

SUPERCONDUCTIVITY AND PARTICLE PHYSICS

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1. INTRODUCTION

Condensed matter physics and particle physics have very different goals, and consequently, they require rather different attitudes on the part of the physicists who pursue them. In condensed matter, one does not doubt the fact that basic physics is already known at the level of the atoms and the electron. Nevertheless, condensed matter physics has been rich in interesting and often unexpected phenomena because of the complexities arising from the very large degrees of freedom. This state of affairs seems to continue even now. In particle physics, on the other hand, new phenomena turn up because there seem to be more and more layers of entities and physical laws that govern them.

It is possible, however, that the above conventional distinction may be illusory to a large degree. Over the years people have come to realize that there is much common ground between these two branches of physics. This trend has in fact become increasingly visible in the activities of theorists in the last two decades. The basic underlying reason for this is the fact that the vacuum of the world is not a void; it is packed with very large virtual degrees of freedom, and in this sense the vacuum is not different from a medium of condensed matter, except that it does not have a preferred rest frame, and it occupies the entire world. What degrees of freedom can actually be excited will depend on energy and the mode of excitation. The so-called elementary particles are like quasi particles, collective modes, and even solitons that show up at certain energy scales. What, then, are the analogs of the basic individual atoms and electrons? Because one cannot get out of the vacuum, and presumably the scale of energy at which they show up is so large, one can only speculate. Current theoretical thinking places the ultimate scale to be in the realm of the Planck energy 10^{28} eV (10^{33} cm) and the GUT (grand unification) energy $\sim 10^{24}$ eV (10^{23} cm), in contrast to the scale of the order of eV in condensed matter physics.

Another operational difficulty in the case of particle physics is that one cannot make observations on the vacuum from the outside or change its property by acting on it; we are in

the situation of Archimedes trying to move the earth with a lever. Nevertheless, it is still theoretically conceivable that, for example, the vacuum can undergo phase transitions from one type of medium to another during the evolution of the universe, and its consequences may be testable in a historical context, just as biological evolution is a testable thesis. This is the reason why particle physics and cosmology have recently developed a close alliance with each other.

Now coming back to the history of the interaction between condensed matter physics and particle physics, it is remarkable how the phenomenon of superconductivity and the theoretical problems behind it have served as a model laboratory in the development of particle physics. The main lessons one has learned from it are, as is well known now, the subtleties about gauge invariance and the concept of spontaneous breakdown of symmetry. Following T. Kuhn, one may count them among the paradigms that have guided the course of particle physics in the past two decades.

In the following, I will review this development in two parts. The first part will be concerned with basic theoretical problems and model building leading to the Weinberg-Salam theory of the unified electroweak interaction. In the second part I will go on to discuss the grand unified theories and the variety of topics that have sprung up around them.

2. PART I

1.1 London, Ginzburg-Landau and BCS Theories
Superconductivity has revealed to us throughout its history deep theoretical principles which have universal implications. This can be easily seen by following the three landmark theories that have contributed to our understanding of superconductivity, namely those of London, Ginzburg-Landau²(GL), and Bardeen-Cooper-Schrieffer³ (BCS). Simply put, the London theory made us aware of the various nontrivial aspects of the gauge field and gauge invariance. The GL theory has introduced to us the idea of the effective field theory for an order parameter. The BCS theory showed us the mechanism of energy gap generation and dramatized the concept of spon-

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taneous breaking of symmetry.

With respect to gauge invariance, there are two main lessons we have learned from London. One is the transformation of the massless Maxwell field into a massive Proca field, which produces the Meissner effect and at the same time raises the question of how to reconcile it with gauge invariance. [Of course a similar phenomenon also occurs in a plasma as described by the Bohm-Pines theory, but only to an imperfect degree.] The other has to do with the role of gauge invariance under nontrivial topologies. This leads to the quantization of magnetic flux, which is closely related to the problem posed by Aharonov and Bohm.⁴

The GL theory, like the London theory, is a phenomenological theory, but it goes one step further by introducing a dynamical field for the superconductive medium, with a Lagrangian which is capable of causing a phase transition.

