Ref.TH.3143-CERN

HIGH ENERGY PHYSICS AND COSMOLOGY

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A B S T R A C T

The merger of high energy physics and cosmology leads to several interesting consequences. Some of these are discussed.

Invited Plenary Talk at the
International Conference on High Energy Physics
Lisbon, Portugal
9-15 July, 1981

Ref.TH.3143-CERN
20 August 1981

INTRODUCTION

Most of you are probably familiar with the well-known book of S. Weinberg[1] called "The First Three Minutes". Written about four years ago, the book nicely describes the evolution of the early Universe according to big bang cosmology 10^{-2} sec. after its birth. Recent progress in high energy physics, in particular the advent of unified gauge theories (GUTs) has opened up exciting new possibilities for exploring the history of the Universe at times even earlier than 10^{-2} sec. Indeed, we may now even speculate on the evolution of the Universe at times as early as 10^{-35} sec. after the big bang ! In this talk I propose to do just that*). After briefly reviewing the salient features of unified gauge theories and cosmology, I would like to present some of the consequences that ensue when these two subjects are merged together. The two most interesting ones are:

i) a possible explanation of the observed matter-antimatter asymmetry;

ii) the inevitable presence of primordial magnetic monopoles.

Other consequences depict how high energy physics sheds light on some long-standing cosmological puzzles. Cosmology in turn, provides important constraints on GUT model building.

HIGH ENERGY PHYSICS (GUTS)

It is generally accepted that the standard SU(3) × SU(2) × U(1) gauge model[2] provides a satisfactory description of the presently observed strong, weak and electromagnetic interactions. The temptation to embed the standard model in a unified gauge theory (also called GUT)

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*) An alternative title of this talk, following Weinberg, could be "<u>Before</u> the First Three Minutes"!

is obvious*), and the first attempts in this direction were made in 19 by Pati and Salam[3]. The simplest GUT model based on the unifying gau symmetry SU(5) was introduced in 1974 by Georgi and Glashow[4]. The elementary fermions (quarks and leptons) belong to the $\bar{5}_L$ and 10_L representations of SU(5). The gauge symmetry is spontaneously broken in stages to $SU(3) \times U(1)_{em}$ as follows:

$$SU(5) \xrightarrow[10^{15}\,GeV]{\underset{\sim}{24}} SU(3) \times SU(2) \times U(1) \xrightarrow[10^{2}\,GeV]{\underset{\sim}{5}} SU(3) \times U(1)_{em}$$

The inevitable appearance of a superheavy mass scale in GUTs was first noted in Ref. 5). Energies of order 10^{15} GeV (and even higher !) were presumably achieved in the very early stages of the Universe. Consequently, we must turn to cosmology and the early Universe in order to provide a suitable setting for directly testing GUTs. Let us therefore take a journey back in time. But first one may ask, "why believe in the big bang ?"

BIG BANG COSMOLOGY

There exist several good observational reasons for believing in a big bang cosmology. Let me list some of them:

i) Hubble expansion (1929)

Galactic clusters and other very distant objects seem to be receding from us and from each other at a uniform rate

$$H_0 = 100\ h_0\ \mathrm{km\ sec^{-1}\ Mpc^{-1}}$$

$$0.4 \lesssim h_0 \lesssim 1$$

On a sufficiently large scale the present Universe appears to be homogeneous and isotropic. Extrapolating back in time suggests that all matter and radiation were on top of each other at some initial time t_i

ii) Cosmic Microwave Radiation Background

At very early epochs (high temperature), matter and radiation were presumably in thermal equilibrium. As the Universe expanded both radiation and matter cooled. Below a temperature of about

*) At least now !

4000 K (10^{10}K $\sim$ 1 MeV) the thermal contact between matter and radiation got broken. This radiation still fills the space around us but is enormously red-shifted due to Hubble expansion. Such background radiation with black body spectrum (T $\sim$ 2.7^{0}K) was first observed in 1965 by Penzias and Wilson.

iii) Helium Synthesis (Gamov et al.)

The present abundance of He^4 (and D) provides good evidence that the temperature of the Universe was once $\gtrsim$ 0.1 - 1 MeV. At temperatures between 0.1 to 1 MeV, nuclear fusion reactions would have taken place which would be responsible for the bulk of He^4 that is observed today (there are no other "simple" astrophysical explanations for the large abundance of He^4).

Let us then believe in the big bang model and list its salient features here for future use[6]: the initial Universe is assumed to be homogeneous and isotropic and is characterized by the famous Robertson-Walker metric:

$$d\tau^2 = dt^2 - R^2(t)\left\{ \frac{dr^2}{1-kr^2} + r^2 \, d\Omega^2 \right\} \tag{1}$$

Here R(t) is the scale factor and the curvature parameter k can be +1, 0 or -1, according to whether the Universe is closed, flat or open respectively. General relativity determines the evolution of R(t) and gives us the following two equations:

$$\ddot{R} = -\frac{4\pi}{3} G R \left(\rho + 3p \right) \tag{2}$$

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

where ρ is the energy density, p is the pressure and G is Newton's constant. Conservation of energy implies

$$\frac{d}{dt}\left(\rho R^3 \right) = -p \frac{d}{dt} R^3 \tag{4}$$

and if an adiabatic expansion is assumed, one also has

$$\frac{d}{dt}(R^3 s) = 0 \tag{5}$$

where s denotes the entropy density.

