Phase Transitions in Early Universe

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Abstract

The concepts of spontaneous symmetry breaking(SSB) and phase transition in condensed matter are introduced to field description of universe. Due to the inflation of universe, its preferred vacuum state breaks the gauge symmetry of Lagrangian for the particle and gauge fields and imposes mass on the corresponding gauge bosons, which provides us a promising frame to unify the electromagnetic force, weak and strong force in the same gauge symmetry group. Meanwhile, the related inflationary cosmology also becomes an open window to explore the property of universe.

1 Background and Introduction

In the past few decades, people's knowledge on the universe and the elementary particles has boosted a lot. In the cosmology, many interesting and puzzling results have enriched our understanding about the universe while we have been trying to unveil its origin and future since early human history. In 1924, Edwin Hubble made the incredible discovery that the galaxy is actually moving away from us due to the red-shift spectrum experiment and the universe is in expansion. In 1946, George Gamow, a Russian astronomer, proposed a theory later known as big bang theory that the universe emerged from a hot and dense soup of particles in the primordial time and has been expanding ever since. While in the elementary particle physics, the four basic force in nature(electromagnetic force, weak force, strong force and gravity) has been tried to unified into only one fundamental force especially after the development of unification on the electromagnetic and weak force proposed by Glashow, Salam and Weinberg independently at around 70's.[6]. However, the most amazing things are that these two subdisciplines so different in scales are not separated, they actually benefit from and to each other as the concept of phase transition is the mysterious trick to correlate them together. The underlying essence of this theory is the idea of spontaneous symmetry breaking which is quite familiar even by the students in condensed matter physics.

According to the standard inflationary universe model, the universe started from a state of enormously high density, at a temperature much higher than the critical temperature where the symmetry($SU(5)$) has been restored between the strong and electroweak interactions in grand unified theories(GUTs). As the universe expanded and the temperature decreased to $T \sim T_{c1} - 10^{15} Gev$, a phase transition(or more) occurred which breaks the gauge symmetry of strong and electroweak forces into $SU(3) \times SU(2) \times U(1)$ groups. Even after the temperature drops further below $T_{c2} \sim 200 Gev$, the symmetry between electromagnetic and weak force are broken. Finally, at $T \sim 10^2 Mev$ The chiral symmetry of strong interactions breaks and leads to the coalescence of quarks into hadrons.

2 Basic Ideas

2.1 Particles,Forces and Universe

According to modern physics, the most fundamental bricks of universe till now are quarks and leptons which display hierarchy among them. Now physicists divide them into there generations and the components in different generations have quite similar properties with their counterparts except for huge mass distinctions. For example, electron and muon are quite similar leptons while muon is totally $200 \sim 300$ times heavier. Following are the twelve basic blocks for the world arranged by the generation. However,we should also consider the gauge bosons mediate the interactions between fermions. Interactions among charged particles are due to the exchange

of quanta of EM filed ie.photons which is massless and thus its interaction distance is infinite. Meanwhile, the strong force is mediated by the massless gluons which possess color charge. The color force increases in strength with increasing distance and thus quarks and gluons can't appear as free particles,but only exist inside composite hadrons. The even shorter range of weak force between quarks and leptons is associated with the charged W and neutral Z bosons while One special feature is that W's couple only to left-handed fermions[2].

Fermions	1st	2nd	3rd
Quarks	u,d	c,s	b,t
Leptons	e, ν_e	μ, ν_μ	τ, ν_τ

	Strong	Weak	Electromagnetic
Gauge Bosons	gluons(8)	$W^\pm, Z^0$	photon

2.2 Gauge Invariance(Symmetry)

Symmetry has played an important role in the history of Physics. The most awesome discovery would be Noether's theorem that every symmetry would correspond to a conserved variable for the system(i.e. If the action is invariant under some group of transformations, there exist some one or more conserved quantities associated with the transformations). During the construction of quantum field theory for the weak and strong force, gauge invariance had been the trick to propose the right form of Lagrangian for the gauge field.