The real microscopic origin of the London and GL theories becomes clear with the BCS theory. In addition, the BCS theory contains a new element, i.e., the creation of an energy gap through the condensation of Cooper pairs. The electrons in the BCS medium behave as quasiparticles which are not eigenstates of charge, to be described by the Bogoliubov-Valatin equation.

The BCS theory, being a microscopic theory, and therefore at a more fundamental level than the preceding theories, has stimulated one to seriously investigate all the theoretical questions just mentioned. The significance of the earlier phenomenological theories could then be better understood in light of the results obtained.

The activity along this line took place mostly in the 1960's. It is perhaps not surprising that many of the participants were particle physicists, who then started to investigate its implications in their own domain. I will now briefly look at the development of individual topics from this point of view.

1.2. Spontaneous Symmetry Breaking in General

The name "spontaneous breakdown of symmetry" (coined by Baker and Glashow)⁵, may not be a very succinct one, but it has stuck for lack of a better name. Underlying this is the recognition that the symmetry of physical laws and the symmetry of a state are two different things, and moreover, the ground state of a system need not be invariant under the symmetry in question. This latter statement applies to finite as well as infinite systems. In the former case, one has dull examples like particles with nonzero spin (electron, nitrogen nucleus, etc.) and a little more interesting examples like the Jahn-Teller effect in molecules. More dramatic are the effects that show up in infinite systems, to which the name is usually reserved, but they are actually rather familiar phenomena after all, as in the case of idealized ferromagnet or idealized crystal. In the former, the relevant symmetry is the rotational invariance, whereas

in the latter, it is the translational invariance (under infinitesimal translations).

Characteristic to the spontaneous symmetry breaking in infinite media is the existence of symmetry restoring excitations (the Goldstone modes⁶) which will be discussed below. In the present examples, these are spin waves and sound waves, respectively.

Thus the only really new element here is the recognition of the general principle as such, which also applies to the case of superconductivity, and by extension, to particle physics as a possibility. Actually the concept of spontaneous breakdown already appears in Heisenberg's work⁷ on nonlinear theory of elementary particles; it included an attempt to interpret the photon as a Goldstone particle. But the theory itself failed to generate a lasting impact.

1.3. The Goldstone Modes

In a medium with a spontaneously broken symmetry, the symmetry does look actually broken, because the medium is characterized by an order parameter which is not a scalar under the symmetry operation, as would also be the case if there was no symmetry from the beginning. But the two cases differ in the spectrum of low energy excitations. In the former case, a small change in the order parameter induced by a localized symmetry operation will generate a massless excitation, as is intuitively obvious, whereas this is not expected in the latter. The statement has been promoted to a theorem by Goldstone and others⁸.

The above theorem holds, however, only if there are no other long range forces with which the Goldstone mode can mix. Otherwise the mixing will result in the lifting of their masses from zero.

According to the BCS theory, a superconductor is not an eigenstate of charge, but the Goldstone mode mixes with the Coulomb field, and gets promoted to the usual plasmon mode.

This situation was first clarified in the analysis of the BCS theory⁹, but its recognition as a general theorem is due to Schwinger, Anderson, Brout and Englert, and Higgs¹⁰. In this connection it is instructive to make a distinction between a global or ungauged symmetry and a local or gauged symmetry. The latter contains the former as a special case. The spontaneous breaking pertains only to the global symmetry; it cannot destroy the general local symmetry. This leads to the above mentioned evasion of the Goldstone theorem.