The above equations have to be supplemented by an equation of state before we can determine the evolution of R(t). Thus, for an ideal relativistic gas,

$$\rho = 3p = \frac{\pi^2}{30} N(T)\, T^4 \tag{6}$$

where N(T) denotes the relevant number of degrees of freedom at temperature T. For non-relativistic matter,

$$\rho = \sum_i m_i n_i(T) \ , \quad p = 0 \tag{7}$$

where $n_i(T)$ denotes the number density of particles of type i at temperature T.

In the three most frequently discussed cases, the evolution of R(t) is as follows:

$$\begin{array}{rll} \text{i)} & R(t) \propto t^{1/2} & \text{(radiation dominated era)} \\ \text{ii)} & R(t) \propto t^{2/3} & \text{(matter dominated era)} \\ \text{iii)} & R(t) \propto e^{t} & \text{(de Sitter phase)} \end{array} \tag{8}$$

Since we are interested in the physics of the very early Universe we need to know a few things about the behaviour of non-Abelian gauge theories at non-zero temperatures. This will be our next topic.

PHASE TRANSITIONS IN GAUGE THEORIES

In recent years, a great deal of attention has been focused on understanding the behaviour of Yang-Mills theories at non-zero temperatures. It has been argued that these theories undergo a phase transition at some critical temperature T_c. Both confining, (e.g., QCD)[7] and spontaneously broken, [e.g., SU(2) × U(1)][8] gauge theories are expected to undergo such phase transitions, and the properties of the high temperature phase ($T > T_c$) are expected to be similar in the two cases.

Let us first consider QCD. For $T < T_c$, QCD is presumably in the confining phase[9]. For $T \gtrsim T_c$, QCD is expected to lose the confining property. Recent Monte Carlo studies[10] of the pure SU(2) gauge system (i.e., without dynamical quarks) at non zero temperature support this conjecture. The order parameter that signals the occurrence of phase transitions in pure lattice gauge theories is the thermal Wilson loop:

$$L = \mathrm{Tr}\,(U_{i_1 i_2} U_{i_2 i_3} \cdots U_{i_{N_t} i_1})$$

where $i_1, i_2, \ldots, i_{N_t}$ denotes a sequence of successive lattice sites along the positive Euclidean time axis and $U_{i_1 i_2}, \ldots,$ are the link variables. The expectation value of L determines the phase of the system. It is related to the free energy F of an isolated quark in a thermal bath at temperature T by

$$\langle L \rangle = \exp(-\beta F)$$

We note that $\langle L \rangle = 0$ implies quark confinement whereas $\langle L \rangle \neq 0$ means that quarks are liberated.

For SU(2) one finds that $\langle L \rangle$ becomes non-zero for $T \gtrsim 200$ MeV. Moreover, for $T > 200$ MeV the SU(2) gauge system can be thought of as a plasma of "massless" spin one gluons whose thermodynamic behaviour is close to that of an ideal gas.

Let us next consider the phase transition in the standard SU(2) × U(1) model. At $T = 0$, $SU(2) \times U(1) \xrightarrow{\langle\phi\rangle} U(1)_{em}$. A qualitative study of the free energy density of the system reveals that the expectation value $\langle\phi\rangle$ becomes zero for $T \gtrsim T_c \sim 100$ GeV (Fig. 1). Symmetry restoration takes place.

To summarize, at temperatures above 100 GeV the SU(3) × SU(2) × U(1) gauge symmetry is fully restored. One can even show that above 10^{15} GeV, the full GUT symmetry is restored. Such temperatures were achieved at cosmic time $t \sim 10^{-35}$ sec. The early Universe was the ultimate high energy accelerator !

