It is easy to estimate the rate of the R-breaking processes to be of order [?]

$$\Gamma_R \simeq \sqrt{m_S T} \quad (6)$$

where $m_S \simeq m_W$. Thus for temperatures below $10^7 - 10^8 GeV$ the R-breaking processes are in thermal equilibrium and they will wash out any memory of the previous charge. This is a remarkable situation. We may have a dramatic impact of R-charges on cosmology without them leaving any trace today.

It is interesting to see what happens in the context of GUTs. In general R-symmetries are not automatic and, in fact, in the minimal supersymmetric $SU(5)$ GUT there is no such symmetry. On the other hand, in the minimal model the GUT scale is put in by hand, or better yet, the ratio between the GUT and the weak scale is fine-tuned. It is far more appealing to have this ratio determined dynamically through radiative corrections and soft supersymmetry breaking. Fortunately, this attractive scenario cries for R-symmetry.

Let me illustrate this on a simple model [?] based on $SU(6)$ grand unified theory and an adjoint representation superfield Φ . If one adopts a philosophy of not introducing any mass terms by hand, the most general superpotential for Φ has the form

$$W = \lambda Tr \Phi^3 \quad (7)$$

It has a manifest $U(1)$ R-symmetry $\Phi \rightarrow e^{i\alpha} \Phi$, $\theta \rightarrow e^{3i\alpha/2} \theta$, i.e. $\phi \rightarrow e^{i\alpha} \phi$, $\psi \rightarrow e^{-i\alpha/2} \psi$, where ϕ and ψ are the scalar and fermionic components of the superfield Φ . At zero temperature, from

$$F_\phi = \lambda(\phi^2 - \frac{1}{6} Tr \phi^2) = 0 \quad (8)$$

and with ϕ diagonal as to make V_D vanish, the supersymmetric minimum has a flat direction

$$\phi = \phi_0 \text{diag}(1, 1, 1, -1, -1, -1) \quad (9)$$

The flat direction is a result of the original R-symmetry and it will be lifted by the soft supersymmetry breaking terms. In the usual manner the scale ϕ_0 is then determined radiatively and it is naturally superlarge. The original $SU(6)$ symmetry gets broken to its $SU(3) \times SU(3) \times U(1)$ subgroup, which implies the existence of monopoles. We shall not dwell on this here, for us it is sufficient to note the role that R-symmetry plays in this picture. In the same manner as before, if the background charge is large enough, the $SU(6)$ symmetry will not be restored at temperatures above the GUT scale. The effective potential at high temperature and high density has a form

$$V(n, T) = \frac{n^2}{2(4Tr \Phi^\dagger \Phi + (105/4) T^2)} + 6g^2 T^2 Tr \Phi^\dagger \Phi + V_F + V_D \quad (10)$$

where V_F and V_D are the $T = 0$ potentials. It is easy to see that in this case for the density bigger than the critical one

$$n > n_C = \frac{105}{4} \sqrt{3} g T^3 \quad (11)$$

the symmetry remains broken and no phase transition takes place. This provides a solution to the monopole problem. One can implement the same idea in the $SU(5)$ theory, but in order to make it work one needs to increase the Higgs sector to two adjoint and one singlet representation [?]. The model is identical in spirit to Witten's original idea [?].

3 Discussion and outlook

We have seen above that the idea of high T symmetry breaking is quite legitimate and has important cosmological consequences. Let us discuss the most important ones.

3.1 Domain wall problem

The phenomenon of symmetry nonrestoration in general works perfectly well, as long as the discrete symmetry in question is broken by a gauge singlet field. There are numerous examples of singlets in this role, the most notable one being the invisible axion model which suffers from the axionic domain walls [?]. They get formed at the temperature on the order of the QCD phase transition when the walls get attached to strings formed earlier [?]. All we need is to eliminate the original phase transition at the scale of the breaking of the $U(1)_{PQ}$, so that the strings do not get formed in the first place. This is easily achieved. One must worry also about the thermal production of domain walls, but this too is under control [?, ?]. Of course, unless inflation had taken place before, there would be no reason for the Higgs field to have the same orientation throughout the universe. Thus this program depends on inflation -here we are completely orthodox, however inflation is allowed to take place at any time before the scale of would have been defect formation, i.e. the $T = 0$ mass scale of the theory. This is a general feature of everything we say in the rest of this talk.

3.2 Monopole problem

In order to solve the monopole problem we can either nonrestore the grand unified symmetry above the unification scale [?] or break electromagnetic charge invariance at nonzero temperatures below it [?]. Due to large next-to-leading terms in gauge theories, this is hard, if not impossible, to achieve in the microscopic scenario. It is here where the external background charge of the universe plays a natural role. In the SM it could be a large lepton number, in which case it becomes easy to incorporate the breaking of electric charge [?]. The same can be said of the MSSM. This is in principle observable (although difficult in practice) and it will be important to know the content of the neutrino sea, hopefully to be observed in not too distant future.

On the other hand, in supersymmetry the natural candidate is provided by the often present global continuous R-symmetries. The MSSM, and its extension without matter parity, have an automatic $U(1)$ R-symmetry at the renormalizable level, and it is rather easy and appealing to construct GUTs with R-symmetries, as a way of generating the GUT scale dynamically.

3.3 Baryogenesis and spontaneous breaking of P and CP

Why should one resort to the spontaneous breaking of parity and time-reversal? Well, there is an aesthetic motive, for these are fundamental space-time symmetries. More important, spontaneous breaking means less divergent high energy behaviour and this may be instrumental in the solution of the strong CP problem. Namely, in models with spontaneous breaking of these symmetries, especially if supersymmetric [?, ?, ?], the strong CP phase can be calculable and small. These theories, though, are plagued with the domain wall problem which can be solved via high T nonrestoration.

The nonrestoration is also crucial for baryogenesis [?] in order to satisfy the breaking of P and CP as one of the three Sakharov's conditions. This issue was raised in the context of $SO(10)$ GUT [?], where C is a gauge symmetry and is necessarily spontaneously broken. If the scale of the breaking of C is much below the GUT scale, and if baryogenesis originates at the GUT scale, we must have nonrestoration [?].

We make one final comment. In the minimal model of spontaneous CP violation with two Higgs doublets [?], in the absence of external charge at high temperature the symmetry is restored [?]. Here the charge (such as the lepton number of the SM) makes it work [?], eliminating the domain wall problem and making the case for high T baryogenesis.

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