1.4 Chiral Symmetry and Pion Physics

The conscious and direct application of the idea of spontaneous symmetry breaking in particle physics originates with the Nambu-Jona-Lasinio (NJ) model¹¹ which was directly inspired by the BCS theory. A similar model was also independently considered by Vaks and Larkin¹². The analogy here is almost perfect in the correspondence: Dirac equation vs Bogoliubov-Valatin equation, Dirac mass vs energy gap, electric

charge vs chirality. In the NJ model, the particle in question was the nucleon N , and the pion π was to be regarded as the Goldstone mode resulting from the breaking of chirality due to the appearance of a mass term in an originally almost massless nucleon. The finite pion mass was attributed to a small bare nucleon mass

m_{NO} .

$$m_{NO} = 0(m_\pi^2/m_N)$$

[A modern interpretation of this bare mass would be that it is of electroweak origin, as it is built into the Weinberg-Salam theory (below).]

Direct support for this interpretation of the pion is found in such results as the Goldberger-Treiman relation, the partial conservation of axial vector (chiral) currents, and soft pion theorems. These enable one to relate various pion coupling constants to each other via Ward identities and the algebra of currents. They have been successfully applied, for example, to weak decays involving pion emission.

Although the original NJ model was based on elementary nucleons, it can be readily transferred to the level of quarks. In any case, the model was primarily aimed at the hadrons because of the special role of the pion. Similar bosons did not seem to exist for the leptons.

1.5. Effective Lagrangian Description

In modern terminology, the Ginzburg-Landau theory is an effective Lagrangian field theory which explicitly displays spontaneous symmetry breaking. The field (the order parameter) may be regarded as a composite operator representing the Cooper pairs in the BCS theory, and therefore the GL theory is derivable from the latter as an abstraction. But it can also stand on its own. [Sometimes the name spontaneous breaking is specifically applied to this "Higgs (or GL) mechanism", distinguishing it from the "dynamical breaking" which occurs at the level of the BCS rather than the GL theory.] It is in this context that it has come to serve as a prototype for model building in particle physics.

The GL model was reinvented in a relativistic form by Goldstone⁶ and Higgs¹², respectively with and without the gauge field, as a means to illustrate the symmetry breaking mechanism. But a similar construction was done earlier by Gell-Mann and Levy¹³ in pion physics. It involves both the fermions (nucleons) and the bosons (pseudoscalar pion and scalar sigma meson). An analogous description of superconductivity would correspond to an amalgamation of BCS and GL theories, thus displaying quasielectrons as well as collective excitations.

The class of models discussed here are examples of what is generically called the sigma model, which is characterized by nonlinear boson fields, often coupled to fermions, and possessing an internal symmetry which can be spontaneously broken. [Viewed as a mathematical realization of a broken symmetry, models of this type

for pion physics were also constructed by Gürsey¹⁴.]

1.6. The Weinberg-Salam Theory

The pion physics discussed above may be said to be an application of the BCS mechanism to strong interactions, dealing with an ungauged chiral symmetry. A more dramatic success came with the model of Weinberg¹⁵ and Salam¹⁶, who applied it to the realm of weak and electromagnetic interactions. These two seemingly very different interactions are viewed as being mediated by a unified non-Abelian gauge field with an $SU(2) \times U(1)$ symmetry, which is, however, spontaneously broken so that its four components split into three "plasmons" (the W^+ , W^- and Z^0) which mediate the weak forces, including a new neutral (non-charge changing) counterpart of the beta decay process, and the massless photon which survives the symmetry breaking.

The dream of an electroweak unification is not new (Glashow¹⁷ and others), but its manifest realization in terms of a spontaneous symmetry breaking is. To do this, a Higgs field is introduced to simulate the GL mechanism, turning original massless gauge fields into massive weak bosons whose masses m may be related to the Fermi constant F and the fine structure constant α as

$$F = 1/m_W^2,$$

$$m_W^2 = \frac{1}{2}g^2\langle h \rangle^2,$$

so that $F \propto 1/\langle h \rangle^2$ is independent of g . Here $\langle h \rangle$ is the nonzero expectation value of the Higgs field, i.e., the order parameter characterizing the Cooper condensate in the vacuum. The second relation above is a direct analog of the familiar plasma frequency formula