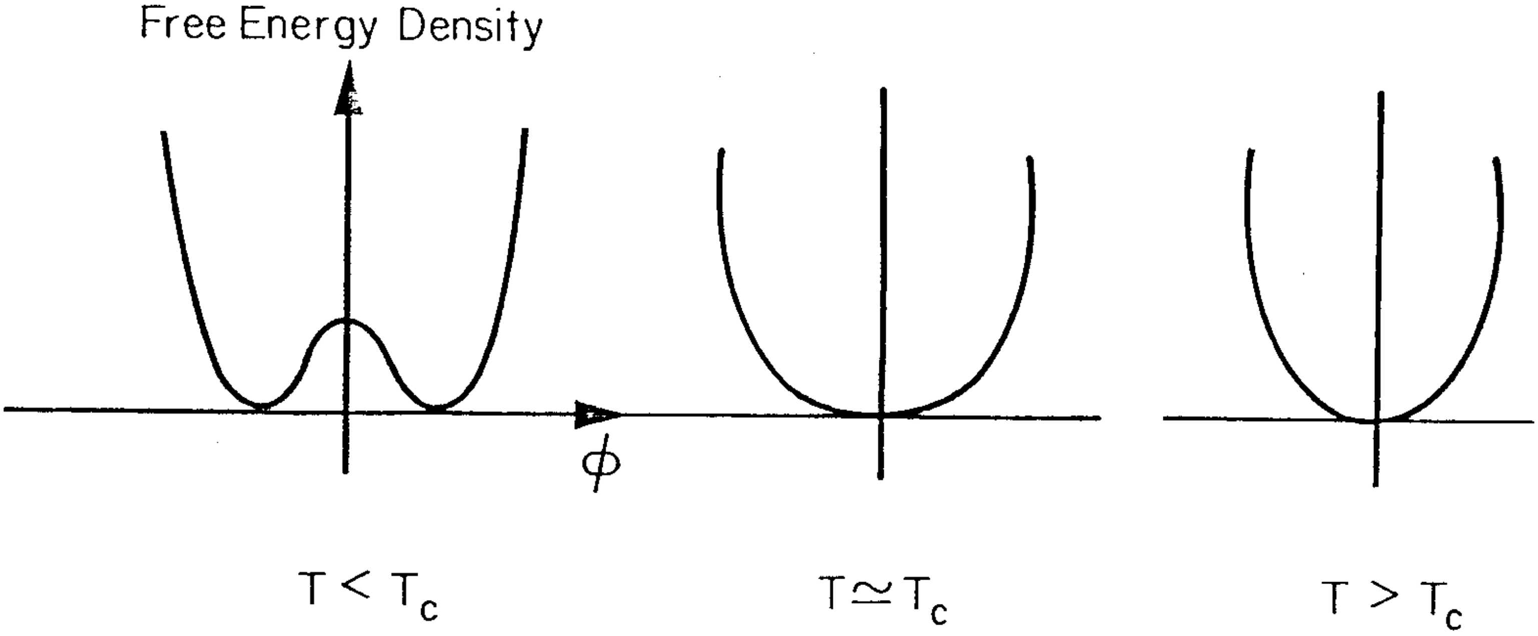

Fig. 1

Plot of free energy density versus ϕ displaying phase transition from broken (low temperature) phase to symmetric (high temperature) phase.

Let us now combine what we learnt about phase transitions in gauge theories with big bang cosmology. The following remarkable prediction emerges. As the Universe expands and cools, it undergoes a series of phase transitions. These phase changes occur as the high degree of symmetry at temperatures close to the Planck mass $G^{-1/2} = 1.22 \times 10^{19}$ GeV is reduced in stages to the present "zero" temperature symmetry $SU(3) \times U(1)_{em}$. The precise nature of the phase transformation depends on the surviving symmetry at a given temperature. It also depends on the Higgs potential which breaks this symmetry on further cooling through a critical temperature. Depending on the form and parameters of the Higgs potential, a given phase transformation will either be strongly or weakly first order (for an example of the latter, see Fig. 1). Let us summarize the simplest scenario for the minimal SU(5) model:

Cosmic time	Temperature	Phase
$t \lesssim 10^{-43}$ sec	$T \gtrsim 10^{19}$ GeV	Quantum gravity, SO(8) supergravity preons, black holes, ..., space time foam ?
10^{-35} sec > t > 10^{-43} sec	10^{15} GeV < T < 10^{19} GeV	SU(5) unbroken; quarks and leptons are the elementary fermions; X bosons in abundance; QCD does not confine; ... net baryon number zero ?
10^{-10} sec > t > 10^{-35} sec	10^{2} GeV < T < 10^{15} GeV	$SU(5) \xrightarrow[t\sim 10^{-35}\,sec]{\langle\Phi_{24}\rangle} SU(3) \times SU(2) \times U(1)$ $n_b/s \neq 0$ (baryon asymmetry) extended structures (monopoles, strings and domain walls) can appear
10^{-3} sec > t > 10^{-10} sec	few hundred MeV < T < 10^{2} GeV	$SU(2) \times U(1) \xrightarrow[t\sim 10^{-10}\,sec]{} U(1)_{em}$ $W^{\pm}$, Z bosons become massive at $t \sim 10^{-10}$ sec
$t \sim 10^{-3}$ sec	Few hundred MeV	QCD enters confining phase; chiral symmetry breaking occurs; protons and neutrons are born

$t \gtrsim 10^{-3}$ sec - end of High Energy Physics

Read Weinberg's book

From now I shall concentrate on the phase transition GUT → SU(3) × × SU(2) × U(1) which can lead to some interesting consequences. Let me list some of them:

a) generation of baryon number-to-specific entropy ratio (provided some general requirements are met);
b) inevitable production of topologically stable magnetic monopoles;
c) possible appearance of extended structures such as strings and domain walls;
d) possible resolution of some old standing puzzles in the standard big bang model (horizon problem, flatness problem).

I shall now discuss these in turn.

a) Baryon number-to-specific entropy ratio

The observed Universe does not appear to contain large concentrations of antimatter ($n_{\bar{b}} << n_b$). There seems to be a global matter-antimatter asymmetry. Moreover, the baryon density is relatively low with

$$\left(\frac{n_B}{s}\right)_{now} \simeq 10^{-11\pm 1} \tag{9}$$

Here $n_B = n_b - n_{\bar{b}}$ and s denotes the entropy density. Prior to the appearance of GUTs there was no satisfactory explanation of this number. Now there seems to be one.

The general requirements for generating a successful baryon asymmetry were pointed out by Sakharov[11] and others well before the advent of GUTs. The three essential ingredients are[12]:

i) baryon number (B) violating interactions;
ii) the B violating interactions must also violate C and CP;
iii) the B violating interactions must be out of thermal equilibrium.

Remarkably enough, all of these conditions can be met by GUTs. The latter contain B violating interactions that may also violate C and CP. Moreover, these interactions can be forced out of thermal equilibrium by the expansion of the Universe. The most promising mechanism for generating the desired baryon asymmetry appears to be the out-of-equilibrium decay of some superheavy Higgs bosons. Detailed numerical investigations have shown that this mechanism is likely to work[13]. One estimates[13]

$$\frac{n_B}{s} \simeq \frac{\epsilon}{g^*} \left(1 + K^{1.3}\right)^{-1} \tag{10}$$

where

$$K = \left.\frac{\text{decay rate of Higgs boson}}{H}\right|_{T = M} \tag{11}$$

$$\simeq (3 \times 10^{17})\,\mathrm{GeV} \cdot (\alpha/M)$$

Here ε measures CP violation and $g^* \sim 10^2$ is the number of relativistic degrees of freedom at $T \sim 10^{15}$ GeV.

