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Baryogenesis from the inflaton field

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ABSTRACT

In this letter we show that the inflaton can generate the cosmological baryon asymmetry. We take the inflaton to be a complex scalar field with a weakly broken global symmetry and develop a new variant on the Affleck–Dine mechanism. The inflationary phase is driven by a quadratic potential whose amplitude of B-modes is in agreement with BICEP2 data. We show that a conserved particle number is produced in the latter stage of inflation, which can later decay to baryons. We present promising embeddings in particle physics, including the use of high dimension operators for decay or using a colored inflaton. We also point out observational consequences, including a prediction of isocurvature fluctuations, whose amplitude is just below current limits, and a possible large scale dipole.

1. Introduction

One of the outstanding challenges of modern particle physics and cosmology is to explain the asymmetry between matter and anti-matter throughout the universe. This asymmetry is quantified by the baryon-to-photon ratio η, which shows an over-abundance of matter at the level of $\eta_{obs} \approx 6 \times 10^{-10}$, as measured in [1]. One might try to dismiss this problem by assuming the universe simply began with the asymmetry. However, such a proposal appears both unsatisfying and unlikely due to cosmological inflation; a phase of exponential expansion in the early universe that helps to explain the large scale homogeneity, isotropy, and flatness, as well as the density fluctuations [2]. Such a phase would wipe out any initial baryon number. It is usually thought that this requires new fields to enter after inflation in the radiation (or matter) eras to generate the asymmetry (for reviews see [3]), such as at the electroweak phase transition (e.g., see [4]). Since we have yet to see new physics beyond the Standard Model at the electroweak scale [5], it is entirely possible that baryogenesis is associated with much higher energies, and inflation is a probe into these high scales.

In this letter, and accompanying paper [6], we show that although inflation wipes out any initial matter/anti-matter asymmetry, the asymmetry can still be generated by the inflaton itself. The key reason this is possible is that the inflaton acquires a type of vev during inflation and this information is not wiped out by the inflationary phase. In order to connect this to baryogenesis, we will put forward a new variation on the classic Affleck–Dine [7] mechanism for baryogenesis, which uses scalar field dynamics to obtain a net baryon number. In the original proposal, Affleck–Dine used a complex scalar field, usually thought to be unrelated to the inflaton but possibly a spectator field during inflation, to generate baryons in the radiation or matter eras. Various versions, often including connections to supersymmetry, have been found for these Affleck–Dine models, e.g., see [8].

In this letter we propose a new model where the aforementioned complex scalar field is the inflaton itself. In the accompanying paper [6], we develop and provide details of this proposal, including both particle physics and cosmological aspects, and discuss current observational constraints. Our key ideas and findings are summarized as follows: We propose that the inflaton is a complex scalar field with a weakly broken global $U(1)$ symmetry. For simplicity, we consider inflation driven by a symmetric quadratic potential, plus a sub-dominant symmetry breaking term. The quadratic potential establishes tensor modes in agreement with recent BICEP2 results [9]. Given these recent cosmological observations, it is very important to establish a concise, predictive model as we do here. We show that a non-zero particle number is generated in the latter stage of inflation. After inflation this can decay into baryons and eventually produce a thermal universe. We propose two promising particle physics models for both the symmetry breaking and the decay into baryons: (i) Utilizing high dimension operators for decay, which is preferable if the inflaton is a gauge singlet. (ii) Utilizing low dimension operators for decay, which is natural if the inflaton carries color. We find that model (i) predicts the observed baryon asymmetry if the decay occurs

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through operators controlled by $\sim$ GUT scale and this is precisely the regime where the EFT applies, while model (ii) requires small couplings to obtain the observed baryon asymmetry. We find a prediction of baryon isocurvature fluctuation at a level consistent with the latest CMB bounds, which is potentially detectable.

