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BARYOGENESIS IN THE DESERT BETWEEN ELECTROWEAK AND GRAND UNIFICATION SCALE

B. P. GONG[1]
(Revised)

ABSTRACT

As the Universe is dominated by of baryons, there must have been a process in early Universe creating such a asymmetry via baryon number violation. However, until recently all the confirmed experimental data indicate that lepton and baryon number are conserved in agreement with Standard Model of quarks and leptons. This paper proposes an alternative path of baryogenesis. Once the over abundant magnetic monopoles predicted by grand unification emerged at universe temperature of 10^{16} GeV, then their annihilation should first give rise to photons driving the expansion of the early universe. As the universe temperature dropped to the desert scale of around 10 EeV, departure from thermal equilibrium occurred. Thus the annihilation produced photons give rise to electron-positron pairs, which collide with remnant magnetic monopoles and antimonopoles. The resultant unstable intermediate X and antiX particle become asymmetric, and thereby leading to baryon asymmetry. The excess of antimonopoles corresponding to ten times of mass comparing with that of baryons provides a natural candidate for dark matter. The physics of such a desert regime baryogenesis can be simply characterized by three parameters. The collision predicts a ratio of particle and anti-particle equivalent to that of ultra-high-energy neutrino to their anti-particle, which can be tested by future observations, e.g., the constructing IceCube-Gen2.

Subject headings: cosmology, inflation, baryogenesis, magnetic monopole

1. INTRODUCTION

The grand unification Theories (GUTs) attempting to unify the strong, weak, and electromagnetic interactions and the quarks and leptons have two startling predictions: the existence of stable, superheavy magnetic monopoles (MMs), and interactions that violate baryon number (B) and lepton number (L) and thereby lead to the instability of the proton. Both predictions have very significant cosmological consequences.

With a net B from the universe beginning with baryon symmetry, most GUTs predict baryogenesis through the decay of supermassive (GUT-scale) X particles with interactions violating B conservation ('t Hooft 1976b; Kibble 1976; Kolb & Turner 1983; Bhattacharjee 1998; Kolb & Turner 1990).

Such a decay process based on GUTs requires that the superheavy bosons were as abundant as photons at very high temperatures of $\sim M_{GUT}$ which is questionable if the heavy X particles are the gauge or Higgs bosons of Grand Unification. Because the temperature of the universe might always have been smaller than M_{GUT} and, correspondingly, the thermally produced X bosons might never have been as abundant as photons, making their role in baryogenesis negligible(Riotto & Trodden 1999).

Therefore, the GUTs based baryogenesis is still short of suitable environment to invoke the assumed decay of superheavy particles, evenif the B nonconservation is valid. The problem of such baryogenesis may originate in physical process before the decay of superheavy X particles, the inflation.

The first inflationary model, so called old inflation, was thus proposed (Guth 1981) based on a scalar field theory undergoing a first order phase transition. The scalar field was initially trapped in a local minimum of some potential, and then leaked through the potential barrier and rolled towards a true minimum of the potential. The transition from initial "false vacuum" phase to the lower energy "true vacuum" phase, so called the super-cooling, corresponds to a difference in energy density which drives the exponential expansion of the Universe.

The process cannot be simultaneous everywhere, small bubbles of true vacuum, would be carried apart by the expanding phase too quickly for them to coalesce and produce a large bubble. The resultant Universe would be highly inhomogeneous and anisotropic, opposite to what is observed in the cosmic microwave background.

The successor to the old inflation was new inflation(Linde 1982; Albrecht et al. 1982). This is again a theory based on a scalar field. The field is originally in the false vacuum state, but as the temperature lowers it begins to roll down into one of the two degenerate minima. There is no potential barrier, so the phase transition is the second order. Problem of such inflationary models is that they suffer from severe fine-tuning problem and requires very specific scalar field(Steinhardt 2011). One of the most popular inflationary models is the chaotic inflation(Linde 1983), which is based on a scalar field, but it does not require any phase transition. In such cases, the standard model of cosmology is in fact separated from the standard model of particle physics.

This paper shows that simply replacing driving energy of inflation by annihilation of magnetic monopoles (MMs), the first order phase transition of Guth's still work. Moreover, the subsequent evolution of the universe at the desert regime automatically gives rise to sufficient intermediate supermassive particles to account for the baryogenesis.

As over abundant MMs predicted by GUTs('t Hooft 1974; Carrigan & Trower 1983; Preskill 1984) nucleated in bubbles at the critical temperature of the phase transition, $T_c \sim M_{GUT}$, their annihilation would invoke enormous radiation to drive the inflation. With such a heat source, the universe would undergo a free expansion which expands exponentially by smooth temperature drop. Therefore, supercooling and reheating expected by adiabatic expansion models can be avoided, as well as the difficulties of owing to vacuum field driven inflation mentioned above.

[1] Department of Astronomy, Huazhong University of Science and Technology, Wuhan, 430074, People's republic of China; bpgong@mail.hust.edu.cn

At the end of such a inflation, the spread out energy has straighten curves and warps of the universe, which resulted in departure from thermal equilibrium. Then begins the baryogenesis. The continuing annihilation of MMs at much reduced rate would give rise to photons producing electron-position pairs rather than expanding the universe.

And the collision of electron-positron with the remnant MMs can reproduce not only sufficient but also intermediate superheavy X particles.

As a baryon changes sign when charge conjugation (C) and charge conjugation combined with parity(CP) are violated, the chemical potentials of the superheavy intermediate X particle and antiX particle have opposite sign, which results in asymmetry on number of X and antiX particles. And the decay of such X and antiX particles automatically can account for baryon asymmetry.