Actually, in QED, the existence and some properties of the gauge field-photons just follow the requirement of Lagrangian invariance under the local gauge transformation of U(1)group. As we know, the Dirac free Lagrangian is

$$\mathcal{L} = \overline{\psi}(i\gamma_u \partial^u - m)\psi \tag{1}$$

which is not invariant under the local gauge transformation $\psi(x) \rightarrow \psi'(x) = exp[-i\alpha(x)]\psi(x)$, since

$$\mathcal{L}' = \mathcal{L} + \overline{\psi}\gamma_u \psi \partial^u \alpha(x)$$

However,we can define a gauge field through the minimal coupling as following:

$$D_u = \partial_u + ieA_u(x) \quad while \quad A'_u(x) = A_u(x) + \frac{1}{e}\partial_u\alpha(x) \tag{2}$$

Thus the Lagrangian is invariant as below:

$$\mathcal{L}_{\psi'} = \overline{\psi'}(i\gamma_u D'^u - m)\psi' = \overline{\psi}e^{i\alpha(x)}\left[i\gamma_u D^u - \gamma_u\alpha(x) - m\right]e^{-i\alpha(x)}\psi = \overline{\psi}(i\gamma_u D^u - m)\psi = \mathcal{L}_\psi \tag{3}$$

while the electromagnetic strength tensor and its Lagrangian are:

$$F_{uv} = \partial_u A_v - \partial_v A_u \quad and \quad \mathcal{L} = -\frac{1}{4}F_{uv}F^{uv} \tag{4}$$

More generally, for the non-Abelian transformation group G with generators T_a which satisfies the Lie algebra $[T_a, T_b] = iC_{abc}T_c$, where C_{abc} is the structure constant for the group, the Lagrangian should still be invariant under the matter field transformation $\psi \rightarrow \psi' = \Omega\psi$ with $\Omega = exp[-iT^a\alpha^a(x)]$.

Let us introduce the covariant derivative $D_u \equiv \partial - igT^aA_u^a$. This will ensure the invariance of local non-Abelian gauge transformation as long as

$$T^aA_u^a \rightarrow T^aA'^a_u = \Omega(T^aA_u^a + \frac{i}{g}\partial_u)\Omega^{-1} \Rightarrow A_u^{a\prime} = A_u^a - \frac{1}{g}\partial_u\alpha^a + C_{abc}\alpha^bA_u^c \qquad (5)$$

While we should also generalize the gauge field strength tensor and its invariant Lagrangian for the non-Abelian group as:

$$F_{uv}^a = \partial_uA_v^a - \partial_vA_u^a + gC_{abc}A_u^bA_v^c; \qquad \mathcal{L} = -\frac{1}{4}F_{uv}^aF^{a\ uv}$$

2.3 Spontaneous Symmetry Breaking

As we can check, if we just insert the gauge boson mass term in the Lagrangian, it will break the local gauge invariance explicitly. However, the gauge bosons for the weak and strong interaction of matter field do have mass from the experiments. How to solve this paradox had been a great challenge to the theorists for a long time. Finally, the particle physicists got inspiration from a quite popular phenomenon in condensed matter physics called spontaneous symmetry breaking(SSB) such as in the Ferromagnetic phase transition: 1964, Higgs; Englert and Brout; Guralnik etc separately proposed the scalar field theory later known as Higgs field with SSB and predicted massive vector bosons for the gauge field. In 1967 and 1968 Weinberg and Salam independently introduced the unified Lagrangian for the electroweak and attributed the mass differences between photons and $W^\pm, Z^0$ to the SSB of $SU(2) \times U(1)$ groups.

During the SSB, an interesting phenomenon will occur, where the system is in a vacuum state and loses some of its symmetries while the Lagrangian still preserve the total group symmetry. Now let us follow the argument to illustrate the appearance of gauge boson mass term without breaking the gauge invariance of Lagrangian.

Consider the self-interacting scalar field $\psi(x)$ with a Lagrangian:

$$\mathcal{L} = \frac{1}{2}\partial_u\psi^*\partial^u\psi - V(\psi) = \frac{1}{2}\partial_u\psi^*\partial^u\psi - \left[\frac{1}{2}\mu^2(\psi^*\psi) + \frac{1}{4}\gamma(\psi^*\psi)^2\right] \qquad (6)$$