$$\omega_p^2 = 4\pi N/m,$$

(N = density, m = mass, of the electrons in the plasma). The value $\langle h \rangle$ turns out to be 250 GeV, which is the characteristic energy scale around which the weak interactions should reveal its substructure. [Compare this to the corresponding scales in superconductivity (10^{-4} eV) and pion physics (10^2 MeV)]. On the other hand, the precise values of the W and Z masses depend on another parameter (the Weinberg mixing angle), related to the ratio of the $SU(2)$ and $U(1)$ gauge coupling constants, and thereby controlling that of the charged and neutral weak currents. Needless to say, however, the existence of neutral weak currents as well as the W and Z bosons have now been experimentally established^{18,19}. The W and Z mass values are around 80 and 90 GeV, respectively, in agreement with theoretical relations.

The Weinberg-Salam theory contains another element which is not mandatory for the weak interactions and logically independent of it, but comes natural in view of our experience with the BCS theory and the chiral dynamics. Namely

the same Higgs field is assumed to couple to the fundamental fermions (quarks and leptons) so that $\langle h \rangle$ is responsible for giving them their masses. The Weinberg-Salam Lagrangian, therefore, looks rather similar to that of the amalgamated BCS-GL theory, except that the quarks and leptons are not considered dynamically responsible for the spontaneous symmetry breaking in the Higgs sector, but they simply inherit its effects. In this sense it is more akin to the GML model.

This aspect of the Weinberg-Salam theory concerning the fermion masses is unsatisfactory in that the Higgs coupling has to be adjusted for each fermion flavor to give its observed mass. The mass of the Higgs is also an arbitrary parameter not related to low energy weak interaction phenomenology. Although common sense would place it at the scale of $\langle h \rangle$, this is not a theoretical requirement. At any rate, the simplicity and elegance of the gauge principle responsible for the electroweak unification gets compromised by the realities of particle mass spectrum, the true origin of which still remains unknown.

PART II

2.1 The Basics of GUTS

Once the unification of weak and electromagnetic interactions becomes a reality, an obvious next goal would be to include the strong interactions as well. Two theoretical developments have made it possible.

First, the dynamics of the hadrons has been reduced to that of the quantum chromodynamics (QCD) of the quarks. The situation is similar to the case of molecular and atomic physics. The hadrons, made up of quarks, are like neutral (nonionized) molecules and atoms, which are made up of electrons and nuclei. The interactions among hadrons are like those among neutral atoms and molecules. These rather complicated forces (e.g., the van der Waals force) are just secondary manifestations of the dynamics of their constituents governed by a gauge field, i.e., the color SU(3) gauge field (gluon field) for the quarks and the electromagnetic gauge field for the electrons and nuclei.

The second development is the important discovery²⁰, by 't Hooft, Gross and Wilczek, and Politzer, of the asymptotic freedom of non-Abelian gauge fields, which marks a difference between an Abelian gauge theory like QED (quantum electrodynamics) and a non-Abelian one like QCD. In the former, the effective strength of a test charge looks more reduced at larger distances by the screening action of virtual particles in the vacuum, whereas in the latter, the virtual gluons themselves act as antiscreening agents for color charge. Thus the effective electric charge will grow, whereas the color charge will tend to diminish, as a function of the momentum scale of the process in question. This has two implications: the gluonic forces become stronger at

larger distances, or lower energy scales, leading to the possibility of permanent quark confinement, and the tendency for apparently small electromagnetic and large gluonic couplings to approach each other at shorter distances, or higher energies. One should also remark that the SU(2) \times U(1) gauge theory of Weinberg and Salam, with its extra Higgs mechanism, has been shown by 't Hooft²¹ to be renormalizable, making it qualify as a bona fide quantum field theory.

Under these circumstances, the three observed low energy couplings, i.e., the SU(2) and U(1) couplings in WS theory and the SU(3) gluonic coupling, have been shown by Georgi, Quinn and Weinberg²² to in fact merge when theoretically extrapolated to an energy scale of $\sim 10^{24}$ eV $\sim 10^9 \rightarrow 10^{-9}$.