In such a case more X particles decay into baryons than those of antiX particles into antibaryons. Correspondingly the remnant MMs is less than that of antiMMs. Due to the X particles decay into quarks, leptons, and pions, so that approximately 10% of X particles convert to baryons(Bhattacharjee 1998). Consequently, the total mass of baryons should be only $\sim 10\%$ of the antiMMs, which automatically account for dark matter.

In such a scenario, the annihilation of over abundant MMs can not only predicts sufficient energy to drive the inflation itself, avoiding some difficulties of inflationary models like no ending and very limited parameter spaces(Steinhardt 2011); but also provides superheavy particles, leptons and suitable temperature for the occurrence of collision and decay which lead to baryogenesis under baryon conservation. It turns out that GUTs incorporating R-parity(Dreiner et al. 2012; Corianò et al. 2008), which ensures a stable proton and achieves baryon and lepton conservation is consistent with the new path of baryogenesis. Such a process occurs in scale, $\approx 10EeV - 1EeV$, which is so called the great desert, between the Standard Model particle physics describing physics at the electroweak scale of $\sim 100-200$ GeV and the standard model of cosmology with GUTs scale of $\sim 10^{16}$GeV.

The collision induced baryogenesis includes three steps: the annihilation of MMs started before the collision and ended after the decay, Sect(4); the collision of leptons with MMs, Sect(2); the decay of intermediate X particle, Sect(3).

Sect(5) estimates parameters of annihilation, collision and decay processes, and predicts that the collision and decay can give rise to extremely high energy neutrinos, the ratio of which can test the validity of the new scenario. The association of baryon asymmetry with charge neutrality, and the remnant antiMMs as possible a candidate of dark matter, are also addressed. The three major parameters characterizing the universe evolution from GUT to desert scale are summarized.

2. THE COLLISION

As shown in Sect(4), the annihilation of over abundant MMs emerged at phase transition of GUTs can lead to an inflation driven by MM annihilation. At the end of inflation when the universe temperature is around 10 EeV, begins processes out of thermal equilibrium.

It seems inevitable that electrons and positrons emerged at the desert scale of 10 EeV collide with remnant MMs with much reduced number through previous annihilation. The collision of positron with MMs is read,

$$e^{+} + M \leftrightarrow X + \bar{\nu} \ . \tag{1}$$

Such a collision results in intermediate X particles as shown in Eq(1) which can rapidly decay into baryons and leptons. And during such collision and decay processes the annihilation of relics MMs continues at much small rate comparing with the primary inflation.

Therefore, the change of number density of MMs in the departure from thermal equilibrium can be described by Boltzmann equation as,

$$a^{-3}\frac{d(n_M a^3)}{dt} = \langle anni\rangle + \langle colli\rangle + \langle decay\rangle \ . \tag{2}$$

As discussed in detail in Sect(5), from $T \sim 10^{16}$ GeV to 10 EeV, the universe is dominated by the radiation originating in annihilation of MMs, so that the right hand side of Eq(2) is governed by the first term. And from 10 EeV to 1 EeV, the rate of annihilation is much reduced, thereby the universe departs from thermal equilibrium and coasting. In such case all the three terms at right hand side of Eq(2) work.

The collision process, corresponds to the second term at right hand side of Eq(2). In general the Boltzmann equation are a coupled set of integral partial differential equations for the phase space distributions of all the species present. For a few species of interests to us, like positrons and MMs as shown in Eq(1), should have equal phase space distribution function because their rapid interactions reducing the problem to a single integral partial differential equation for the one species of interests.

Therefore, the Boltzmann equation corresponding to the collision of electron or positron (of number density n_e) with MMs or antiMMs (of number density n_M), and thereby producing intermediate superheavy particle (with number density n_X), and neutrinos (of number density n_ν), can be written,

$$a^{-3}\frac{d(n_M a^3)}{dt} = n_M^{(0)} n_e^{(0)} \langle\sigma v\rangle [\frac{n_X n_\nu}{n_X^{(0)} n_\nu^{(0)}} - \frac{n_M n_e}{n_M^{(0)} n_e^{(0)}}] \ , \tag{3}$$

where the definition of number density in terms of the phase space density for species in kinematic equilibrium is read,

$$n_i = g_i exp(\mu_i/T)\int \frac{d^3 p_i}{(2\pi)^3} exp(-E_i/T)$$

$$n_i^{(0)} = g_i \int \frac{d^3 p_i}{(2\pi)^3} exp(-E_i/T)$$

with g_i denotes the degeneracy of the species, while E_i and μ_i represent the energy and chemical potential of species respectively.

The left hand side of Eq(3) is of order of n_M/t or expressed with the Hubble constant, $n_M H$. The right hand side is of order of $n_M n_e \langle\sigma v\rangle$. The cross section of the collision between positron and MM as shown in Eq(1) is given,

$$\langle\sigma|v\rangle = (n_M^{(0)} n_e^{(0)})^{-1} \int d\pi_M d\pi_e d\pi_X d\pi_\nu (2\pi)^4$$

$$\times \delta^4(p_M + p_e - p_X - p_\nu)|f(q)|^2 \exp(-E_M/T)\exp(-E_e/T) \ , \tag{4}$$

where $d\pi_i = g_i d^3 p_i/[(2\pi)^3 2E_i]$.

The rate of a particular reaction mediated by boson exchange is proportional to $|f(q)|^2$ multiplied by a phase-space factor, which determines the rate of an unstable state, or the cross section for a collision process. The large the value of $|f(q)|^2$ corresponds to a high the cross section of collision.