In summary, our new results beyond the existing literature include: (a) the direct comparison to the latest data; this includes the latest bounds on tensor modes, scalar modes, and baryon asymmetry, (b) the development of a broad framework to identify inflation with the origin of baryon asymmetry, without the detailed restrictions of supersymmetry, (c) specific model building examples including the cases of a singlet inflaton and a colored inflaton, (d) predictions for isocurvature modes and compatibility with existing bounds, while standard Affleck–Dine models are ruled out if high-scale inflation occurred, (e) predictions of a large scale dipole.

2. Complex scalar model

Consider a complex scalar field ϕ, with a canonical kinetic energy $|\partial\phi|^2$, minimally coupled to gravity, with dynamics governed by the standard two-derivative Einstein–Hilbert action. Our freedom comes from the choice of potential function $V(\phi,\phi^*)$. It is useful to decompose the potential into a "symmetric" piece V_s and a "breaking" piece V_b piece, with respect to a global $U(1)$ symmetry $\phi \to e^{-i\alpha}\phi$, i.e., $V(\phi,\phi^*) = V_s(|\phi|) + V_b(\phi,\phi^*)$. In order to describe inflation we assume that the symmetric piece V_s dominates, even at rather large field values where inflation occurs. For simplicity, we take the symmetric piece to be quadratic $V_s(|\phi|) = m^2|\phi|^2$. It is well known that a purely quadratic potential will establish large field, or "chaotic" inflation [10]. This is a simple model of inflation that will provide a useful pedagogical tool to describe our mechanism for baryogenesis. Such a model is in good agreement with the spectrum of density fluctuations in the universe [1], it is in agreement with the measured tensor modes from BICEP2 data [9], and is motivated by simple symmetry arguments [11]. Generalizing to other symmetric potentials is also possible.

The global symmetry is associated with a conserved particle number. So to generate a non-zero particle number (that will decay into baryons) we add a higher dimension operator that explicitly breaks the global $U(1)$ symmetry $V_b(\phi,\phi^*) = \lambda(\phi^n + \phi^{*n})$, with $n \geq 3$. We assume that the breaking parameter λ is very small so that the global symmetry is only weakly broken. This assumption of very small λ is motivated by two reasons: Firstly, since λ is responsible for the breaking of a symmetry, it is technically natural for it to be small according to the principles of effective field theory. Secondly, the smallness of λ is an essential requirement on any inflationary model so that such higher order corrections do not spoil the flatness of the potential V_s. We also note that our model carries a discrete $\mathbb{Z}_n$ symmetry that makes it radiatively stable.

3. Particle/anti-particle asymmetry

We assume the field begins at large field values ($|\phi| \gg M_{Pl}$) and drives inflation. The field exhibits usual slow-roll and then redshifts to small values at late times, where it exhibits elliptic motion. This evolution is seen in Fig. 1 for two different initial conditions. Since $n \geq 3$, then at late times the inflaton ϕ becomes small, the $\phi \to e^{-i\alpha}\phi$ symmetry violating term becomes negligible, and the symmetry becomes respected. By Noether's theorem this is associated with a conserved particle number. In an FRW universe with scale factor $a(t)$ and comoving volume V_{com}, this is

$$\Delta N_\phi = N_\phi - N_{\bar\phi} = i\, V_{com}\, a^3\left(\phi^*\dot\phi - \dot\phi^*\phi\right). \tag{1}$$