An explicit construction of this grand unification scheme was given by the SU(5) model of Georgi and Glashow²³. The SU(5) gauge symmetry spontaneously breaks in two steps:

$$\text{SU}(5) \rightarrow [\text{SU}(3)] \times [\text{SU}(2) \times \text{U}(1)],$$

and the Weinberg-Salam step,

$$[\text{SU}(2) \times \text{U}(1)] \rightarrow \text{U}(1),$$

leaving us with the unbroken gauge groups of color and electric charge. The first step should occur at the grand unification energy scale due to a superheavy Higgs field. This would interrupt the asymptotic freedom of the SU(5) gauge field as a whole, and start the three subgroups on their respective ways toward low energy scales. The SU(3) color group is considered to be intact because its breaking would spoil the permanent confinement of quarks. More complicated models have also been proposed, but all these grand unification theories (GUTS) rely on the GL-Higgs mechanism for symmetry breaking, and therefore also suffer from the necessity for ad hoc phenomenological parameters, which proliferate as one tries to take more phenomenological constraints into consideration.

Because of the extremely large energy scales involved, there are not many direct experimental handles to constrain the GUTS except for qualitative features and rare processes like proton decay. Instead, GUTS have come to play an important role in cosmology and astrophysics, which in turn serve as constraints for the former. One of the important features of GUTS in this respect is the possibility of phase transitions during the evolution of the universe as it expands and cools starting from the Planck scale. Here condensed matter physics, particle physics, and cosmology get inseparably intertwined, but the topic would be beyond the scope of this review.

2.2 Chiral Symmetry Breaking in QCD

The Higgs fields had to be invoked in forcing the splitting of the single SU(5) gauge field into three physically different pieces.

On the other hand, the original ideas behind chiral dynamics may be tested in the framework of the QCD without introducing phenomenological assumptions. That is to say, the possibility of spontaneous mass generation for quarks due to strong color forces may be addressed at the level of the BCS theory rather than the GL theory. In fact, the lattice gauge theory of Wilson²⁴ and the recent advances in the use of computers have made it possible to study the question of confinement as well as chiral symmetry breaking at a fairly quantitative level²⁵. It has indeed been shown that both phenomena do happen in the lattice QCD; moreover, at finite temperatures, the quark-gluon system undergoes two kinds of phase transitions, one for deconfinement and the other for chiral symmetry restoration. The former is like a neutral-to-ionized gas transition, whereas the latter is a direct analog of the superconductive-to-normal transition. These transitions seem to be independent of each other, the chirality restoration occurring in general at a higher temperature than for deconfinement.

2.3 Topological Configurations

Topology plays an important role in quantum mechanics as well as field theory in general through its effects on the boundary conditions. But in gauge theory, which may be said to be geometrical in nature, its manifestations are particularly interesting. Superconductivity provides some typical examples like magnetic flux quantization, but there are many others in condensed matter physics. It is not surprising, then, that in particle physics, too, various topological phenomena have been uncovered during the past decade. Although of purely theoretical nature so far, they are nevertheless inevitable consequences of the underlying theory or model. A few representative examples will be discussed here.

a) Strings

Nielsen and Olesen's flux tube²⁷ is to a relativistic Higgs model what the Abrikosov flux tube²⁷ is to the GL theory of superconductivity. Nielsen and Olesen revived the Abrikosov magnetic flux tube as a dynamical model for the hadron string, which is a phenomenological representation of interquark forces. Quarks attached to the two ends of the string are pulled together by the constant string tension. In the Nielsen-Olesen interpretation, this would arise from the magnetic flux trapped in the tube. The flux is quantized and stable because it has a nonzero winding number (analogous to angular momentum) under the gauge group. It is as if the quarks were magnetic monopoles placed in a superconductor²⁸. In QCD, on the other hand, the quarks carry electric-type non-Abelian color charges, but it is believed that the QCD vacuum mimics a magnetic superconductor, leading to an effective electric flux tube formation (without a need for a Higgs field). This mechanism is explicit in the Wilson lattice gauge theory.