Consider a particle being scattered by a potential provided by an infinitely massive source, the effect of which is observed through the angular deflection of the particle or, equivalently, the momentum transfer, q. The potential $A(r)$ of the massive source in coordinate space will have an associated amplitude, $f(q)$, for scattering of the particle; which is simply the Fourier transform of the potential(Perkins 2000),

$$f(q) = e\int A(r)e^{i\bar{q}\cdot\bar{r}}dV \ .$$

And the integration over volume can be obtained by setting, $\bar{q}\cdot\bar{r} = qr\cos\theta$, $dV = r^2 d\phi \sin\theta d\theta dr$, which yield,

$$f(q) = 4\pi e\int_0^\infty A(r)\frac{\sin qr}{qr}r^2 dr \ .$$

The magnetic potential of a MM with charge g satisfies, $\oint AdR = 4\pi g$, thereby, $A = -2ig/R$, substitute into the equation above, one has, $f(q) = -2ieg/|\vec{q}|^2$, and square of which yields,

$$f^2(q) = \frac{4e^2g^2}{|\vec{q}|^4} = \hbar^2/q^4 \ . \tag{5}$$

For an electron interacting with a MM, the 4 momentum of an electron becomes, $q^2 = p^2 - E^2/c^2 \approx p^2$, because it gets much greater momentum than its own rest energy, $p^2 \gg E^2/c^2$, during the interaction. The momentum relates with the impact parameter b by,

$$q \approx \Delta P_y = \frac{egvb}{4\pi}\int_{-\infty}^{b}\frac{dt}{(b^2+v^2t^2)^{3/2}} = \frac{eg}{4\pi b} \ , \tag{6}$$

Substituting Eq(6) into the cross section of Eq(4) yields,

$$\begin{aligned}\langle\sigma|v\rangle &= \frac{1}{(2^{12}\pi^8)}\frac{qc}{2M_mc^2}\frac{qc}{2M_Xc^2}|f(q)|^2\frac{q^8}{c^2} \\ &= \frac{1}{(2^{14}\pi^8)}\frac{G^2 l_{Pl}}{\hbar^4c^5}\frac{qc}{M_mc^2}\frac{qc}{M_Xc^2}q^4 \ . \end{aligned} \tag{7}$$

Notice that the cross section of collision of Eq(7), $\langle\sigma|v\rangle \propto q^6$, is very sensitive to the momentum, q. Now the Boltzmann equation responsible for positron and MM collision of Eq(1) becomes,

$$a^{-3}\frac{d(n_Ma^3)}{dt} = n_M^{(0)}n_e^{(0)}\langle\sigma v\rangle exp(\pm\mu_X/T)exp(\pm\mu_\nu/T) \ , \tag{8}$$

where μ_X and μ_ν are chemical potentials of the intermediate particle X and antineutrino respectively, which satisfy, $\mu_X \gg \mu_\nu$, so that $exp(-\mu_\nu/T) \approx 1$. According to Eq(8) the chemical potential determines the particle to antiparticle ratio, which further governs the ratio of baryons to antibaryons through the decay of superheavy X particles.

3. THE DECAY OF INTERMEDIATE X PARTICLES

The decay of the intermediate particle X and its antiparticle can be expressed,

$$\dot{n}_B \equiv \dot{n}_b - \dot{n}_{\bar{b}} = \Gamma_{12}^X|M_0|^2F(f_b, f_{\bar{b}}) \ , \tag{9}$$

where Γ_{12}^X is the integral operator, $|M_0|$ is the decay amplitude for X and $\bar{X}$, and f_i is the phase-space density of species i(Harvey & Kolb 1981), given by $f_b = e^{-(E-\mu)/T}$ and $f_{\bar{b}} = e^{-(E+\mu)/T}$. Apparently, one have $f_b = f_{\bar{b}}$ in the case of $\mu = 0$, which results in $F(f_b, f_{\bar{b}}) = 0$ and thus $\dot{n}_B = 0$ in Eq(9). Obviously, such a decay process satisfies C or CP invariance.

On the other hand, suppose a volume of early universe containing equal numbers of X and $\bar{X}$ bosons. The mean net baryon number produced by the decay of an X to quark/lepton final states $p_1 = qq(B = 2/3)$ and $p_2 = \bar{q}\bar{l}(B = -1/3)$ is $B_X = r(2/3) + (1-r)(-1/3)$, where r is the decay rate. In contrast, the net number generated by decay of an $\bar{X}$ to $\bar{p}_1 = \bar{q}\bar{q}$ (B=-2/3) and $\bar{p}_2 = ql(B = 1/3)$ is $B_{\bar{X}} = \bar{r}(-2/3) + (1-\bar{r})(1/3)$. The mean net baryon number resulted in the decay of an X and $\bar{X}$ pair is $B_X + B_{\bar{X}} = r - \bar{r}$. The conservation of C and CP lead to $r = \bar{r}$, and hence baryon invariance, $\dot{n}_B = 0$(Kolb & Turner 1990).

Therefore, the models of baryogenesis directly through decay superheavy particle requires all the three ingredients of Sakharov (1967), (1) B-nonconserving interactions, (2) a violation of both C and CP, (3) a departure from thermal equilibrium.

In comparison, the scenario of collision induced baryogenesis can be achieved in the absence of the first one, the B nonconservation, while holding the other two ingredients.

Therefore, as shown in Eq(1), from an initial B and L symmetry Universe (B=L=B-L=0), the collision of lepton with MMs can result in B and L asymmetries while preserving both $B+L = 0$ and $B-L = 0$. In fact, the new scenario can be consistent both with experiments on C and CP nonconservation(Christenson et al. 1965; Kleinknecht 1976), and the limit of proton decay(Abe et al. 2014).