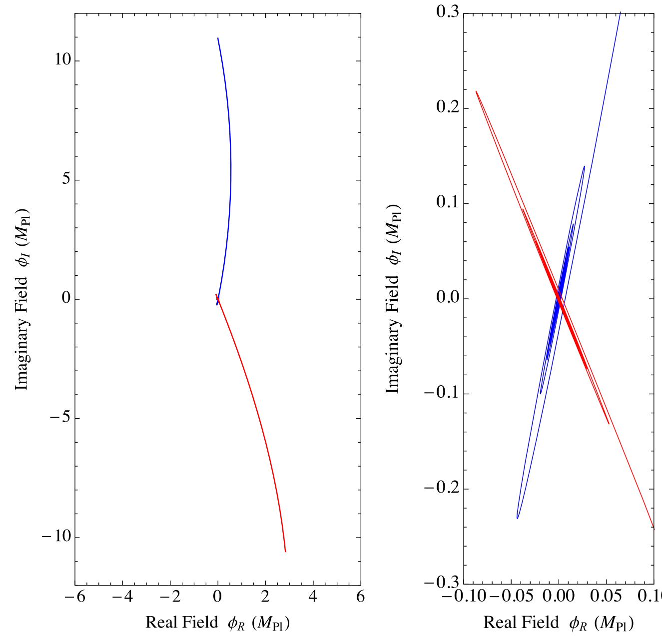

Fig. 1. Field evolution in the complex ϕ-plane for $n = 3$ and $\lambda M_{Pl}/m^2 = 0.006$, with initial condition $\rho_i = 2\sqrt{60}\,M_{Pl}$. Left is zoomed out and shows early time behavior during slow-roll inflation. Right is zoomed in to $\phi = 0$ and shows late time elliptic motion. Blue (upper) curve is for initial angle $\theta_i = \pi/2$ and red (lower) curve is for initial angle $\theta_i = -5\pi/12$.

To be self-consistent we ignore spatial gradients, and the equation of motion for ϕ is: $\ddot\phi + 3H\dot\phi + m^2\phi + \lambda\, n\, \phi^{*n-1} = 0$, where $H = \dot a/a$ is the Hubble parameter.

For small λ we can reduce the complexity of the problem significantly. By using the equation of motion, we can obtain an integral expression for ΔN_ϕ which is proportional to λ. This allows us to compute the evolution of the field to zeroth order in λ, which implies radial motion in the complex plane. We rewrite the zeroth order motion of the field in polar co-ordinates as $\phi_0(t) = e^{i\theta_i}\rho(t)/\sqrt{2}$, where θ_i is the initial angle of the field at the beginning of inflation. The problem then reduces to solving only a single ordinary differential equation. At first order in λ, ΔN_ϕ is simply

$$\Delta N_\phi(t_f) = -\lambda \frac{V_{com}\, n}{2^{\frac{n}{2}-1}} \sin(n\,\theta_i) \int_{t_i}^{t_f} dt\, a(t)^3 \rho_0(t)^n. \tag{2}$$

Here ρ_0 is a real-valued function satisfying the quadratic potential version of the equation of motion $\ddot\rho_0 + 3H_0\dot\rho_0 + m^2\rho_0 = 0$, with corresponding Friedmann equation (we assume flat FRW) $H_0^2 = \varepsilon_0/3M_{Pl}^2$ and energy density $\varepsilon_0 = \dot\rho_0^2/2 + m^2\rho_0^2/2$, where $M_{Pl} \equiv 1/\sqrt{8\pi G}$ is the reduced Planck mass. So by solving for a single degree of freedom in a quadratic potential, we have an expression for the particle number in the small λ regime. We note that for particular values of the initial angle θ_i, such that $\theta_i = \frac{p\pi}{n} \mid p \in \mathbb{Z}$, no asymmetry is generated due to the $\sim \sin(n\,\theta_i)$ factor. Since we are interested in baryogenesis, we consider θ_i to be a typical generic value rather than these special ones.

The integrand in Eq. (2) is plotted in Fig. 2 using dimensionless variables $\tau \equiv mt$ and $\bar\rho \equiv \rho_0/M_{Pl}$. In the limit in which we take τ_i very early during slow-roll inflation and we take τ_f very late after inflation, then the integral in Eq. (2) becomes independent of both τ_i and τ_f. The dominant contribution to the integral, and in turn the dominant production of ϕ particles (or anti-particles) occurs in the latter stage of inflation. This is nicely seen in Fig. 2. It can be shown that for the parameters of the figure, the end of inflation is