Given a definite GUT, the baryon asymmetry can be computed as a function of ε and K. In most cases the parameter ε cannot unfortunately be predicted and can indeed be adjusted to suit one's needs. For sample calculations of the baryon asymmetry see Ref. 13).

It should be noted that the baryon number-to-specific entropy ratio predicted by the minimal SU(5) turns out to be too small by several orders of magnitude. This may be cured either by introducing a second Higgs $\underset{\sim}{5}$ plet[14)] or by invoking the existence of heavy fermion generations[15)]. The minimal Higgs systems of larger GUT models such as SO(10) and E_6 are probably complicated enough (!) to ensure that a satisfactory baryon number asymmetry is generated.

Finally, we note an interesting recent observation due to Ellis et al.[16)] They point out that in a large class of GUTs, diagrams contributing to ε also contribute to the renormalization of the θ parameter of QCD. They find that this can be used to relate the neutron dipole moment to the baryon asymmetry

$$d_n \gtrsim 3 \times 10^{-18} \left(\frac{n_B}{n_\gamma}\right) e\text{-}cm$$

an amusing relation indeed !

b) Magnetic Monopoles

This year marks the 50th anniversary of Dirac's suggestion that magnetic monopoles may exist[17]. He showed that the quantum mechanics of an electrically charged particle of charge e and a magnetically charged particle of charge g is consistent only if

$$e g = 2\pi n \quad , \quad n = 0, \pm 1, \pm 2, \ldots \tag{12}$$

Gauge theories in which electromagnetism arises from the spontaneous breakdown of a compact gauge group are known to have topologically stable magnetic monopoles[18]. In particular, all GUTs predict the presence of stable superheavy (mass $\sim 10^{16}$ GeV) magnetic monopoles. Let us give two examples:

$SU(5) \to SU(3) \times SU(2) \times U(1) \to SU(3) \times U(1)_{em}$

$Spin(10) \to SU(4) \times SU(2) \times SU(2) \to SU(3) \times SU(2) \times U(1) \to SU(3) \times U(1)_{em}$

In both these examples superheavy magnetic monopoles are produced in the first step of the symmetry breaking. The monopoles that carry one unit of Dirac magnetic charge ($2\pi/e$) also carry colour magnetic fields (see Fig. 2).

COSMOLOGICAL MONOPOLES

Monopoles are produced in the very early Universe ($t \sim 10^{-35}$ sec) during the GUT phase transition., e.g., $SU(5) \to SU(3) \times SU(2) \times U(1)$. They come equipped with a superheavy core of size $\sim 10^{-28}$ cm and carry $SU(3)_c$, $SU(2)$ and $U(1)$ magnetic fields. They acquire their final Dirac magnetic charge after $SU(2) \times U(1)$ breaks down to $U(1)_{em}$ at $t \sim 10^{-10}$ sec.

The present monopole to baryon ratio may be bounded by noting that the monopole mass density should not exceed the limit on the mass density of the Universe imposed by the observed Hubble constant H_0 and the deceleration parameter. This gives

$$\left(n_M / n_B^{vis} \right)_{\substack{\text{cosmic} \\ \text{bound}}} \lesssim \frac{3 H_0^2 m_p}{4\pi G M \rho_B^{vis}} \sim 10^{-14} \tag{13}$$