It appears that scenario favors GUTs incorporating R-parity(Dreiner et al. 2012; Corianò et al. 2008), which can ensure a stable proton and achieve baryon and lepton conservation at the renormalizable level. Future results of ratio of extremely high energy neutrino to antineutrino predicted by the collision may test the validity of such a baryogenesis occurring in the desert regime.

The collision induced baryogenesis can undergo with sufficient leptons and superheavy particles at the universe temperature around 10 EeV. Because 10 EeV corresponds to a critical temperature, when the inflation transferring from thermal equilibrium to out of equilibrium, the leftover MMs from the prior annihilation of of abundant MMs is sufficient to account for the subsequent baryongenesis, which avoids the difficulties of Riotto & Trodden (1999) mentioned in the introduction.

The next section will show that the annihilation of over abundant MMs from the initial temperature of 10^{16} GeV to 10 EeV can invoke a radiation that expands the universe exponentially to a volume sufficient to account for the flatness problem, so that baryogenesis may occur in the out of equilibrium state with temperature between 10 EeV and EeV.

4. ANNIHILATION OF MMS

To explain the unacceptable large number of MMs generated at the early Universe, Preskill (1979) suggested that MMs can be suppressed through annihilation if the phase transition at the GUT is strongly first order.

Here a big step is made, which proposes that the driving energy of the inflation is the energy release of the annihilation of the over abundant MMs rather than vacuum energy. Simply change to the rate of annihilation of MM(Preskill 1979) from adiabatic expansion to free expansion, the annihilation driving inflation can be achieved.

The rate of annihilation of MMs (Preskill 1979) was estimated by the Boltzmann equation, originating in the covariant conservation of the energy-momentum tensor in the comoving frame, in which the number density, n (where $n = \rho/m$, and m is the mass of the particle), and the annihilation term, Dn^2 are related by,

$$dn/dt + (3\dot{a}/a)n = -Dn^2 \ , \quad (10)$$

where D is the velocity-averaged product of the cross-section and the velocity, characterizing the annihilation process, with the number density of monopoles, M, and anti-monopoles, $\bar{M}$ assumed to be equal.

The relationship between the scale factor and temperature can be written in a general form of $Ta^{\beta} = const$, which reduces to the widely used adiabatic expansion in the case of $\beta = 1$,

$$\beta\dot{a}/a = -\dot{T}/T = T^2/(Cm_P) \ . \quad (11)$$

The estimation of MM annihilation(Preskill 1979) corresponds to $\beta = 1$; whereas, the free expansion of Universe corresponds to $\beta \neq 1$. In the case of thermodynamic equilibrium D relates with the temperature by a power law, and thus Eq(10) and Eq (11) can be integrated,

$$r(T) = \frac{1}{\kappa\hbar^2}[\frac{4\pi}{\hbar^2}]^2 \frac{m}{(\beta Cm_p)} = \frac{n}{T^3} \ , \quad (12)$$

where $\kappa = \frac{3}{4\pi^2}\zeta(3)\sum_i(\hbar q_i/4\pi)^2$ with the sum over all spin states of relativistic particles, and $\zeta(3) = 1.202$ is the Riemann zeta function. By the number density of MMs given by Eq (12), the energy release of such an annihilation in a comoving volume corresponding to the right hand side of Eq (10) is

$$\dot{\rho}_m = -M_m Dn^2 \ , \quad (13)$$

Due to the number of MMs reduces as their annihilation proceeds, the number of MMs in a comoving volume decreases with the time of evolution, so that $\dot{\rho}_m < 0$, which is analogy to the decay of a massive particle species dominating the energy density of the universe (Kolb & Turner 1990).

Similar to the release due to decay of a massive particle species, the annihilation of MMs transfer energy from the heavy particles to radiation also, so that the first law of thermodynamics, $dU + pdV = dQ$ (where U is the internal energy of the volume, pdV denotes work done to the surrounding, and Q respresents energy supply to the volume as heat), becomes,

$$d(a^3\rho_R) + p_R d(a^3) = -d(a^3\rho_m) = -3a^2\dot{a}\rho_m dt - a^3\dot{\rho}_m dt \ . \quad (14)$$

As the early universe is radiation dominant, Eq (14) can be rewritten as,

$$\dot{\rho}_R + 12Hp_R = -\dot{\rho}_m \ , \quad (15)$$

where $H = \dot{a}/a$. The decrease of energy density of MMs in a comoving volume, $\dot{\rho}_m < 0$ as shown in Eq (13), plays the role of heat source to the energy density of the universe residing in two components: non-relativistic MMs and radiation. Consequently, we have $-\dot{\rho}_m > 0$ in Eq (15), which corresponds to a negative pressure repulsing the gravity and resulting in an expansion of the universe with $H = \dot{a}/a > 0$. Notice that the annihilation term at right hand side of Eq (15) deviating from the linear relationship of normal matter with $p = w\rho$.

With E_m denoting the overall energy release of annihilation of MMs during the inflation, it requires $E_m \sim 4\times10^{103}(erg)$ in order to solve the flatness problem(Weinberg 2008), which corresponds to a total number of MMs of $N_m \sim 4\times10^{88}$ annihilated during the inflation (with each MM of mass of $M_m \sim 1\times10^{16}GeV$).

The work done responsible for a free expansion of the universe initiating at temperature 10^{16}GeV can be estimated,

$$W \approx \frac{1}{\gamma-1}g^{\star}N_m k_B T_i \approx 2\times10^{103} \quad (16)$$

where k_B is the Boltzmann constant, and γ is the polytropic index. With an initial temperature of inflation of $T_i \sim 10^{28}K$; MMs number $N_M \sim 4\times10^{88}$, $\gamma \approx 0.1$ and the effective number of degrees of freedom of $g^{\star} = 100$, one gets, $W \approx 2\times10^{103}$ by Eq (16).

