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Cosmology—particle physics interface*

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Abstract. Some of the areas of cosmology which have been activated by new developments in particle physics are reviewed. A brief review of the essential ideas of the big bang model and models of particle physics with spontaneously broken symmetry is given. The ideas of inflationary expansion of the universe and of baryogenesis at weak scale are then discussed.

Key words : cosmology—particle physics

1. Introduction

George Gamow was among the earliest to apply ideas of nuclear particle physics to cosmology and astrophysics. Bethe was another pioneer to apply the ideas of nuclear physics to energy generation in stars (like Sun). The importance of particle physics or subnuclear physics has been appreciated in astrophysics and cosmology now for about 60 years. So what is new?

There are many areas of natural, life and other sciences which use physics; there are many areas of physics which use particle and nuclear physics. But people working in frontier areas of particle physics do not expect to learn anything new from these applications. However in the cosmology-particle physics interface, that we are now talking about, it is the frontiers of the two subjects that have intermingled. Progress in particle physics implies progress and understanding in cosmology and vice versa, that is what is new!

As a result of all these, cosmology has gained a lot of importance in recent years and has started attracting observers (experimentalists), theorists and numerical simulation experts. It is this exciting development that we wish to discuss in this talk. We shall briefly review the essential ideas in cosmology and the relevant areas of particle physics and then go on to discuss the ideas of inflation and baryogenesis in cosmology.

The currently accepted model of cosmology, the standard or the big bang model is based on the assumption of cosmological principle; the idea that the description of the universe from any point in three dimensional space is equivalent. This is the assumption of homogenity and isotopy in space. Though this can only be a simplifying assumption

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for the present universe with its clumpiness in the form of galaxies, stars and planets, it seems to be remarkably satisfied for the early universe as indicated by the very small anisotropy shown by microwave background radiation

$$\left(\frac{\Delta T}{T} \approx \frac{\Delta\rho}{\rho} < 10^{-5}\right).$$

This assumption leads to the Robertson-Walker metric for space time.

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\right]. \qquad \ldots(1)$$

In Einstein's general relativity gravitation is described by the function $g_{\mu\nu}(x^\lambda)$ (with μ, ν, $\lambda = 0, 1, 2, 3$) which describes the geometry through the line element

$$ds^2 = \sum_{\mu,\nu=0}^{3} g_{\mu\nu}\, dx^\mu\, dx^\nu.$$

The cosmological principle reduces the $g_{\mu\nu}$ to just two unknowns—a function $R(t)$ called scale factor and a parameter k which can take the value 0, ± 1. These are further determined by solving Einstein's field equation which is a non linear differential equation for $g_{\mu\nu}$ in terms of the stress energy tensor density of the universe viz $T_{\mu\nu}$.

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu} \qquad \ldots(2)$$

If we take the stress energy tensor to be that of a perfect fluid, $T_{\mu\nu} = pg_{\mu\nu} + (p+\rho)\, U_\mu\, U_\nu$ where

$$U_\mu\left(\equiv \frac{\partial x^\mu}{\partial s}\right)$$

is the four velocity, the field equation then leads to the dynamical equations of cosmology which are

$$\left(\frac{dR}{dt}\right)^2 + k = \frac{8\pi G}{3}\rho R^2 - \text{Friedman equation}, \qquad \ldots(3)$$

$$\frac{d}{dt}(\rho R^3) + p\,\frac{dR^3}{dt} = 0 - \text{Conservation equation}, \qquad \ldots(4)$$

$$p = p(\rho) \qquad \text{—Equation of state} \qquad \ldots(5)$$

All lengths are determined by the scale factor $R(t)$ and so wavelength at the time of emission by a distant source (say galaxy) is $\lambda_e \propto R(t_e)$ while at the time of reception by us is $\lambda_o \propto R(t_o)$. Redshift Z is defined by

$$Z \equiv \frac{\lambda_o - \lambda_e}{\lambda_e} \approx \frac{\lambda_o}{\lambda_e} - 1 = \frac{R(t_o)}{R(t_e)} - 1.$$

Hubble observed a positive red shift of galaxies indicating an expanding universe.

The future course of the universe is given by Friedman equation and indicates that there is a critical mass density (ρ_c) and if the present mass density ρ exceeds it $(\rho > \rho_c)$

the expansion will stop and contraction will begin, implying a closed universe. For $\rho \leqslant \rho_c$ the universe will continue to expand as a open universe. Thus $\Omega \equiv \rho/\rho_c$ is a crucial physical quantity whose value is still uncertain.