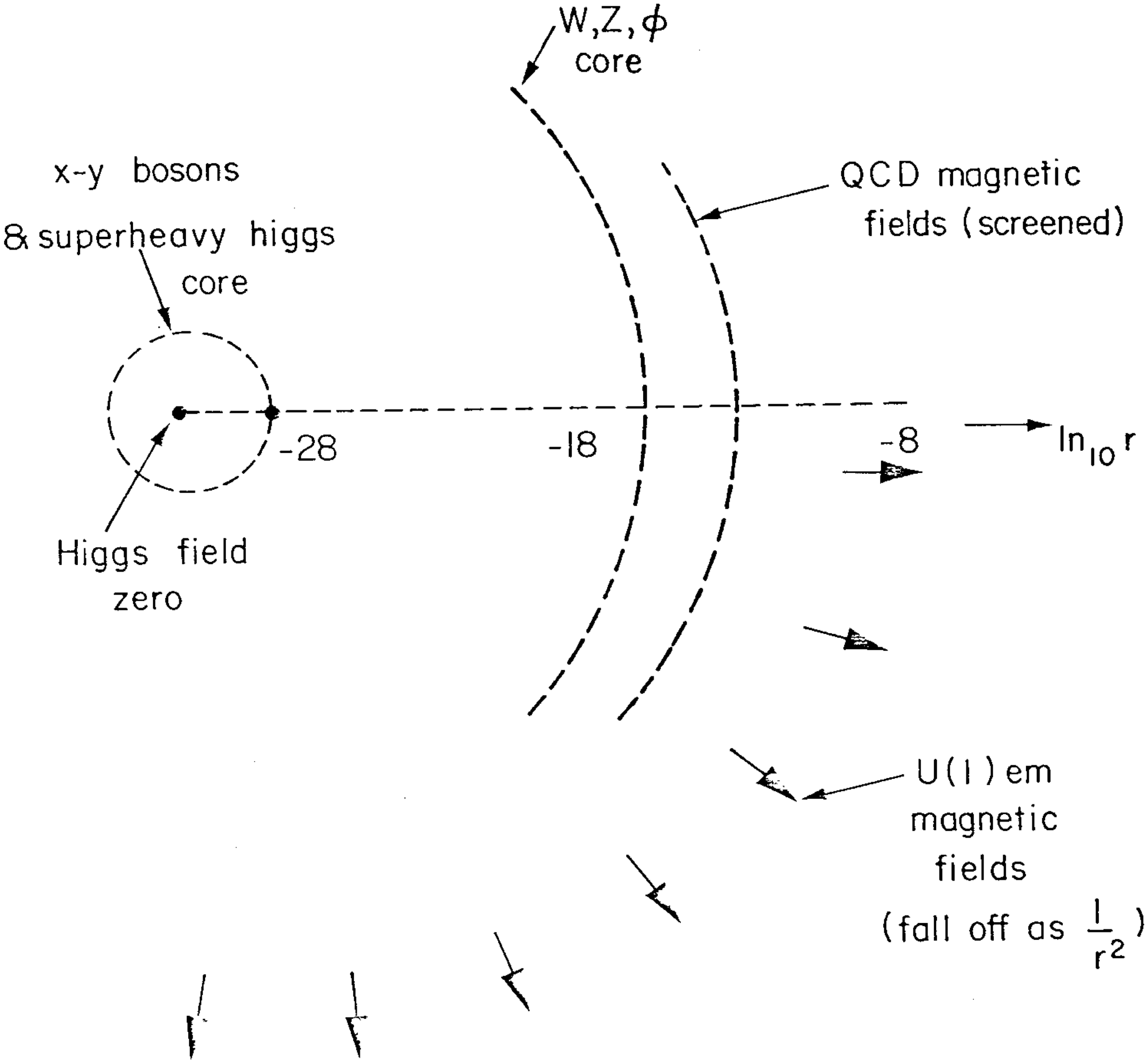

Fig. 2

Qualitative structure of SU(5) magnetic monopole where n_B^{vis} (ρ_B^{vis}) is the visible baryon number (mass) density, $H_0 = 100\ h_0\ k_m\ sec^{-1}\ Mpc^{-1}$ and m_p and G are the proton mass and Newton's constant. Using the above bound and assuming a uniform distribution of monopoles in the Universe one gets the following bound on the local monopole flux

$$F(\beta) \lesssim 10^{-3}\beta\ cm^{-2}\ yr^{-1}\ ,\ \beta = v/c \tag{14}$$

If $\beta \sim 10^{-3} \sim 10^{-4}$, then

$$\text{Monopole Flux} \lesssim (10^{-6} - 10^{-7})\ cm^{-2}\ yr^{-1} \tag{15}$$

One might suspect that β is somewhat larger than 10^{-3} because of the presence of large scale galactic magnetic fields. Our own galaxy has a large scale azimuthal magnetic field, presumably driven by the effect of differential rotation on ionized gas[19]. Such fields may act as monopole accelerators and in this case $\beta \sim (1-3) \times 10^{-2}$ is not unthinkable. Let us consider the local flux of monopoles which are currently being accelerated and subsequently ejected from our own galaxy. A bound on this flux may be derived by assuming[19] that the monopole magnetic current does not cause the galactic magnetic field to decay faster than the galactic dynamo effect regenerates it. A recent estimate is[20]

$$F_{Gal} \lesssim B_G/8\pi g\tau \sim 10^{-7}\ cm^{-2}\ yr^{-1} \tag{16}$$

where $B_G \sim 5 \times 10^{-6}$ gauss and $\tau \sim 10^8$ gr. is the regeneration time[19] for the field.

MONOPOLE PRODUCTION IN GUT PHASE TRANSITION

For $T > 10^{15}$ GeV, the expectation value of the Higgs field $\langle\phi\rangle$ is zero and the GUT symmetry is unbroken. As the Universe cools below 10^{15} GeV, $\langle\phi\rangle$ starts to acquire a non zero value. In the simplest situation,

$$\langle \phi \rangle_T^2 \simeq \langle \phi \rangle_0^2 \left(1 - \frac{T^2}{T_c^2} \right) , \quad T \lesssim T_c \tag{17}$$

For any given T, the magnitude of $\langle \phi \rangle$ is fixed but its direction may vary (think of a ferromagnet cooled below the critical temperature).

According to Kibble and others[21], we expect the appearance of nodes of the Higgs field, (i.e., monopoles) every few correlation volumes (see Fig. 3).

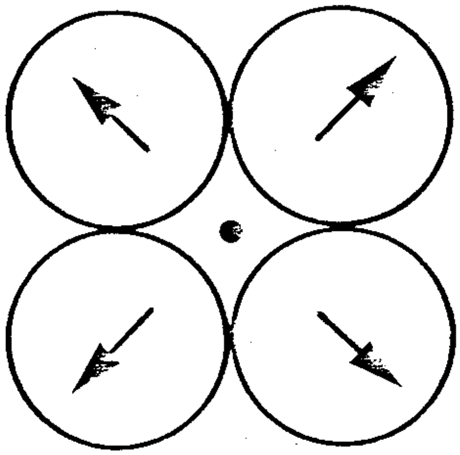

Fig. 3

Kibble's scenario for producing magnetic monopole in a GUT phase transition. The Higgs vector is supposed to rotate slowly over correlation volumes (circles).

By taking some annihilation into account, one estimates[22] the present number density of monopoles n_M to be

$$n_M \sim 10^{-10} \ cm^{-3}$$

which, together with $n_B^{vis} \sim 10^{-6} \ cm^{-3}$, gives

$$(n_M / n_B^{vis})_{th} \sim 10^{-4} \tag{18}$$

in gross violation of the bound set by Eq. (13).

