PHYSICAL PROCESSES AT SUPER-HIGH ENERGIES

B Datta

Introduction

This paper presents an account of the possible physical processes that can be associated with enormously high (and spanning a wide range of)energy scales (1 MeV - 10^{19}GeV). The only conceivable scenario for such super-high energy scales is the universe in its very early epochs. Physical processes at super-high energy, therefore, amounts to a study of cosmology at high energies.

The Standard Model Of Cosmology

The present day generally accepted model of cosmology suggests that the universe is expanding from an initial stage when it was extremely hot and dense and also very tiny in size. This phase of the universe characterized by very high temperature, and consequently matter existing in the most elementary form (such as hadrons and leptons and possibly quarks and gluons), is estimated to have existed about twenty billion years ago. The temperature of the universe inthis so-called standard model of cosmology gets to bearbitrarily high for time scales very close to the 'beginning' - referred to as the big bang. While the big bang itself is yet to be satisfactorily explained, it is nevertheless possible to imagine the physical scenario in the early universe from our current knowledge of nuclear physics, statistical mechanics and the general theory of relativity (see reference 1). This scenario is summarized in Table given below.

Table

Thermal history of the universe according to the standard model of cosmology.

Temperature (^{0}K)	Energy	Time (Sec)	Physical Process	Epoch
?	?	?	?	?
10^{32}	10^{19} GeV	10^{-44}	Particle Production	Quantum Era
10^{28}	10^{15} GeV	10^{-36}	Baryon nonconservation	Grand Unification Era
10^{16}	1 TeV	10^{-12}		
10^{13}	1 GeV	10^{-6}		
10^{12}	100 MeV	10^{-4}		Hadron Era
10^{11}	10 MeV	10^{-2}		Lepton Era
10^{10}	1 MeV	1	Neutrino 'freezeout'	
			and	
10^{9}	0.1 MeV	180	Nucleosynthesis	Nuclear Era
4×10^{3}	0.4 eV	10^{12}	Recombination, Matter-radiation Decoupling	
		10^{16}	Galaxy Formation	Matter dominated Era
3	3×10^{-4}eV	3×10^{17}	NOW	

The main evidence taken in support of the hot big bang cosmological model are (1) the expansion of the universe, (2) the existence of a microwave radiation background and (3) observed abundance of light nuclei.

The idea that the universe is expanding is based on the discovery in the 1920's by Hubble that distant galaxies all show red shifts in their spectral lines, and the conventional interpretation that these red shifts are due to Doppler recession. The existence of a microwave background of radiation pervading all space around us was discovered experimentally in 1964. Measurements indicate that this radiation has an energy spectrum that is similar to the Planck black-body radiation corresponding to a temperature of about 2.7 K, and is highly isotropic. These two phenomena, global expansion and the existence of an isotropic 2.7 K microwave radiation background, taken together and extrapolated backward in time, suggest that the universe 'began' in a hot, dense phase of matter about twenty billion years ago. As the universe expanded, the temperature dropped rapidly. Throughout the first minute, however, the temperature was greater than ten billion degrees. Under these conditions atoms and nuclei could not have existed in their usual forms but were dissolved into their constituent elementary particles and electromagnetic radiation. By about the first three minutes the temperature dropped to a value when the primordial protons and neutrons could combine to form nuclei of the helium atom (^{4}He). The lighter nuclei in the periodic table of elements like helium, deuterium, lithium are believed to have been synthesized primordially in this way. The heavy elements, comparatively rarer in the universe, are believed to be formed inside stars during their evolution and during supernova explosions. Within the frame-work of the standard hot big bang model, it is possible to theoretically estimate the mass ratio of all helium (^{4}He) formed primordially to all hydrogen (which is the main constituent of the universe at the present epoch). This ratio is one in three, and agrees reasonably well with helium abundance observed in a variety of stellar sites.

Another possible relic of the hot big bang universe is neutrinos. When the temperature of the universe was in excess of about a hundred billion degrees, neutrinos could have been easily created and annihilated by means of weak interaction processes. Neutrinos are massless particles, come in various species (such as electron-type neutrino, muon-type neutrino, etc.) and have negligible interaction with matter. Now, with the expansion of the universe and the consequent drop in temperature, the scattering cross-section of these weak interaction processes as well as the equilibrium number density of the particles got reduced. So after a certain stage in the expansion, when the temperature was less than about ten billion degrees, the neutrinos would have formed a non-interacting background somewhat similar to the background of the microwave radiation. It is possible to theoretically predict the density of left-over primordial neutrinos using statistical mechanical arguments, and it comes out to be

$$n_{\nu+\bar{\nu}} = 160 \text{ cm}^{-3}$$

per species of neutrino. However, since neutrinos have negligible interaction with matter, it is extremely difficult to verify the existence of the primordial neutrino background. In recent times suggestions, both theoretical and experimental, have been made that neutrinos are not strictly massless particles but possess a small rest mass. If this turns out to be correct, then the neutrino background assumes great cosmological significance. For one thing, it can then provide enough mass density so that the present expansion of the universe will eventually stop after a finite span of time, and will be followed by a general collapse. Secondly, massive neutrinos can provide an explanation for the 'missing mass' inferred in clusters of galaxies.