The equation of state can take the forms

$$p = W\rho \quad \text{with } W = \begin{cases} 1/3 & \text{radiation} \\ 0 & \text{matter} \\ -1 & \text{constant energy } (T_{\mu\nu} = \Lambda\, g_{\mu\nu}). \end{cases}$$

The conservation equation and Friedman equation for these three cases lead to

$$\rho \propto \begin{cases} R^{-4} \\ R^{-3} \\ \text{constant} \end{cases} \Rightarrow R(t) \propto \begin{cases} t^{1/2} \\ t^{2/3} \\ e^{\mathrm{Ht}} \end{cases}$$

The thermodynamics leads to the relation RT = constant where R and T are scale factor and temperature. This tells us $T \to \infty$ as $R \to 0$ at early times. As we go back in time in early universe we can have very high temperatures which provides the high energies needed to observe many particle physics phenomena.

Thermal history : As the universe expands it cools and as the temperature (thermal energy) gets smaller in comparison to the binding energy, bound systems start making their appearance out of elementary particles like p, e^-, n, ν etc. The first to be formed is the deuteron or ^{2}H with a binding energy of 2.2 MeV. Gamow was the first to discuss the formation of Helium and light elements in early universe.

$$p + n \to d + \gamma$$

$$d + d \to {}^3\mathrm{He} + n \leftrightarrow {}^3H + p$$

$$^3\mathrm{He} + d \to {}^4\mathrm{He} + n.$$

From the requirement that the helium abundance should correspond to the observed quarter by weight of all elements one can estimate the density of baryons, at the time of helium formation. Estimate of the present baryon density then enables us to conclude that scale factor $R(t)$ has increased by a factor of 10^9. This leads to the prediction that the radiation present at that time must have cooled down to about 5K now—a prediction made by Gamow and his students Alphar and Hermann. The discovery of this cosmic microwave background radiation (CMBR) independently by Penzias and Wilson in 1963 is one of the greatest successes of the big bang model. The isotropy of this radiation is an indication of the smoothness of the universe at the time this radiation last interacted with matter (when the universe was about 10^6 years old). The high degree of isotropy ($\Delta T/T < 10^{-5}$) is an embarassment at the moment as one requires density perturbations in the universe larger than these to explain galaxy formation. (A more extensive discussion is given by other speakers at this symposium).

The presently observed helium abundance also constrains the number of neutrinos to be less than 3.4—a result now sharpened by laboratory experiments with accelerators.

Particle physics : In the last twenty years remarkable progress has been made towards achieving Einstein's dream of unification of the forces of nature. This has been done in a way undreamt of by even Einstein; using Gauge theories with spontaneous symmetry breaking (SSB). These new approaches were directly influenced by developments in condensed matter physics specially superconductivity.

Symmetry breaking : Consider a potential $V = \lambda(\phi^2 - \sigma^2)^2$.

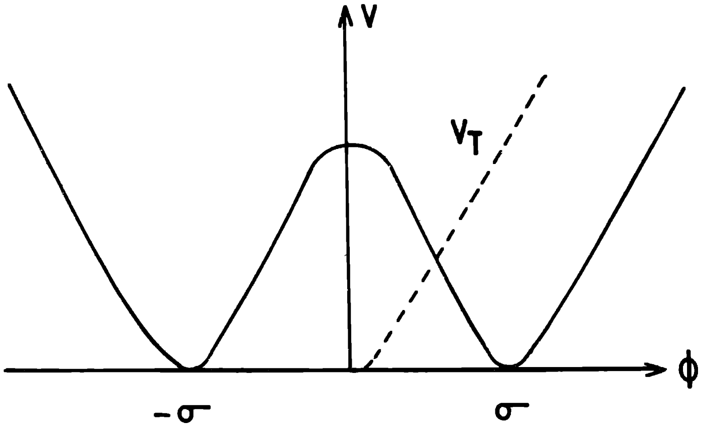

Figure 1

The minimum of the potential is at $\phi = \pm\sigma$ (see figure 1). Choice of any one of these breaks the reflection symmetry ($\phi \to -\phi$) present in the potential (and the Lagrangian). Theories, like this, whose vacuum (or ground state) breaks the symmetry of the potential (and the Lagrangian) are called spontaneous symmetry broken (SSB) theories. A familiar example is the ferromagnetic transition at Curie temperature which breaks rotation invariance by choosing a particular direction of magnetization at lower temperatures.

In the unification of electromagnetism and weak interaction (electro weak theory) suggested by Weinberg and Salam the unified theory obeys the gauge symmetry under $SU(2) \times U(1)$ and the vacuum breaks the symmetry down to $U(1)$. When the symmetry is unbroken the field quanta are massless and the forces are of long range. However when symmetry is broken the quanta acquired mass and the forces have a short range. In the electroweak theory, after symmetry breaking, the weak interaction becomes of short range while electromagnetism mediated by the photon continues to be long ranged. In superconductivity theory vacuum expectation value (VEV) of a composite field made up of cooper pair (or two electron system) leads to the symmetry breaking. In electroweak theory VEV of an intrinsic field called the Higgs field breaks the symmetry. Its quanta, the Higgs particle, is yet to be observed experimentally.