At this stage the pessimist is probably thinking that GUTs are ruled out because they predict too many monopoles ! However, this need not be so. Even though the arguments that led up to (18) may sound plausible, some objections can still be raised. For instance,

i) one might argue that the production of monopoles is controlled by thermodynamics just like the production of any other massive object[23]. In this case,

$$n_M \propto \exp\left(-\frac{c\,M(T)}{T}\right)$$

If $c(M(T)/T) \gg 1$, the number density of monopoles will be suppressed.

ii) GUT phase transitions tend to be strongly first order involving, in general, a certain amount of supercooling. This may help in suppressing the monopole production density[24].

To summarize, it seems that monopole production can be suppressed to acceptable levels. Consider, for example, the model of Ref. 25) based on SU(5). There are two Higgs potential parameters ξ and η, and n_M/n_B can be small. But making n_M/n_B much smaller than, say, 10^{-20} requires careful tuning of parameters which is probably not reasonable. In particular, for a range of values of ξ and η the monopole production density is compatible with the bound given in Eq. (16).

MONOPOLE SEARCH

Almost all previous monopole searches are irrelevant for the superheavy magnetic monopole predicted by GUTs. For instance, the accelerator and cosmic ray production experiments operate well below the threshold for monopole production. Cosmic ray experiments on any pre-existing monopole flux are probably not sufficiently sensitive at high masses. Searches in bulk matter generally use magnetic fields to extract or accelerate monopoles or pass them through superconducting coils. However, the monopole density on or in the earth (moon) is only tenuously related to the primordial density.

Future monopole searches should bear in mind the following characteristics of the GUT monopoles:

i) their velocity is expected to be in the range $(1-5)(10^{-2}-10^{-3})c$;

ii) because of their huge kinetic energy ($\sim10^{13}$ GeV) they should be highly penetrating;

iii) for velocities $\sim10^{-2}c$, the ionization in metals is expected to be appreciable. For example, the energy loss in copper is a few GeV per cm.

Monopoles can be distinguished from cosmic ray heavy nuclei by measuring both the energy loss as well as the velocity, (e.g., by time of flight). Proving that a magnetic charge is present would require a super conducting coil or a SQUID. It would have to be big !

The observation of magnetic monopoles is probably within the reach of a reasonable large scale experiment[26]. The importance of such an experiment cannot be overemphasized.

c) Cosmic strings and domain walls

A system undergoing a phase transition may develop topological structures or textures. These may be points, lines or surfaces where the higher temperature symmetric phase is preserved by a topological conservation law. We thus expect monopoles, strings[27] and domain walls[28]. As mentioned before, all GUTs lead to topologically stable magnetic monopoles. This occurs independently of the exact form of the symmetry breaking pattern. Deciding whether strings or domains are formed requires a more careful examination of the symmetry breaking pattern.

The possible cosmological implications of strings and domain walls can be made clear by simple arguments. If the vacuum expectation value of the Higgs field is ϕ_0 (GUT scale), then the string mass per unit length σ is of order $|\phi_0|^2$ and the domain wall mass per unit area μ is of order $g|\phi_0|^3$, where g is a typical GUT coupling. If we take $|\phi_0| \gtrsim 10^{15}$ GeV, then $\sigma \gtrsim 10^{20}$gm/cm and $\mu \gtrsim 10^{48}$gm/cm^2. The radius (thickness) of these structures is $\lesssim10^{-29}$cm. A string passing through our horizon will have $\gtrsim10^{-6}$ of its total mass. A domain wall of the dimensions of our horizon would have a mass at least 50 orders of magnitude larger than the observed mass of the Universe. Our very existence is enough to exclude the presence of such a wall.

COSMOLOGICAL DOMAINS OF SU(5) AND SO(10)

Consider first SU(5) which breaks down to SU(3) × SU(2) × U(1) when a single real 24 Higgs field acquires a vacuum expectation value. If we impose the discrete symmetry $\phi \to -\phi$ on the Higgs potential or assume that the symmetry breaking is triggered by the Coleman-Weinberg mechanism domain, walls will be produced when the Higgs field ϕ acquires a vacuum expectation value[29]. Such symmetry breaking scenarios should therefore be avoided. This is easily achieved for SU(5) by adding the SU(5) invariant term $tr(\phi^3)$ to the Higgs potential. Domain structure also arises in the conventional minimal breaking of SO(10)[29]:

$$SO(10) \xrightarrow[M_s]{\underset{\sim}{16}} SU(5) \xrightarrow[M_X]{\underset{\sim}{45}} SU(3) \times SU(2) \times U(1)$$

Here $M_S \gtrsim 10^{17}$ GeV and $M_X \sim 10^{15}$ GeV. The domain wall mass per unit area is of order $10^{48} gm/cm^2$ as for the SU(5) example.

COSMOLOGY IN PRESENCE OF DOMAIN WALLS

Consider a GUT phase transition at some temperature T_C. The original symmetric vacuum will be replaced by a domain structure as the Universe falls into different $(\pm|\phi_0|)$ vacua in different places. Let ℓ_C be the characteristic size of the domains at T_C and t_0 the cosmic time after which the domain walls dominate the expansion. Then

$$\rho \propto R^{-4} \quad , \quad R \propto t^{1/2} \quad , \quad t < t_0 \tag{19}$$

and

$$\rho \propto R^{-1} \quad , \quad R \propto t^{2} \quad , \quad t > t_0 \tag{20}$$

The horizon size grows as (for k = 0)

$$R(t) \int_0^t \frac{dt'}{R(t')} \sim 3t^2/t_0 \tag{21}$$

After t_0 the scale factor and the horizon radius keep pace with each other and no new domain walls enter the horizon. One estimates t_0 to be of order $t_c(\ell_c T_c)^{2/3}$. It seems reasonable to assume that $\ell_c \lesssim 2t_c$. Then $t_0 \sim 10^{-32}$sec. Thus, domain walls dominate the expansion of the Universe soon after the GUT phase transition which takes place at $t_c \sim 10^{-35}$sec.