This again indicates that the annihilation of MMs of number $N_M \sim 4\times10^{88}$, corresponds to a radiation field which is repulsive to gravity, so that the negative pressure required in driving inflation can be satisfied automatically. Thus the inflation of the Universe can be described as free expansion, with temperature and volume related by $TV^{1/3\omega} = const$ where $1/(3\omega) = \gamma - 1$. By e.g., $\omega = 3.35$ (corresponding to $\gamma = 0.1$), it can have a huge change in volume, with e–foldings of scale factor ($a_f/a_i \sim e^N$) accounting for solving flatness problem(Weinberg 2008), while keeps relative smooth change in temperature.

Such a free expansion of the early universe can be well described by a relationship of scale factor, time and temperature of the Universe(subscript P denotes Planck value),

$$\frac{a}{a_P} = \frac{t}{t_P} = (\frac{T_P}{T})^{\omega} \ , \quad (17)$$

where the Planck temperature, time, and scale factor, are $T_P = 10^{32}K$, $t_P = 10^{-43}s$ and $a_P = 10^{-32}cm$ respectively.

The annihilation of MMs generated a radiation equivalent to a repulsive gravitational force that drove space to swell rapidly momentarily. For that to occur, the field's energy density has to vary with strength corresponding to value change of ω in Eq (17), such that it had a high-energy plateau, 10^{16} GeV and a low-energy valley, e.g., 1 EeV (as discussed later).

Correspondingly such an expansion of universe can be represented by a polytropic process of AB', which is infinitively close to the ideal isothermal process, AB, denoting the irreversible process of free expansion.

As a result, the energy exchange of universe with surroundings outside the universe predicted by adiabatic expansion can be avoided by free expansion.

Moreover, the free expansion of the universe with $Ta^{\beta} = const$, where $\beta = 1/\omega < 1$ (due to $3 < \omega < 4$ as shown later), allows many e-foldings expansion of volume at very smooth change of temperature. In contrast, the adiabatic expansion corresponds to $\beta = 1$, which gives rise to enormous volume expansion at the expense of supercooling in universe temperature, to avoid too low a temperature a reheating process is assumed. This requires that after many e-foldings of expansion, the inflaton energy that drove the inflation must be rapidly converted to radiation to reheat the universe. The outcome of a huge volume with too high a density and wrong distribution of galaxies are resulted in such special inflaton energy curve(Steinhardt 2011). Apparently, such problems are naturally avoided in the free expansion of the universe.

The essential scenario is that at around the critical temperature, $T_c \sim M_{GUT}$, quantum tunneling occur and nucleation of bubbles (containing huge number of MMs) of the true vacuum in the sea of false vacua begins. At a particular temperature below T_c, the annihilation of MMs in bubbles begins which invokes the first generation of bubble collisions, with resultant radiation repulsing gravity and driving exponential expansion of the universe.

Later on, MMs residing in remnant condensations get annihilated which leads to the second generation of bubble collisions and expansion, and so on until the universe expansion satisfying the flatness condition(Weinberg 2008).

As the bubble walls pass each point in space, the order parameter changes rapidly, as do the other fields, so that departure from thermal equilibrium occurs.

In such a new scenario, the large structure of the universe at the end of inflation was formed by the annihilation induced collision of bubbles for enormous number of generations.

In comparison, both the first order phase transition of Guth's and later second order phase transition predict bubbles expanding with the universe and we are in one of them, which are difficult to account for the uniformity problem. And with the adiabatic assumption these models lead to problems of no ending and extremely narrow range of parameter space (Steinhardt 2011). Apparently, these problems can be avoided in the annihilation driven inflation. Moreover, the three longstanding problem, over abundant MMs, flatness and uniformity can also be explained in a simple and natural way.

5. PARAMETER ESTIMATION AND DISCUSSION

As shown in Preskill (1979), the limit of annihilation of MMs can be defined by the dimensionless ratio between the number density and temperature, as shown in Eq (12), which can be estimated by the relation of free expansion of Eq (17),

$$r = N_m a^{-3} T^{-3} = N_M (a_P^{-3} t_P^{-3\omega}) T^{(3\omega-3)} \,. \tag{18}$$

The criteria of Preskill (1979) is that once the MMs abundance is comparable to $r \sim 10^{-10}$ or smaller, MM annihilation cannot further reduce the MM density per comoving volume.

At the beginning of the inflation with temperature $T \sim 10^{28}$K and of number of MMs, $N_M \sim 10^{88}$, one can have $r \sim 10^{60}$ which corresponds to an exponential expansion of the universe.

As temperature drops to T$\approx$ 10 EeV, the scale factor reaches $a \approx 50$cm (with $\omega = 3.35$) by Eq (17), which corresponds to an expansion of scale factor of $a/a_0 \sim 10^{26}$. Then begins the departure from equilibrium, in which case a reduced number of MMs of $N_M \sim 10^{79}$ corresponds to a ratio of $r \sim 10^9$, so that the annihilation of MMs continues along with the collision of leptons with remnant MMs, and the decay of intermediate X particles leading to baryogenesis. Furthermore, when temperature further drops to $T \approx 1$ EeV, a remnant number of MMs of e.g., $N_M \sim 10^{67}$ corresponds to a ratio of $r \sim 10^{-10}$, which means that the annihilation is coming to an end.

Therefore, the inflation can be divided into two stages by the ratio of r given by Eq (18). The first stage started from the temperature 10^{16} GeV, followed by the annihilation of a number of MMs of $N_M \sim 4 \times 10^{88}$. Correspondingly, photons of approximately $N_\gamma \sim 10^{88}$ were produced which drove exponential expansion of the universe.