As we have seen in class, when $\mu^2 < 0$, the vacua state is corresponding to the non-zero field $|\psi| = \sqrt{-\mu^2/\gamma} = \nu$. However, once one phase is chosen, the system has broken its rotational symmetry even though the Lagrangian is still invariant, thus we call it spontaneous symmetry breaking. For example, if we set the vacua state is $\psi = \frac{\psi_1 + i\psi_2}{\sqrt{2}}$, where $\psi_1 = \nu$ and $\psi_2 = 0$. Thus
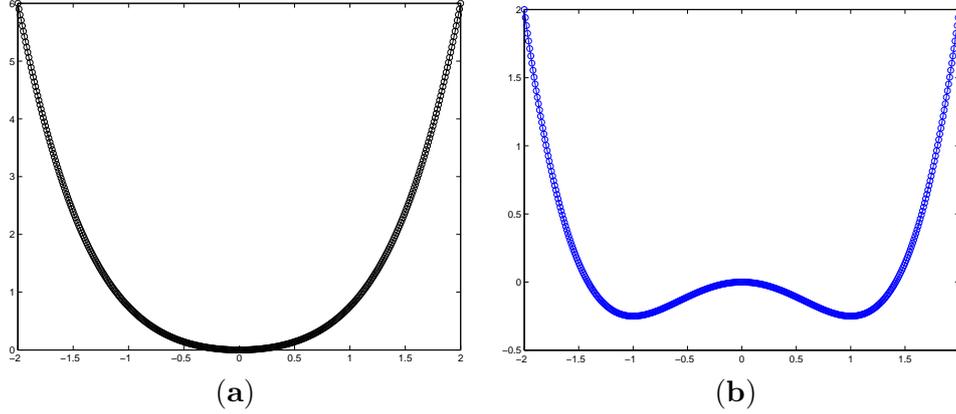
Figure 1: Scalar field potential for (a) $\mu^2 > 0$ *and* (b) $\mu^2 < 0$

for a small perturbation, the state can be defined as $\psi_1 = \nu + \psi_1'$ *and* $\psi_2 = \psi_2'$. In terms of the new fields, the Lagrangian can be written as:

$$\mathcal{L} = \frac{1}{2}\partial_u \psi_1' \partial^u \psi_1' - \frac{1}{2}(-2\mu^2)\psi_1'^2 + \frac{1}{2}\partial_u \psi_2' \partial^u \psi_2' + Interaction\ terms \tag{7}$$

It is clear that now we get a positive massive scalar field ψ_1' as well as a massless field ψ_2' while the massless field is called Goldstone boson field. Actually, a more general conclusion about continuous SSB is the Goldstone Theorem: When each continuous symmetry is broken spontaneously, ie it is not symmetric for the vacuum state of system anymore, there exist one massless scalar particle(Goldstone Boson) for each broken generator of the initial symmetry group.

2.4   Higgs Mechanism

Goldstone Theorem implies the existence of massless scalar particles, however, we have never observed such kind of particles in nature. Meanwhile, we need to explain the massive gauge boson to mediate the electroweak interactions within the requirement of local gauge invariance. Higgs mechanism was proposed to get rid of the Goldstone bosons. An extra bonus is that gauge bosons become massive, which is just what we are expecting.

In order to make the Lagrangian in Eq. (6) invariant under the U(1) rotational transformation $\psi \rightarrow e^{iq\alpha(x)}\psi$, we should introduce the gauge field A_u and covariant derivative as in section 2.2. Meanwhile, we can express the field in a more convenient way and Thus the Lagrangian becomes:

$$\psi = exp(i\frac{\psi_2'}{\nu})\frac{\psi_1' + \nu}{\sqrt{2}} \simeq \frac{1}{\sqrt{2}}(\psi_1' + \nu + \psi_2') = \psi' + \frac{\nu}{\sqrt{2}} \tag{8}$$

$$\mathcal{L} = \frac{1}{2}\partial_u\psi_1'\partial^u\psi_1' - \frac{1}{2}(-2\mu^2){\psi_1'}^2 + \frac{1}{2}\partial_u\psi_2'\partial^u\psi_2' + Interaction\ terms$$

$$- \frac{1}{4}F_{uv}F^{uv} + \frac{q^2\nu^2}{2}A_uA^u + q\nu A_u\partial^u\psi_2'$$