Physical Processes At Super-High Energies

From Table, we see that the energy scales in the early universe in the first few seconds were very high- much higher than the maximum energies attained in the terrestrial high-energy particles accelerators. In order to understand the physical processes that might have taken place at such early eras, it is necessary to have a theory that would tell us the nature of interactions among elementary particles at such high energy scales.

Recent experimental successes of the gauge theories for the weak and electromagnetic interactions (the Weinberg-Salam model) and the strong interactions(quantum chromodynamics) have encouraged the hope that these interactions may be unified in a general theory of all elementary particle interactions. For an introduction to unification theories see ref.2. In the picture provided by grand unified theories (gravitation is not included because of as yet unresolved theoretical complications), there is only one single force which manifests, at low energies, in three different forms : the weak, the electromagnetic and the strong interaction. But at sufficiently high energies, corresponding to temperature $\gtrsim 10^{28}$ degrees, these forces merge into one single force. Now, grand unified theories have quarks and leptons as the fundamental particles of nature, belonging to one single family of fermions. Further, there exists, in these theories, a symmetry between the members of this family so that quarks and leptons may transform into each other. This implies that neither baryon number nor lepton number, which are conserved in physical processes at ordinary energies, will be conserved at very high energies characteristic of the early universe. The concept of baryon number violation in particle interactions has in recent times, gained importance towards providing a natural theoretical explanation to an old puzzle in cosmology : the seeming asymmetry between matter and antimatter. The existence of antimatter is predicted on the basis of well established concepts of quantum field theory.

For instance, for every elementary particle there is an antiparticle that is identical in mass but opposite in other properties such as electric charge. Particles and antiparticles have often been created and observed in high energy accelerators. However, observations on a larger scale indicate an absence of any significant amount of antimatter in our galaxy, and this seems to be the case for other nearby galaxies as well.

To understand how grand unified theories attempt to explain the symmetry between matter and antimatter, it is necessary to recall certain ideas regarding symmetries of physical laws. The first is the left-right symmetry or parity, denoted by P. It says that the laws of physics are invariant under P, that is, under a mirror-reflection of all space coordinates. In the late 1950's it was experimentally found, however, that the parity symmetry was not valid for the case of weak interactions. It was then suggested that the laws of physics be invariant under a more general symmetry called CP, where C stands for charge conjugation operation which changes the electric charge of an elementary particle to its opposite value.

If CP-symmetry were universally obeyed, then there cannot be an imbalance between matter and antimatter. So far, CP-symmetry is found to be a 'good' symmetry criterion except in one known case : the decay of the long-lived neutral K-meson. CP-symmetry is thus an approximate symmetry and not an exact one. Hence, if we allow a small violation of baryon number conservation as well as of CP-symmetry in the early universe or, equivalently, at very high energies, it is possible to start from a most natural initial matter-antimatter symmetric universe and subsequently build up a scenario in which matter at some stage became more abundant than antimatter, this scenario has 'frozen in ' ever since.

The variation of baryon number is built-in feature of all the present models of grand unification. These theories, in their simplest form, postulate the existence of certain heavy particles (mass 10^{15} GeV), called X particles, whose decay or exchange violate baryon number conservation. The amount of CP-violation that is needed for a net baryon generation enters as a parameter in all models. There is one more requirement for this scheme to work : departure from thermal equilibrium. This, however, comes about naturally during the course of the expansion of the universe.