Symmetry restoration : Just as raising the temperature of the ferromagnetic system above Curie temperature removes magnetization and restores the rotational symmetry. The electroweak symmetry $SU(2) \times U(1)$ is also restored at high temperatures. This phase transition occurs around $T = 20$ GeV(10^{14}K) and is expected to play a crucial role in cosmology.

Grand unified theory : Spurred by the success of electroweak theory many attempts have been made to unify strong interactions (nuclear interaction) with electroweak. They predict the decay of protons to non baryonic matter like e^+, π^0 or $\bar{\nu}$, π^+ which have not been observed yet. The phase transition of this unification takes place at $T \sim 10^{15}$ GeV (10^{28}K).

(The simplest version based on SU(5) → SU(2) × U(1) × SU(3)$_{\text{colour}}$ is ruled out by proton life time being greater than 10^{32} years).

Problems of big bang model

(1) *Horizon problem* : In our model all parts of the Universe now accessible to observation could not have causally interacted; which makes it difficult to explain the observed isotropy of CMBR without assuming special initial conditions. In the R-W model the distance that light signals can travel is given by horizon distance d_H where

$$d_H = R(t) \int_t^0 \frac{dr}{1 - kr^2} = R(t) \int_0^t \frac{dt'}{R(t')} \propto \frac{t^{1-n}}{(1-n)}$$

for $R(t) \sim t^n$ $(n < 1)$.

The observed or comoving length is $\propto R(t) \sim t^n$. As we go back in time the horizon was always smaller than the observed comoving volume which makes it impossible for different parts of the observed universe to have interacted. (If $R(t) \sim t^n$ with $n > 1$ then $d_H \rightarrow \infty$ and so is always greater than comoving volume which goes like t^n).

(2) *Flatness problem* : The present value of $\Omega (\equiv \rho / \rho_c > .01)$ when extrapolated back in time using Friedman equation implies that $\Omega = 1 + 10^{-35}$ at $t = 10^{-35}$s or a very fine tuning. In the absence of fine tuning a closed universe would have had a life time $\sim t_{\text{Planck}} \sim 10^{-43}$ sec, the only scale of time available. Such a finely tuned value of Ω as an initial condition also seems unsatisfactory.

It was realised by Guth (1982) that these and related problems are solved if universe went through a phase of exponential or inflationary expansion. The constant energy density needed for such an expansion is provided by the extra free energy (or latent heat) available at the time of phase transition if the universe gets into a metastable state. Such an "Inflationary Scenario" has been studied extensively in the last 10 years and has served to bring cosmology and particle physics closer.

Inflation : At the time of GUT phase transition at $T \sim 10^{15}$ GeV if the potential has a barrier between the state at $\phi = 0$ and the broken symmetric phase at $\phi = \sigma$ the transition takes some time due to the necessity of tunnelling. During this time the available free energy $V(0)$ (figure 2) serves as a constant energy density and causes an

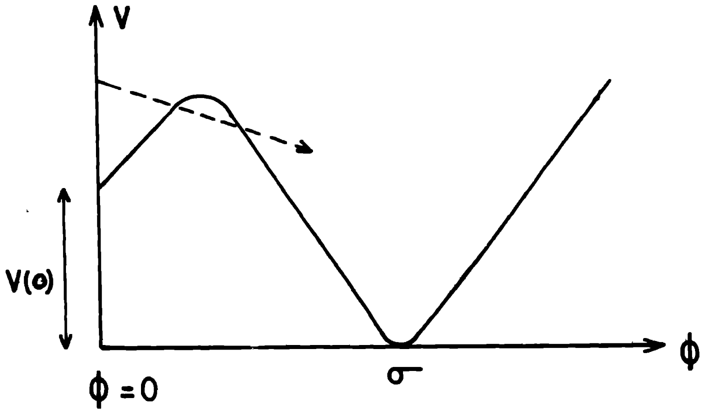

Figure 2

exponential increase in scale factor R. This is called the inflationary stage and serves to solve the difficulties of the big bang model, mentioned earlier.

The original model suggested by Guth (Now known as "old" inflation) had difficulties in completing the phase transition as the bubbles of the new phase could not grow, collide and thermalise due to the exponential expansion of the universe. In the "new inflation" model the transition time is made so large (by choosing a flat potential) that our universe is within one expanding bubble and bubble collisions are not needed.