When the total number of MMs reduces to $N_M \sim 10^{79}$ at the universe temperature of 10 EeV, the inflation enters its second stage, departure from thermal equilibrium. Owing to the change in N_M and temperature, the work done from $T \approx 10$ EeV to 1EeV via annihilation of MMs is significantly reduced as shown in Eq (16), which also results in a profound change of the ratio of Eq (18). Thus the universe expands at much slower rate (coasting) than that of the first stage from 10^{16} GeV to 10 EeV.

In the second stage, most photons produced by annihilation of MMs of number 10^{79} give rise to electron and positron pairs and colliding with remnant MMs of number 10^{79} rather than driving the inflation.

As the bubble collision undergoes in the second stage of inflation, the bubble walls continue passing points in unbroken phase, CP violation and the departure from equilibrium occur while the Higgs field is changing, until the point of the true vacuum at 1 EeV, thus ends the baryogenesis.

The collision of leptons with MMs, and thereby the decay of intermediate particles occur in the second stage of inflation, from 10 EeV to 1 EeV, reduces the number of MMs from $N_M \approx 10^{79}$ to $N_M \approx 10^{65}$, the remnant of which is limited by the total mass of current epoch.

The electrons and positrons generated at universe of temperature, $T \approx 10$EeV correspond to a thermal energy of $T = qc \approx 10^{-6} M_m \approx 1(J)$. Colliding with MMs of mass $M_m \approx 10^{16} GeV$, results in the cross section of collision of $\langle\sigma v\rangle \approx 10^{-82} m^3 s^{-1}$, which is very sensitive to the temperature, T (or q), e.g., 50% change of T can vary the cross section for 11 times by Eq(7).

The energy release of the collision corresponding to Eq(8) is read,

$$\epsilon_X = (\frac{E_e}{1J})(\frac{N_{e^+}}{10^{79}})(\frac{N_M}{10^{79}})(\frac{\langle\sigma v\rangle}{10^{-82}}) \cdot \tau \cdot exp(\mu/T) \,, \tag{19}$$

where parameter, $\tau \equiv a^{-3} t = t_P a_P^{-3} T_P^{-2\omega} T^{2\omega}$, is composed of the magnitude of scale factor a and time t of the universe related by Eq (17).

The collision induced energy release of Eq (19) at temperature, 10EeV, is equivalent to a conversion of number of MMs of 10^{65} to energy of other forms, which can quickly decay into a shower of secondary particles, with an efficiency of 10%(Bhattacharjee 1998). If the resultant number of quarks and leptons is of $\sim 10^{79}$ which is $\sim 10^{15}$ times of the number of MMs (the mass of a MM is $\sim 10^{15}$ times of a baryon), then the total baryons at current epoch can be explained,

$$\epsilon_X \to N_M \to N_M \cdot 10^{15} \cdot 10\% \to N_b \approx 10^{79} \,, \tag{20}$$

where $N_M = 10^{70} \tau e^{\mu/T}$ denotes the equivalent number of MMs corresponding to the energy release of Eq(19); and 10^{15} denotes the ratio of baryon number to that of MM.

In fact, the baryon number of Eq (20), $N_b \approx 10^{79}$, requires MM number of $N_M \approx 10^{65}$, which can be satisfied by different combinations of parameters, like $\omega = 3.30$, $\tau \approx 10^{-7} m^{-3} s$ and $e^{\mu/T} \approx 10^2$; or $\omega = 3.35$, $\tau \approx 10^{-8} m^{-3} s$ and $e^{\mu/T} \approx 10^3$.

The baryogenesis estimated by the collision of Eq (19) and decay of Eq (20) depend on three parameters, one is the number of remnant MM, $N_M \sim 10^{79}$, which thereby generate number of leptons of, $N_{e-} = N_{e+} \sim 10^{79}$. And the other is the out of equilibrium temperature, assumed to be $T \approx 10$ EeV, which determines the magnitude of collision cross section of Eq(7) and parameter τ as shown under Eq(19). And the value of parameter τ depends on the index ω characterizing the free expansion as shown by the relation of Eq (17).

On the other hand, $T \approx 10$EeV also corresponds to a ratio of annihilation, $r \sim 10^9$, as shown in Eq (18), which is much less than that of first stage of inflation, $r \sim 10^{60}$, and much greater than that of the end, $r \sim 10^{-10}$. In other words, the assumption of $N_M \sim 10^{79}$ and $T \approx 10$EeV can be consistent with both the requirements of baryogenesis and the inflation.

From the point of the new baryogenesis, the possibility of N_{e^-} and N_{e^+} much larger than 10^{79}, and reproducing number of baryons and antibaryons much larger than 10^{79}, which finally achieve a ratio satisfying current epoch through the annihilation of baryons and antibaryons are very unlikely.

In contrast to the reaction of positrons and MMs of Eq(1), the collision of electrons with anti-MMs,

$$e^- + M^- \leftrightarrow X^- + \nu \ , \tag{21}$$

is suppressed by the chemical potential with an opposite sign from that of Eq(19),

$$\epsilon_{\bar{X}} = (\frac{E_e}{1J})(\frac{N_{e^-}}{10^{79}})(\frac{N_{\bar{M}}}{10^{79}})(\frac{\langle\sigma v\rangle}{10^{-82}}) \cdot \tau \cdot exp(-\mu/T) \ . \tag{22}$$

Although the decay of antiparticles is of no difference from that of particles (both are B conservative), the two different parameter combinations under Eq (20) predict different production of antiparticles,

$$\epsilon_{\bar{X}} \rightarrow N_{\bar{M}} \rightarrow N_{\bar{M}} \cdot 10^{15} \cdot 10\% \rightarrow N_{\bar{b}} \ , \tag{23}$$

where $N_{\bar{M}} \approx 10^{70}\tau e^{-\mu/T}$. In the case of $\tau \approx 10^{-8} m^{-3} s$ and $e^{-\mu/T} \approx 10^{-3}$, one gets $N_{\bar{M}} \approx 10^{59}$ and $N_{\bar{b}} \approx 10^{73}$.