A more beautiful way to eliminate the term of $A_u\partial^u\psi_2'$ is to make a gauge transformation and the corresponding Lagrangian would be as below:

$$\psi = exp\left[iq\frac{-\psi_2'}{q\nu}\right]exp(i\frac{\psi_2'}{\nu})\frac{\psi_1'+\nu}{\sqrt{2}} = \frac{1}{\sqrt{2}}(\psi_1'+\nu) \tag{9}$$

$$\mathcal{L} = \frac{1}{2}\partial_u\psi_1'\partial^u\psi_1' - \frac{1}{2}(-2\mu^2){\psi_1'}^2 - \frac{1}{4}F_{uv}F^{uv} + \frac{q^2\nu^2}{2}A_u'A^{u\prime} - \frac{\gamma}{4}{\psi_1'}^3(\psi_1'+4\nu)$$

It is amazing that the Goldstone boson ψ_2' disappears and the gauge boson acquires a mass term where $m^2 = \frac{q^2\nu^2}{2}$. Where is the Goldstone bosons? It is actually absorbed by the gauge field because $A_u' = A_u - \partial_u\alpha(x) = A_u + \frac{1}{q\nu}\psi_2'$ after the gauge transformation and turns into the longitudinal degree of freedom of the gauge boson.

A more generalized consideration for the non-Abelian gauge symmetry G of dimension N_G and generators T^a is as following: We can introduce $N-G$ gauge bosons and the covariant derivative is $\partial_u \rightarrow D_u = \partial_u - igT^aB_u^a$. After the SSB, a sub-group g of dimension n_g remains as the symmetry of the vacua, ie.

$$T_{ij}^a\psi_j^0 = 0, \quad for \quad a = 1,\ldots,n_g$$

We would expect $N_G - n_g$ Goldstone bosons and set the original scalar field as $\psi = (\tilde{\psi} + \nu)exp\left(i\frac{\psi_{GB}^aT^a}{\nu}\right)$, where T^a are the $(N_G - n_g)$ broken generators that don't annihilate the vacuum. Choose the right gauge transformation to eliminate the Goldstone fields which will give rise to $(N_G - n_g)$ massive gauge bosons. A detailed check on the degree of freedom as following will prove that we don't lose any one of them.

Before SSB	After SSB
ψ massless scalar: N_ψ	$\tilde{\psi}$ massive scalar: $N_\psi - (N_G - n_g)$
B_u^a massless vector:N_G	$\tilde{B}_u^a$ massive vector: $3(N_G - n_g)$
	B_u^a massless vector:$2n_g$

A good example to combine all the above ideas together is to analyze the elctroweak interaction between leptons. As stated, the Glashow-Weinberg-Salam model is known, at the present time, as the Standard Model of Electroweak Interactions, reflecting its impressive success.Let us just

follow the argument in reference [5] to get the basic idea about it.

Based on a detailed analysis on the chirality of the interaction, we can just choose $SU(2)_L \otimes U(1)_Y$ as the gauge symmetry group and their corresponding gauge fields: $SU(2)_L \rightarrow W_u^1, W_u^2, W_u^3$ and $U(1)_Y \rightarrow B_u$. Meanwhile, the strength tensors for the gauge fields are:

$$W_{uv}^i \equiv \partial_u W_v^i - \partial_v W_u^i + g\epsilon^{ijk} W_u^j W_v^k, \quad and \quad B_{uv} \equiv \partial_u B_v - \partial_v B_u$$

The free Lagrangian for the gauge fields is $\mathcal{L}_{gauge} = -\frac{1}{4} W_{uv}^i W^{i\ uv} - \frac{1}{4} B_{uv} B^{uv}$
Now let us define covariant derivative for the fermion-gauge coupling as:

$$L: \quad \partial_u + i\frac{g}{2}\tau^i W_u^i + i\frac{g'}{2} Y B_u, \quad R: \quad \partial_u + i\frac{g'}{2} Y B_u$$

Therefore, the fermion Lagrangian would become[3]:

$$\mathcal{L}_{leptons} = \bar{l}i\gamma^u \partial_u l + \bar{\nu}i\gamma^u \partial_u \nu + \bar{L}i\gamma^u\left(i\frac{g}{2}\tau^i W_u^i + i\frac{g'}{2} Y B_u\right)L + \bar{R}i\gamma^u\left(i\frac{g'}{2} Y B_u\right) \tag{10}$$

Let us first pick up the "left" piece as

$$\mathcal{L}_{leptons}^{L(\pm)} = -g\bar{L}\gamma^u\left(\frac{\tau^1}{2}W_u^1 + \frac{\tau^2}{2}W_u^2\right)L - g\bar{L}\gamma^u\frac{\tau^3}{2}W_u^3 - \frac{g'}{2}Y\bar{L}\gamma^u L B_u \tag{11}$$