Our past light cone contains no wall. The absence of a domain wall in our horizon means that at $T = T_c$, $\ell_c/2t_c \gg 10^{26}$. It seems quite improbable to us that the initial domain sizes could be so large. Thus, theories which produce domain structure conflict with standard cosmology and should probably be excluded.

COSMIC STRINGS IN UNIFIED THEORIES

The breaking of a simple or semi-simple group can lead to the formation of open and perhaps also closed loops of strings. We give two examples[29]:

i) $$SO(10) \xrightarrow[M_1]{\underset{\sim}{210}} SU(5) \times U(1) \xrightarrow[M_2]{\underset{\sim}{126}} SU(5)$$

ii) $$SU(8) \supset SU(5) \times SU(2) \xrightarrow[M_1]{} SU(5) \times U(1) \xrightarrow[M_2]{} SU(5)$$

[see Ref. 30) for more information on the SU(8) model].
In both cases monopoles are produced in the first stage of the symmetry breaking. At the second stage of symmetry breaking the U(1) flux of the monopoles is squeezed into tubes of thickness $\sim M_2^{-1}$. The flux strings run from a monopole to an antimonopole. There may also appear closed loops of strings.

Recently, several authors[31] have advocated strings as a source of cosmic density perturbations $\delta\rho/\rho$ which can evolve into galaxies. Consider, for instance, a region of size t^3 through which passes just one string. Then,

$$(\delta\rho/\rho) \sim \frac{\rho_{string}}{\rho_{rad}} \sim \frac{\sigma/t^2}{\frac{1}{Gt^2}} \sim G\sigma \sim 10^{-4} \; , \; \sigma \sim (10^{17}\,GeV)^2 \qquad (22)$$

Density perturbations of this magnitude are clearly very desirable since they can probably initiate the process of galaxy formation after matter and radiation decouple.

However, the above picture is probably not tenable in the context of unified theories[29]. The inevitable presence of monopoles leads to a cut-off in the length of the strings. The strings then live far too short in time to be of any relevance to galaxy formation. One might envisage a scenario in which arbitrarily long strings are allowed. This would be possible if large scale fluctuations in the total monopole charge are present. However, the energy density in strings is then so large that one is led to a cosmology totally unlike the observed one. This would mean that theories with strings are excluded.

d) Cosmological puzzles

The standard big bang cosmology relies on initial conditions that seem puzzling in at least two ways[31]:

i) the horizon problem

The early Universe is assumed to be homogeneous and isotropic even though it apparently consisted of an enormous number of causally disconnected regions. The initial conditions, it seems, violated causality.

ii) Flatness problem (or why is the Universe so old ?)

The only natural timescale in the standard model is the Planck time $t_{p\ell} \sim 10^{-43}$s. Typically, a closed Universe will attain its maximum size in a time of order t_p, whereas for a typical open Universe one might expect that the present energy density $(\rho)_{now}$ is very different from the present critical density $(\rho_c)_{now}$. However, $(\rho)_{now}$ is not very much smaller than $(\rho_c)_{now}$, and this can only be achieved by an extremely fine tuning of the initial value of ρ. Indeed, tuning to an accuracy of one part in 10^{55} is apparently necessary !

About a year ago, Guth suggested[31] that an inflationary Universe scenario could resolve these two long-standing puzzles of cosmology*).

*) This must be one of the very few occasions when inflation is expected to solve our problems !

Moreover, he envisaged the scenario to occur in the context of GUT models of elementary particle interactions. Let us briefly describe the scenario and then discuss its feasibility. Consider the GUT phase transition (see Fig. 4)

$$GUT\ (e.g.\ SU(5)) \longrightarrow SU(3) \times SU(2) \times U(1)$$

Let T_c be the equilibrium transition temperature and $T_f \ll T_c$ the temperature at which the transition actually takes place. Thus, the system is supposed to undergo a huge amount of supercooling. This has two immediate consequences:

1) Between about 0.5 T_c and T_f, the vacuum energy density of the false (unbroken GUT) phase dominates over the radiation energy density (we are assuming, of course, that the vacuum energy density of the true vacuum is essentially zero). During this period the Universe undergoes an exponential expansion (de Sitter phase).

2) At the completion of the phase transition a huge amount of latent heat is released which reheats the Universe to a temperature $T_R \sim T_c$.

Because of (1), the initial region $L(t_i)$ which evolved into the presently observed region of the Universe could have been smaller than the horizon distance at that time. That is, $L(t_i) < 2t_i$ at some initial time t_i before the start of the de Sitter phase. The effect of the latter is to inflate the initially smooth patch ($L(t_i) < 2t_i$), which eventually evolves into our presently observed region of the Universe. Because of Eqs. (1) and (2) the flatness problem can also be obviated. Since entropy conservation does not hold in the inflationary scenario, it becomes possible to choose the initial value of $|\rho-\rho_c|/\rho$ (i.e., before the inflationary phase) to be of order unity rather than the previously ridiculous value of 10^{-55}. The exponential expansion ensures that the curvature term in Eq. (3) never becomes important and $(\rho)_{now}$ can still be close to $(\rho_c)_{now}$.