Consequently, different chemical potential of X and $\bar{X}$ particles owing to C and CP violation, result in different rate of collision and thus different number of intermediate particles and finally expecting a ratio of baryons to antibaryons, $N_{\bar{X}}/N_X = N_{\bar{b}}/N_b \approx e^{-2\mu/T}$ as shown in Eq(19) and Eq(22) respectively.

In fact, more MMs have been converted to baryons, $N_b \approx 10^{79}$ (with an efficiency of 10%) which can account for matter of current epoch. This implies that more anti-MMs leftover after the collision, the number of which can be up to 10^{65}, which naturally explains the mass of dark matter (of mass of ten times of baryons). The presence of such dark matter may play important role in the formation of primordial black holes and structure formation of the universe.

On the other hand, as more positrons have been consumed in the collision than those of electrons, one would expect more electron leftover to current universe than those of positrons if there are no other reactions to change them.

If a MM of strength g exists anywhere in the universe, then all electric charge must be quantized, which gives so called Dirac's quantization condition,

$$\frac{g}{\hbar} = \frac{2\pi n}{e} \quad , \ n = 0, \pm 1, \pm 2, ... \tag{24}$$

With the fine structure constant, $e^2/\hbar c = 1/137$, the electric and magnetic charge are related by $g/e = 137n/2$. Therefore, the electric charge corresponding to the number of post collision MMs is $Q_M = gN_M = 137nN_M e/2$. With an initial number of electron and positron pair of 10^{79} at temperature 10 EeV, electrons correspond to a charge of $Q_e = -eN_e^0$.

The universe can achieve charge neutrality, $Q_M = -Q_e$ through adjusting of parameters of expansion like τ (composed of scale factor and time of the universe) as shown in Eq (19)-Eq(23), so that $Q_M = gN_M = g(10^{70}\tau e^{\mu/T}) = -Q_e = eN_e^0$. And further assuming the conversion of MMs to baryons satisfies, $Q_M = Q_p$, we have,

$$\frac{N_e}{N_M} = \frac{N_p}{N_M} = \frac{g}{e} = \frac{137}{2} n \tag{25}$$

Eq(25) requires $n \approx \pm 10^{12}$, in the case of $N_p/N_M \sim 10^{79}/10^{65}$, which can be achieved by e.g., $\tau = 10^{-8} m^{-3} s$ and $e^{-\mu/T} \approx 10^{-3}$. This establishes the relationship of charge quantization condition of Dirac with the evolution of the universe and baryogenesis.

The ideal case of charge neutrality, $Q_M = -Q_e = Q_p$, may disturbed by other factors, which corresponds to a charge ratio of,

$$\frac{\Delta Q}{Q} = \frac{Q_M - eN_e}{eN_e} = \frac{Q_M - e[N_e^0 - 10^{70}\tau \cdot e^{-\mu/T}]}{eN_e} \approx 10^{-9}\tau e^{-\mu/T} \ , \tag{26}$$

where the term in the bracket can be understood as follows. When electrons of number $N_{e-} \sim 10^{79}$ emerged at temperature 10 EeV, the universe did generate equal number of protons to achieve charge neutrality with the original electrons through e.g., adjusting the value of τ. However, during such a baryogenesis, the original number of electrons before the collision have reduced by a small value, $\Delta N_e^0 = 10^{70}\tau \cdot e^{-\mu/T}$ due to the collision as shown in Eq(21), so that deviation in the charge ratio of Eq (26) is made.

Apparently, in the case of $\tau = 10^{-7} m^{-3} s$, the charge neutrality, $\Delta Q/Q \leq 10^{-20}$(Collins et al. 1989), requires $e^{-\mu/T} \leq 10^{-4}$, which is inconsistent with the requirement of baryogenesis of Eq (20).

In contrast, when $\tau = 10^{-8} m^{-3} s$, the ratio of $e^{-\mu/T} \approx 10^{-3}$ can both consists with the charge neutrality, $\Delta Q/Q \leq 10^{-20}$; and the baryogenesis of Eq (20), which corresponds to a ratio of antiparticle over particle of $N_{\bar{b}}/N_b = e^{-2\mu/T} \approx 10^{-6}$.

By Sect(2) and Sect(3), the ratio of baryon to antibaryon; electron to positron; antiMM to MM; and high energy antineutrino to neutrino satisfy,

$$\frac{N_b}{N_{\bar{b}}} = \frac{N_{e^-}}{N_{e^+}} = \frac{N_{\bar{M}}}{N_M} = \frac{N_{\bar{\nu}_e}}{N_{\nu_e}} = e^{2\mu/T} \ , \tag{27}$$

the resultant ratio is most likely around $e^{2\mu/T} \sim 10^6$. The scenario expects a number of superheavy antineutrinos of $N_{\bar{\nu}_e} \leq 10^{65}$ and antiMMs of $N_{\bar{M}} \leq 10^{65}$.

Antiprotons are seen in cosmic rays at about the 10^{-4} level compared to protons(Stephens 1989). However, such a magnitude of the antiproton flux is thought to be consistent with the hypothesis that the antiprotons are secondaries produced by cosmic ray collisions with the ISM, and does not seem to indicate that the presence of antimatter in the galaxy, even at the 10^{-4} level.