Among it, the charged term can be written as: $\mathcal{L}_{leptons}^{L(\pm)} = -g\bar{L}\gamma^u\begin{pmatrix} 0 & W_u^1 - iW_u^2 \\ W_u^1 + iW_u^2 & 0 \end{pmatrix}L$.
We can define the charged gauge boson as $W_u^{\pm} = \frac{1}{\sqrt{2}}(W_u^1 \mp W_u^2)$ in such a way that

$$\mathcal{L}_{leptons}^{L(\pm)} = -\frac{g}{2\sqrt{2}}[\bar{\nu}\gamma^u(1-\gamma^5)lW_u^+ + \bar{l}\gamma^u(1-\gamma_5)\nu W_u^-] \tag{12}$$

Now let us think about the neutral part of $\mathcal{L}$ that contain both left and right fermion components,

$$\mathcal{L}_{leptons}^{(L+R)0} = -g\bar{L}\left(\gamma_u\frac{\tau^3}{2}\right)LW_u^3 - \frac{g'}{2}(\bar{L}\gamma^u Y L + \bar{R}\gamma^u Y R)B_u = -gJ_3^u W_u^3 - \frac{g'}{2}J_Y^u B_u \tag{13}$$

where the currents J_3 and J_Y are defined as:

$$J_3^u = \frac{1}{2}(\bar{\nu}_L\gamma^u\nu_L - \bar{l}_L\gamma^u l_L) \quad ; \quad J_Y^u = -(\bar{\nu}_L\gamma^u\nu_L + \bar{l}_L\gamma^u l_L + 2\bar{l}_R\gamma^u l_R)$$

In order to get the right combination of fields that couples to the electromagnetic current, we can make a rotational transformation in the neutral fields as $\begin{pmatrix} A_u \\ Z_u \end{pmatrix} = \begin{pmatrix} cos\theta_W & sin\theta_W \\ -sin\theta_W & cos\theta_W \end{pmatrix}\begin{pmatrix} B_u \\ W_u^3 \end{pmatrix}$,

where θ_W is called the Weinberg angle and the relation with the SU(2) and U(1) coupling constants hold

$$sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \quad ; \quad cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \tag{14}$$

The neutral part of the fermion Lagrangian becomes

$$\mathcal{L}_{leptons}^{(L+R)_0} = -g sin\theta_W (\bar{l}\gamma^u l) A_u - \frac{g}{2cos\theta_W} \sum_{\psi_i = \nu, l} \overline{\psi_i} \gamma^u (g_V^i - g_A^i \gamma_5) \psi_i Z_u \tag{15}$$

After the SSB, we can chooose the vacuum state of the Higgs field as $< \Psi >_0 = \begin{pmatrix} 0 \\ \nu/\sqrt{2} \end{pmatrix}$, since we want to preserve the exact electromagnetic symmetry to maintain the electric charged conserved, we must break the original symmetry group as $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$. Thus after the SSB the vacuum should still have the U(1) symmetry for the electromagnetic force, which requires that $e^{i\alpha Q} < \Psi >_0 \simeq (1 + i\alpha Q) < \Psi >_0 = < \Psi >_0$, which is true as we can check below:

$$Q < \Psi >_0 = (T_3 + \frac{1}{2}Y) < \Psi >_0 = \frac{1}{2}\left[\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\right]\begin{pmatrix} 0 \\ \nu/\sqrt{2} \end{pmatrix} = 0$$

Meanwhile, we can make a $SU(2)_L$ gauge transformation to get rid of the Goldstone mode due to the gauge symmetry breaking with $\alpha_i = \chi_i/\nu$ and the scalar field and its Lagrangian become:

$$\Psi \to \Psi' = exp\left(-i\frac{\tau^i}{2}\frac{\chi_i}{\nu}\right)\Psi = \frac{\nu + H}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{16}$$

$$\mathcal{L}_{scalar} = |\left(\partial_u + ig\frac{\tau^i}{2}W_u^i + i\frac{g'}{2}YB_u\right)\frac{\nu + H}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix}|^2 - \mu^2\frac{(\nu + H)^2}{2} - \gamma\frac{(\nu + H)^4}{4}$$