The parameter that one wishes to explain quantitatively in discussing matter-antimatter symmetry is the ratio of baryon number density (as deduced from number counts of galaxies in a specified volume of space) to the photon number density (as deduced from the microwave radiation background) :

$$\alpha = n_B/n_\gamma \cong 10^{-10}$$

This ratio remains constant during the expansion of the universe as long as the baryon number is conserved and the expansion of the universe is adiabatic (so that the number of photons is unchanged). The basic idea is that the value of α has been 'frozen in' (or decreasing if there are departures from adiabatic type of expansion) since the time when baryon number violating processes were significant. Thus the scenario is as follows : at temperatures greater than about 10^{28} degrees, baryon number violating interactions were significant and chemical equilibrium could be maintained despite the expansion of the universe. So at this time the baryon number density was zero, and the universe was symmetric in matter and antimatter. However, as temperature dropped below the the above-mentioned value equilibrium could not be maintained. Consequently, the value of α was frozen in. The role of CP-symmetry violation is to ensure this net imbalance of matter over antimatter. Corresponding to every decay mode of an X particle, there would be a decay mode of its antiparticle X. This would then nullify any imbalance of matter over antimatter, unless there was a violation of CP-symmetry. Several quantitative calculations are now available [3-6] which, although not free from uncertainties in the parameters involved, do predict a value for α close to 10^{-10}.

The crucial element in the above scenario to explain matter-antimatter asymmetry is the concept of baryon number violation. The unified theories suggest the life-time for the proton decay process to be of the order of $10^{30\ 2}$ years. Preliminary results of proton decay experiments currently in progress at

Kolar gold mines in India suggest that this may indeed be the case [7].

Apart from baryon number violation, grand unified theories predict the existence of stable magnetic monopoles of mass $\simeq 10^{16}$ GeV [8]. The existence of magnetic monopoles was suggested in 1931 by Dirac in a different connection, namely, to explain the quantization of electric and magnetic charges [9]. Up until recently, experimental search for magnetic monopoles has remained unsuccessful. Recently, however, an experimental evidence consistent with the detection of a single monopole, of one Dirac charge value and corresponding to a flux of 10^{-9} cm^{-2} sec^{-1} but mass undetermined, has been reported by Cabrera [10]. This experiment gives a boost to the grand unification idea.

It should be noted, however, that magnetic monopoles, if they exist, would move along the magnetic field lines of the galaxy, gaining kinetic energy. The gain in kinetic energy would be compensated for by a corresponding loss in the magnetic field energy. If the monopole flux exceeds a certain critical value equal to $10^{-15} cm^{-2}$ sec^{-1}, called the Parker limit [11], it can be shown that the entire galactic field would soon be dissipated. Cabrera has argued that the monopole flux observed in his experiment is consistent with the flux expected from a gravitationally bound galactic halo of Dirac magnetic monopole of mass 10^{16} GeV. There is no definite contradiction in this, however, since it is quite possible that the sun, because of its gravitational attraction on the monopoles, enhances the monopole flux near its own neighbourhood. Recently, Salpeter et al [12] have derived theoretical constraints on a hypothetical galactic halo of magnetic monopoles imposed by the galactic magnetic field : if the field is due to electric currents then a disk-stabilizing galactic monopole halo cannot exist unless the monopole mass $\gtrsim 10^{21}$ GeV and corresponding flux $\lesssim 5 \times 10^{-15}$ cm^{-2} sec^{-1}. However, if the galactic field is due to monopole charge-density fluctuations then a halo can exist provided the monopole mass $\gtrsim 10^{17}$ GeV and a corresponding flux $\lesssim 5 \times 10^{-11}$ cm^{-2} sec^{-1}. The latter seems to be the most stringent bound that can presently to set on the galactic monopole flux from astronomical data.

Magnetic monopoles have interesting consequences for the proton decay in that they can accelerate the proton decay rate [13-15]. This depends upon the monopole flux and the nature of the monopole-induced proton decay interaction, which is not clearly understood at present.

In 1981 Guth suggested a new picture [16] for the very early stages of the universe which attempts to answer in a natural way, rather than postulating ad hoc initial conditions, some long-standing and fundamental cosmological puzzles which are left unanswered in the standard model of cosmology. These problems are : the homogeneity - horizon problem and the flatness problem. The homogeneity problem refers to the problem of explaining why the large-scale distribution of matter in the universe is homogeneous. Galaxies seem to be distributed at remarkably uniform density, and the universe's rate of expansion seems little different locally from its value at the visible edge of the universe. If the origin of universe is to be traced to a big bang explosion, then there is no a priori reason to expect that the result of the explosion will not be turbulent and chaotic. The horizon problem refers to the puzzle as to why the universe is homogeneous irrespective of the direction of observation as borne out by the highly isotropic distribution of microwave radiation background, even though vast areas have been casually unconnected in the past. The flatness problem refers to explaining why the deviations in the value of the matter density of the universe from its critical value for eventual recollapse after a finite time is very small at the present epoch, and has been so all the way back to when the age of the universe was 10^{-43} seconds (called the Planck time). It appears that the big bang explosion was matched so delicately to the attractive self-gravitating force of the universe that the galaxies had just sufficient speed to escape each other's gravitational pull and, at the same time, not so much as to promptly disperse away. To ensure this, a fine tuning of one part in 10^{60} is needed between the matching of the explosive and gravitational forces.