Despite its obviously attractive features, I do not think that the inflationary scenario can be naturally implemented in the context of GUTs. The scenario requires that the Universe supercools to temperatures 28 orders of magnitude below the critical temperature T_c for GUT phase transition. However, a typical GUT theory would already become strongly interacting at temperatures of order 10^8 GeV[32)]

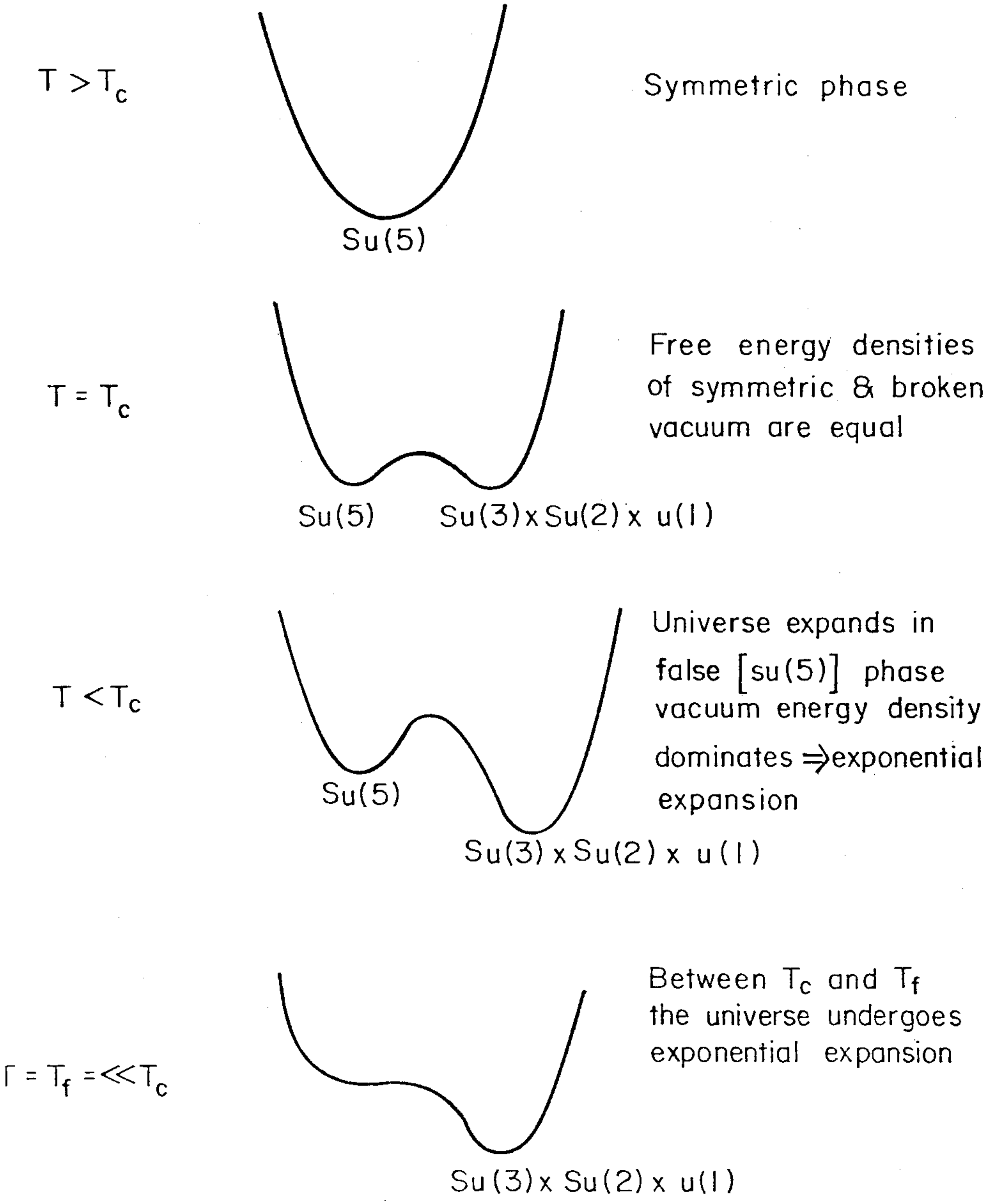

Fig. 4

Example of strongly first order phase transition (note that the effective GUT coupling at $T \sim 10^{15}$ GeV is about 1/40). For instance, at $T \lesssim 10^{8}$ GeV one might expect SU(5) [with $(\bar{5}+10)_L$ fermions] to tumble down to SU(4) which, in turn, becomes confining since it has only real fermion representation. From then on it is not at all clear how one would recover the true SU(3) × SU(2) × U(1) phase.

To summarize, I find the idea of an inflationary Universe attractive but it probably cannot be naturally implemented in the context of GUTs. Maybe gravity (or supergravity) can help[33]?

CONCLUSION

The merger of GUTs and cosmology can have several interesting consequences, the two most remarkable being a possible explanation of the observed baryon number-to-specific entropy ratio and the prediction that there exist primordial magnetic monopoles. Several outstanding problems remain. For instance, the origin of the initial perturbations that led to galaxy formation remains unclear as does the problem of the cosmological constant. One probably has to go beyond GUTs to find an answer to these questions.

ACKNOWLEDGEMENTS

I should like to thank George Lazarides and Tom Walsh for a very enjoyable collaboration and John Ellis for several useful discussions. I am grateful to Henri Ruegg and the University of Geneva for some support. I also wish to thank the Organizing Committee of the Conference, especially our Portuguese hosts, for arranging a very stimulating meeting.

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