As for the vector fields $W^\pm$ and Z^0, the first term in the Lagrangian can be expressed as below:

$$|\begin{pmatrix} 0 \\ \partial_u H/\sqrt{2} \end{pmatrix} + i\frac{g}{2}(\nu + H)\begin{pmatrix} W_u^+ \\ (-1/\sqrt{2}C_W)Z_u \end{pmatrix}|^2 = \frac{1}{2}\partial_u H \partial^u H + \frac{g^2}{4}(\nu + H)^2\left(W_u^+ W^{-u} + \frac{1}{2c_W^2}Z_u Z^u\right)$$

Thus the quadratic terms in the vector fields determine the usual mass for the charged and neutral vector bosons, where we have assumed an experimental value for $S_W^2 \equiv sin\theta_W{}^2 \sim 0.22$

$$M_W = \frac{g\nu}{2} = \frac{e\nu}{2sin\theta_W} \sim 80 GeV, \quad while \quad M_Z = \frac{g\nu}{cos\theta_W} = \frac{e\nu}{2cos\theta_W sin\theta_W} \sim 90 GeV \tag{17}$$

Meanwhile, the scalar Higgs field gives rise to a Boson field with mass $M_H = \sqrt{-2\mu^2}$. However, since μ^2 is actually a priori unknown parameter, Standard Model doesn't predict the exact value of the Higgs boson mass, which is still a great challenge for the hight energy physicist in recent years.

2.5   Phase Transition in the Early Universe

Since Higgs Field is responsible for the symmetry breaking of vacuum state under gauge transformation. Temperature should be the main reason to change the shape of the potential $V(|\psi|^2)$ in the way that its square gives a positive contribution to the mass term of the scalar field $V(|\psi|^2, T) = \frac{1}{2}(-\mu^2 + \alpha T^2)|\psi|^2 + \frac{\gamma}{4}|\psi|^4$. As known, the early universe was so hot that $T^2 > \mu^2/\alpha$, the only one minimum potential is at $|\psi|^2 = 0$ and all the symmetries were restored with all gauge bosons massless. At about $10^{-12} sec$ after the bang, when the temperatures were of the order GeV, the electroweak symmetry was broken and the gauge bosons $W^{\pm}$ and Z^0 obtained masses.

Actually, in the Grand Unified Theories(GUTs), the phase transition for the strong and electroweak symmetry breaking is first-order, where the order parameter doesn't change continuously and makes it more complicated to investigate the transition dynamics from the SU(5)group to $SU(3) \times SU(2) \times U(1)$ groups. Just like the liquid-gas transition, it occurs through the bubble-nucleation of low energy liquid phase in the metastable gas phase. If the bubbles are large enough to grow, percolate, they will eventually convert all the gas volume into liquid phase. More generally, the vacuum state of Higgs field with the Lagrangian $\mathcal{L}(\psi) = \frac{1}{2}(\partial_u \psi)^2 - V(\psi)$ is determined by the global minimum effective potential where $\psi = \psi_0 \neq 0$. However, it also has another local minimum at $\psi = 0$. Surprisingly, the universe can stay in the unfavorable metastable vacuum state $\psi = 0$ for an incredible long time. It decays with formation of bubbles of the field ψ via tunneling excited by thermal or quantum fluctuations[1].

In 1981, Alan Guth proposed the idea known as inflationary cosmology to try to clarify the interplay between cosmology and dynamics of phase transitions. In the theory, as the universe expanded and cooled, the higgs field was trapped in this metastable state. In this case, the energy density of all matter would have two terms, one from radiation and the other from the vacuum energy:

$$\rho = \frac{\pi^2}{30}g_* T^4 + V_0,$$

where V_0 is the constant energy density of the field. When the temperature $T < (30V_0/g_*\pi^2)^{1/4}$, the energy density will be dominated by the constant vacuum energy and the scale factor will expand exponentially fast, $R \propto exp(\sqrt{\Lambda_{vac}}t)$ according to the Einstein's equation:

$$\left(\frac{\dot{R}}{R}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho + \frac{k}{R^2} \tag{18}$$

Thus the universe will expand superluminally and become supercooled. Due to the sudden cool down, the field will decay into the lowest energy state by the mechanism of quantum bubble nucleation and here comes the phase transition.