In the inflationary stage the R-W metric is the de sitter metric which has a horizon of the size of H^{-1}, where $R(t) \propto e^{Ht}$. Quantum perturbations or fluctuations leave the horizon as universe expands but they come into the horizon d_H in the R-W stage after the inflationary stage is over. Thus, these models enable something to be said about the nature of density perturbations at different times (or on different length scales), which form the initial conditions for growth of galaxies and other structures in the universe. Such a prediction of density perturbations, based on classical evolution of the quantum fluctuations gives values for $\delta\rho/\rho$ of the order of unity or more. These values are in disagreement with constraints from CMBR which have $(\Delta T/T)$ $(\sim \delta\rho/\rho) < 10^{-5}$. This serious difficulty with inflationary model persists to this day in spite of modifications like chaotic inflation and extended inflation. Extended Inflation originally proposed by Mathiazhagan & Johri is the model of inflation being studied extensively at the present time. Inflationary models, being an attractive blend of cosmology and particle physics have brought the workers in this field close together.

Baryogenesis : The number of baryons in the universe is a small fraction of the number of photons. The quantity $N_B/N_\gamma (\cong 10^{-8}$ to $10^{-9})$ is called the baryon asymmetry in the universe (BAU) as it represents the excess of baryons over antibaryons. When baryon number conservation seemed absolute this value of BAU had to be either taken as a given initial condition or it had to be argued that matter and antimatter have got separated in the universe with matter dominant in our neighbourhood. The absence of evidence for matter-antimatter annihilation in our neighbourhood seems to rule out the idea of separation. Following the initial attempts of Pati and Salam (1972) many theories of grand unifications have been attempted which lead to proton decay accompanied by baryon number violations. So the question is being raised whether we can explain the BAU starting from a symmetric initial universe ($N_B = N_{\bar{B}}$).

Even earlier (in 1967) Sakharov (father of the hydrogen bomb and Nobel peace prize winner) had discussed the problem in a comprehensive way and laid down the necessary requirements which are:

1. B—violation.
2. C and CP violation—otherwise B and $\bar{B}$ production is same.
3. Departure from equilibrium—otherwise annihilation and creation proceed at equal rate.

These requirements are satisfied in an expanding universe by GUT theories. Based on these, values of BAU $< 10^{-5}$ were obtained (around 1979).

In recent years baryon number violation has been predicted even at the time of Weinberg-Salam or electro-weak transition. The process is sometimes called anomaly based baryon violation (ABV). It was first noticed by t'Hooft in 1976. The violation takes place as the vacuum (ground state) of electroweak theory is a superposition of states with different baryon numbers. This is similar to the situation in a superconductor where the ground state can have any number of Cooper pairs and is hence a superposition of states with different charges. As number and phase are complementary it is the phase (Josephson phase) that is fixed. In electroweak theory the different baryon number states are degenerate in energy but are separated by energy barriers. Baryon number change can take place by tunnelling, but the rate calculated by t'Hooft at $T = 0$ was negligible being $\sim 10^{-164}$

In recent times static unstable solutions called SPHALERONS have been found which have energy comparable to barriers and have half integral baryon member values and sit on top of the barrier (see figure 3). These facilitate tunnelling at high temperatures—close to electroweak phase transition. The ABV can wipe out the asymmetry (BAU) created at the time of GUT. (They conserve $(B - L)$ where B, L are baryon and lepton number respectively).

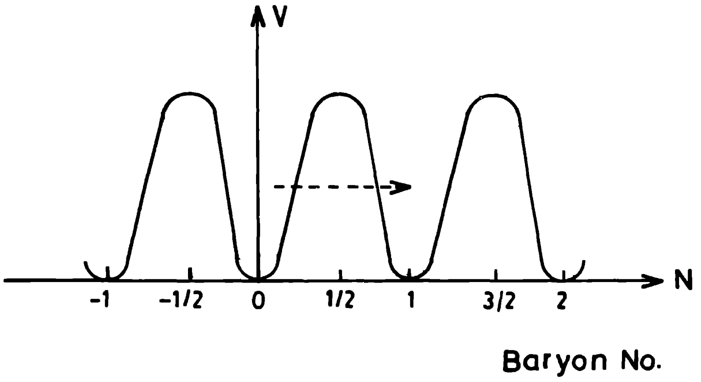

Figure 3

At the moment there are three ways out of this difficulty:

(1) $(B - L)$ violating GUT theories.

(2) Suppression of ABV at electroweak phase transition by the detailed nature of the phase transition.

(3) Creation of BAU at electroweak phase transition.

The discussion of the second alternative by the Russian theorists leads to constraint on Higgs mass ($M_{\mathrm{Higgs}} < 55$ GeV). As this is already violated by experimental results this might indicate the need for a change in the Higgs sector of Electroweak potential from cosmological considerations.

We have given some indications of the interplay between Cosmology and Particle Physics in the examples above. There are many others, which we have not been able to mention like (neutrinos, dark-matter etc.) and the future promises a lot of excitement.

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