The basic idea of the model proposed by Guth is the existence of a universal repulsive force that is negligibly small at the present epoch but was very large at the time the universe was born. So, when the universe was about 10^{28} times hotter than now (corresponding to an age 10^{-35} seconds), this dominant repulsive force would trigger a runaway expansion of the universe, inflating it at an exponential rate and doubling the size every 10^{-35} seconds or so. As a result, any initial turbulence or uneven distribution of energy would be diluted and smoothed away. After the inflationary phase was over, the universe would emerge with a highly uniform distribution of matter, energy and motion. A feature of this scenario is the right prediction for the rate of expansion needed to explain the flatness problem. Further, since the inflationary phase of the universe would bring into causal connection areas stretched over enormous scales, the horizon problem can also be explained.

Now, if the above picture is true, then the universe would cool rapidly as it expanded, thus allowing the strong weak and electromagnetic forces to become distinct and diminishing the strength of the initial universal repulsive force. To avoid this Guth suggested that the universe supercooled by many orders of magnitude below the critical temperature of a grand unified theory phase transition. This is analogous to the super-cooling of water, so that it can remain liquid somewhat below the freezing point for phase transition to ice.

An interesting feature of the inflationary universe scenario is that the inflated epoch could dilute the density of magnetic monopoles, abundant in the early universe, to a small and observationally permissible level.

The original version of the inflationary model required that eventually the bubbles of the new phase would coalesce to fill the space uniformly, a condition that is unlikely under plausible physical assumptions. Subsequently, it has been suggested by several authors [17-19] that under a different class of grand unified theories, it is plausible that a single bubble or a fluctuation can undergo the right amount of inflation to avoid the problem in Güth's original proposal. There is still a snag however : in the 'new' inflationary universe model, the universe emerges from the exponential expansion much too smooth to allow for subsequent development of inhomogeneities needed for formulation of galaxies.

So far, in discussing cosmology at extremely high energy scales and possible unification of the weak, electromagnetic and strong interactions during the very early universe, the gravitational interaction has been left out except in so far as it enters in the Einstein field equations to determine the time evolution of the universe's length scale. It is generally accepted that when the age of the universe was less than about 10^{-43} seconds, quantum mechanical corrections to the general theory of relativity would play an important role. At present, however, there is no theoretical consensus as to the exact role quantum mechanical effects have on gravitation. In some models, the initial singularity at the instant of the big bang perisists, while in others it is removed and the universe bounces. This is an area of much current research with important implications in our understanding of physical processes at ultra-high energies.

References

[1]. B.Datta : Phys.News, 1981, 12, 66

[2] J.C.Pati : Phys.News, 1980, 11,72

[3] M.Yoshimura : Phys.Rev.Lett., 1979, 41, 281

[4] S.Dimopoulos and L.Susskind : Phys.Rev.,1979, D18, 4500

[5] D.Toussaint et al. : Phys.Rev., 1979, D19, 1036

[6] D.V.Nanopoulos and S.Weinberg : Phys.Rev.,1979, D20, 2484

[7] M.Krishnaswamy et al. : Phys.Lett.,1981, B106, 339

[8] A.Polyakov : Sov.Phys. JETP Lett., 1974, 20, 194
G.t Hooft : Nucl.Phys., 1974, B79, 276

[9] P.A.M.Dirac : Proc.Roy.Soc.,1931, A133, 160

[10] B.Cabrera : Phys.Rev.Lett., 1982, 48, 1378

[11] E.N.Parker : Ap.J., 1970, 160, 383

[12] E.E.Salpeter et al. : Phys.Rev.Lett., 1982, 49, 1114

[13]. C.G.Callan : Princeton Univ. Preprint, 1982

[14] V.S.Rubakov : Sov.Phys. JETP Lett., 1981, 33, 644

[15] F.Wilczek : Phys.Rev.Lett., 1982, 48, 1146

[16] A.H.Guth : Phys.Rev., 1981, D23, 347

[17] A.D.Linde : Phys. Lett., 1982, B108, 389

[18] A.Albrecht and P.J.Steinhardt : Pnys.Rev.Lett., 1982, 48, 1220

[19] S.W.Hawking and I.G.Moss : Phys. Lett., 1982, B110, 35