While from the point of the new scenario as shown in Eq(26) and Eq(27), the possibility of $N_{\bar{b}}/N_b \sim 10^{-4}$ cannot be excluded although $N_{\bar{b}}/N_b \sim 10^{-6}$ is more likely.

Moreover, the antineutrino has been recorded on Dec. 8, 2016, at the speed close to light. Deep inside the ice sheet that covers the South Pole, it smashed into an electron in the ice and produced a heavy charged particle that quickly decayed into a shower of secondary particles(IceCube Collaboration & Abbasi 2021). The detector, IceCube-Gen2, under construction may measure the excess of antineutrino over neutrino, which can test the relationship of Eq(27). Together with future measurement of ratio of matter and antimatter and ultra-high energy of cosmic rays, the new scenario can be directly tested.

The collision of leptons with MMs of number 10^{79} at universe temperature of 10EeV, and with a free expansion of index $\omega \approx 3.35$ can be consistent with both the requirement of baryogenesis and inflation as shown in Figure 1.

(1) The inflation driven by annihilation of MM and antiMMs can account for a number of puzzles of inflation both old and new.

(2) The annihilation of MMs induced bubble collisions tend to produce voids and filaments, the relics of which could account for large structure of universe at current epoch.

(3) Such a bubble collisions may give rise to primordial gravitational waves.

(4) The remnant antiMMs may provide a candidate of dark matter at current epoch and seeds of primordial black holes.

(5) Baryon asymmetry is achieved by different cross section of collision among MMs and leptons stemming from C and CP violation, instead of baryon nonconservation. The new model predicts an infinite long lifetime of protons, which expects that the lower limit of the proton lifetime of $> 5.9 \times 10^{33}$ years at 90% confidence level by Super-Kamiokande data(Abe et al. 2014) will continue to increase.

(6) The first stage of inflation from 10^{16}GeV to 10 EeV annihilated MMs of $N_M \sim 10^{88}$, generated photons of $N_\gamma \sim 10^{88}$, and thereby reproduced baryons of $N_b \sim 10^{79}$, which correspond to the ratio of baryon to photon, $\eta \approx (\frac{baryons}{10^{79}})(\frac{10^{88}}{photos}) \sim 10^{-9}$. The universe could have held such a ratio from the midst of inflation to current epoch.

(7) It can consist with the charge neutrality of the universe, and correspond to a large number in the Dirac's quantization condition.

(8) It predicts a lower limit of proton lifetime much larger than that of the current one, $> 5.9 \times 10^{33}$ years.

(9) The collision and decay expect the generation of extremely high energy Cosmic rays and neutrinos (of number $\leq 10^{65}$), as well as ratio of other particles, which can be tested by further observations.

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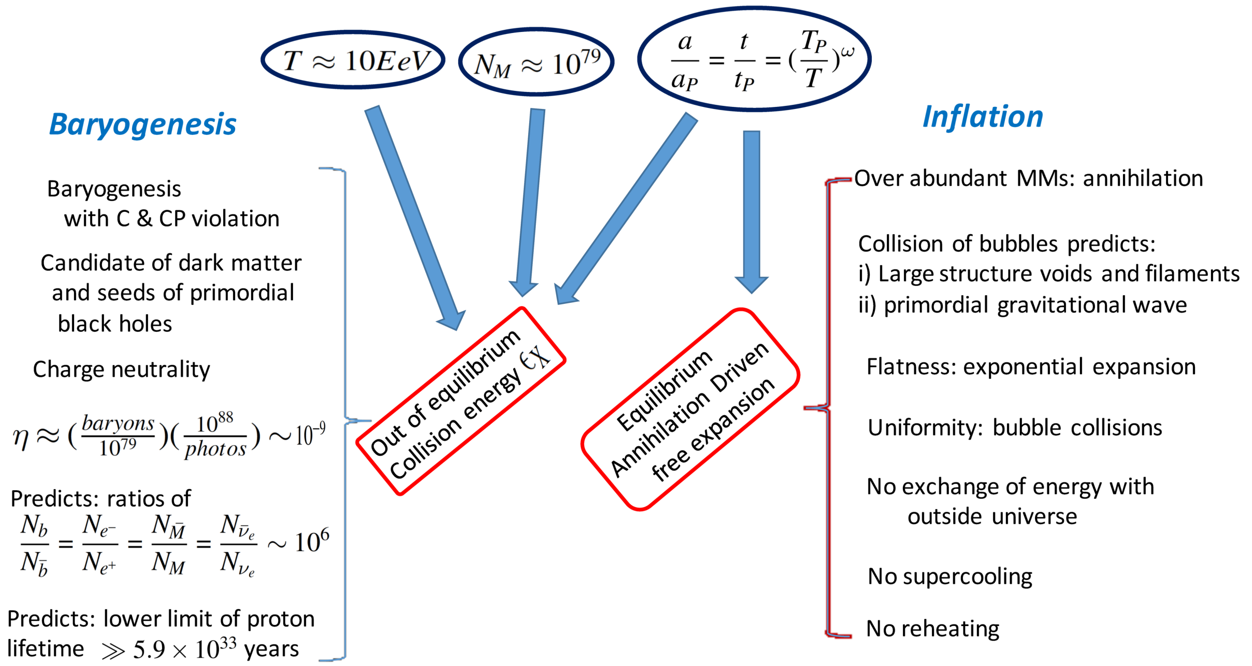

FIG. 1.— Schematic summary of annihilation of MMs induced inflation and baryogenesis.