WHAT IS FOUND UPON DEFROSTING THE UNIVERSE AFTER INFLATION

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At the end of inflation the universe is frozen in a near zero-entropy state with energy density in a coherent scalar field and must be "defrosted" to produce the observed entropy and baryon number. Baryon asymmetry may be generated by the decay of supermassive Grand Unified Theory (GUT) bosons produced non-thermally in a preheating phase after inflation, thus solving many drawbacks facing GUT baryogenesis in the old reheating scenario.

1 Prologo

Before going into details, let me explain the origin of the term "defrost" and its derivatives. After inflation the universe appears slightly boring: no particles around, zero-entropy density, no thermal bath and all the energy density stored in the inflaton scalar field. It is clear that the universe must undergo a sort of phase transition from this state to produce the observed entropy and a thermal bath of particles. This process was denominated "defrosting" by R. Kolb. However, our collaborator A. Linde felt rather uncomfortable with this denomination. He wrote (quote):"... It is a cool idea and I am sure that Rocky will use this word in one of his brilliant talks. However, I really have severe problems with it. First of all, I associate it with the frozen chicken breasts, which I cannot stand...". In spite of Andrei's opinion, I decided to adopt the term "defrosting" anyway when Rocky dropped in my office and, with a very strong Chicago-Mafia accent, asked me how would I have translated the expression "I break your legs" in italian.

2 GUT Baryogenesis at Preheating

In models of slow-roll inflation, the universe is dominated by the potential energy density of a scalar field known as the inflaton. Inflation ends when the kinetic energy density of the inflaton becomes larger than its potential energy density. At this point the universe might be said to be frozen: any initial entropy in the universe was inflated away, and the only energy was in

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*b That sounds something like "Ti spezzo le gambe" in italian.
cold, coherent motions of the inflaton field. Somehow this frozen state must be transformed to a high-entropy hot universe by transferring energy from the inflaton field to radiation.

In the simple chaotic inflation model the potential is assumed to be $V(\phi) = M_\phi^2 \phi^2 / 2$, with $M_\phi \sim 10^{13}$ GeV in order to reproduce the observed temperature anisotropies in the microwave background. In the old reheating (defrosting) scenario, the inflaton field $\phi$ is assumed to oscillate coherently about the minimum of the inflaton potential until the age of the universe is equal to the lifetime of the inflaton. Then the inflaton decays, and the decay products thermalize to a temperature $T_F \approx 10^{-1} \sqrt{\Gamma_\phi} M_P$, where $\Gamma_\phi$ is the inflaton decay width, and $M_P \sim 10^{19}$ GeV is the Planck mass.

In supergravity-inspired scenarios, gravitinos have a mass of order a TeV and a decay lifetime on the order of $10^5$ s. If gravitinos are overproduced after inflation and decay after the epoch of nucleosynthesis, they would modify the successful predictions of big-bang nucleosynthesis. This can be avoided if the temperature $T_F$ is smaller than about $10^{11}$ GeV (or even less, depending on the gravitino mass).

In addition to entropy, the baryon asymmetry must be created after inflation. There are serious obstacles facing any attempt to generate a baryon asymmetry in an inflationary universe through the decay of baryon number ($B$) violating bosons of Grand Unified Theories. The most tedious problem is the low value of $T_F$ in the old scenario. Since the unification scale is expected to be of order $10^{16}$ GeV, $B$ violating gauge and Higgs bosons (referred to generically as “$X$” bosons) probably have masses greater than $M_\phi$, and it would be kinematically impossible to produce them directly in $\phi$ decay or by scatterings in a thermal environment at temperature $T_F$.

However, reheating may differ significantly from the above simple picture. In the first stage of reheating, which was called “preheating” effective dissipational dynamics and explosive particle production even when single particle decay is kinematically forbidden. A crucial observation for baryogenesis is that even particles with mass larger than the inflaton mass, $M_X \sim 10 M_\phi$, may be produced during preheating by coherent effects provided that a coupling to the inflaton field of the type $|X|^2 \phi^2$ is present. A fully non-linear calculation of the amplitude of perturbations $\langle X^2 \rangle$ at the end of the broad resonance regime has been recently done revealing that $\langle X^2 \rangle$ may be as large as $10^{-10} M_P^2$. Since the value of the inflaton field $\phi_i$ at the beginning of preheating is of order of $10^{-2} M_P$, one may assume that the first step in reheating is to convert a fraction $\delta \sim 10^{-4}$ of the inflaton energy density into a background of baryon-number violating $X$ bosons. They can be produced even if the reheating temperature to be established at the subsequent stages of reheating is
much smaller than $M_X$. Here we see a significant departure from the old scenario. In the old picture production of $X$ bosons was kinematically forbidden if $M_{\phi} < M_X$, while in the new scenario it is possible as the result of coherent effects. The particles are produced out-of-equilibrium, thus satisfying one of the basic requirements to produce the baryon asymmetry. The next step in reheating is the decay of the $X$ bosons. We assumed that the $X$ decay products rapidly thermalize. It is only after this point that it is possible to speak of the temperature of the universe. Moreover, we assumed that decay of an $X-\overline{X}$ pair produces a net baryon number $B/\epsilon$ (where $\epsilon$ is the CP-violating factor), as well as entropy. We have numerically integrated the Boltzmann equations describing the temporal evolution of the baryon number, of the energy density of $X$-particles and of the inflaton field. Since the number of $X$ bosons produced is proportional to $\delta$, the final asymmetry is proportional to $\delta$ and we have noted that $B/\epsilon \sim 10^{-9}$ can be obtained for $\delta$ as small as $10^{-6}$.

Our scenario is based on several assumptions about the structure of the theory, but the feeling is that baryon number generation may be relatively efficient. Within uncertainties of model parameters, the value of $\epsilon$, etc., the present $B \sim 10^{-10}$ may arise from GUT baryogenesis after preheating. Of course, additional work is needed to implement the ideas discussed above in the context of a more realistic model and a complete numerical analysis able to describe the dynamics from the end of inflation down to the final baryon asymmetry production through the preheating era is urgently called for.

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