3 Conclusions and Challenges

The beautiful picture above is not only reasonable to explain the origin that different types of forces and their gauge fields have enormously different properties and behaviors for particle physicists, but also opens a new window to explore the puzzles of universe [4] and benefit our understanding on the correlation of various phenomena with so distinctive dimensional scales.

Firstly,one problem physicists and cosmologists should be confronted with is the incredibly uniform cosmic radiation background. When radio antennas are pointed at different directions to measure the temperature of cosmic background, it is found that $T = 2.726 \pm 0.005K$, with deviations of less than 0.05%. Another startling fact is that the galaxies tend to lay on vast sheet-like structures surrounding large empty regions. some of those empty regions have diameters of tens of Megaparsecs, or several million light years. The inflation of universe may be the key to the questions above: due to a sufficiently long inflationary expansion, a small causally connected volume could have grown to encompass the whole of the observed universe today. Actually,a length scale which was 10^{-28} cm before inflation would have been stretched to 10^2 cm after inflation, which would correspond to 10^{28} cm, roughly the current size of the observable universe. Meanwhile, during the inflation when the length scale are stretched exponentially fast($R \propto exp(\sqrt{\Gamma_{vac}}t)$), it is possible for the quantum fluctuation to be amplified into the density perturbations which will cause the gravitational instability and form later structural distributions.

secondly,another nightmare for the physicists is the overwhelming dominance of matter over anti-matter, which obviously breaks the symmetry of matter and anti-matter. Sakharov in 1968 suggested three required conditions in order to produce the matter excess:1) creation of matter and anti-matter 2)bias between them 3)this excess is not erased after. At high energies, the interaction between elementary particles should not conserve the numbers of baryons in the decay of heavy GUTs-scale particles and from the non-trivial vacuum structure of the electroweak theory. Meanwhile, in 1964, J. H. Christenson and his collaborators found experimental evidence that interactions between certain baryons do indeed show its bias toward more baryons known as CP violation. If this is also true for nature, it is easy to explain the dominance of baryons. Finally, in the GUTs-scale, baryogenesis out of equilibrium are achieved by the irreversible decays of heavy particles. Due to the expansion of universe, which makes it hard for the lighter particles to meet and react, the process involving the decay won't be able to keep up with the expansion to balance the baryons and anti-baryons. In the elctroweak baryogenesis, it is usually assumed that a discontinuous phase transition occurs via the bubble nucleation mechanism. In the symmetric high temperature phase, baryon number is freely violated with a rate proportional to T^4, while in the broken-symmetric, low temperature phase, this rate is reduced by Boltzmann factor, $\Gamma_{b-viol} \propto exp[-E/T]$ and thus the excess baryons are generated in the symmetric phase. During the bubble formation and phase transition, the excess baryons have

a probability of going through the bubble wall to the bubble region to generate a net baryon number excess inside the bubble. Since inside the growing bubbles baryon number is conserved and ultimately the universe is made of predominant matter .

although, the inflationary cosmology theory with phase transition has successfully explained some of the fundamental problems on universe and makes an intimate relation with the GUTs or standard Model of particle physics, it is far from perfect and even sometimes controversy: Domain Walls, Strings, and Monopoles are still not satisfactorily solved. Even as the key of spontaneously symmetry breaking in this theory, Higgs boson is still not yet found by high energy experimentalists[7]. However, What can be said is that we are on the right track to follow the hint of god to appreciate the symmetry beneath the nature and the beauty of his design.

References

[1] Andrei Linde, Particle Physics and Inflationary Cosmology,Harwood Academic Publishers, 1990

[2] Mary K. Gaillard, Paul D. Grannis, Frank J. Sciulli, Rev. Mod. Phys. 71, S96(1999)

[3] Y. Kuno and Y. Okada, Rev. Mod. Phys. 73, 151(2001)

[4] Marcelo Gleiser, http://arXiv:hep-ph/9803291 V1 9 Mar 1998

[5] S. F. Novaes, http://arXiv:hep-ph/0001283 V1 27 Jan 2000

[6] A.Salam and J.C. Ward, Phys. Lett. 13, 168(1964); S. Weinberg, Phys. Rev. Lett. 19, 1264(1967); S.L Glashow, J. Iliopoulous and L. Maiani, Phys. Rev. D **2**,1285 (1970)

[7] G. Kane, J. F. Gunion, etc, The Higgs Hunter's Guide, Addison-Wesley Pub. Co. Menlo Park, 1990