More direct analogs of the flux tube are found in the GUTS where the Higgs fields abound.

At least an endless tube (closed or infinite) is possible when there is a stable U(1) gauge subgroup which simulates the GL situation. Existence of cosmic strings spanning the universe and made up of superheavy GUT Higgs fields has been proposed²⁹.

b) Monopoles

The Dirac monopole is an artificial addition to electrodynamics. On the contrary, the 't Hooft-Polyakov monopole³⁰ is a consequence of a Higgsed SO(3) (Yang-Mills) gauge theory, not realizable in the Abelian case. However, the situation may be compared to a spin system where the spins S at different sites are aligned radially around a small hole. The spin represents a vectorial order parameter (Higgs condensate) whose rotation is an SO(3) gauge operation. Since the spin is unaffected by a rotation about itself, the corresponding gauge degree of freedom escapes the Meissner effect, and the hole acts as a source of a magnetic charge g' inversely related to the original gauge coupling constant g as in the Dirac case. Being an extended system, this monopole has a well defined mass of the order of

$$g'S \sim S/g.$$

In the GUTS, the 't Hooft-Polyakov monopoles are superheavy objects. Recently the existence and abundance of such monopoles has become a big cosmological as well as laboratory issue. In essence, too many of them would cause all sorts of theoretical headaches.

2.4 Neo-Kaluza-Klein Theories

One of the important motives for the Kaluza-Klein type theories is to unify gravity and other forces like electromagnetism by regarding the latter as arising from the geometry of extra spatial dimensions. These extra dimensions are attached to each ordinary space-time point as an orthogonal complement. They must be compact and small because one does not see them.

The KL theory has been revived in the last decade³¹. Because of the proliferation of internal symmetries, the number of extra dimensions must also increase. However, a more interesting aspect is an attempt to view the separation of a higher-dimensional space into the ordinary and the compact part as a dynamical phenomenon. The Abrikosov flux tube serves as a simple model to illustrate the point. The interior of the tube is where we live. It has two large dimensions: one time dimension, and one spatial dimension along the tube. The small cross section corresponds to the extra dimensions. Its topology produces a U(1) symmetry, leading to quantization of normal modes. One cannot get out of the tube because it requires enormous energies inversely related to the size of the cross section. It would be natural to set this size to be of the order of the Planck length, so the excitations would be of the order of the Planck mass 10^{27} eV. However, there can be zero (or practically zero)

modes, which would then represent the ordinary particles. These modes may be compared to the near-zero modes of electrons inside the Abrikosov flux tube, found by de Gennes et al.³²

Another part of the modern KL program consists in exploring various possible geometries with respect to dimensionality, topological structure, and patterns of compactification. Supersymmetry and supergravity, which are beyond the scope of this review, become particularly interesting in the context of the KL extension. [For example, the overall dimensionality is restricted to no more than 11].

2.5 Interface Between Low and High Energy Physics.

Coming back from the very speculative regime to the more familiar domain, one can also find interesting phenomena which are closely related to the topics already discussed. The following is such an example.

The Ginzburg-Landau type theories give rise to two kinds of collective modes, normally called phase and amplitude modes. The former is the Goldstone mode which may remain massless or get transformed into a plasmon mode. The other is a scalar excitation with a mass equal to twice the mass (energy gap) m of the quasi-electron. Thus there are simple relations among the three low energy excitations, one fermionic and two bosonic.³³ Such relations are in fact a general consequence of BCS-type theories. Contrast this with relativistic models like Gell-Mann-Levy and Weinberg-Salam, where the counterpart of the massive bosons is respectively the sigma meson and the Higgs boson, but their masses are arbitrary parameters not related to the fermion mass. This is because in these theories one is not at the dynamical level of BCS.

The above mentioned amplitude mode is superconductors has recently been detected.³⁴ The situation is similar in superfluid helium 3, too. Because the Cooper pairs form in triplet P states, there are more collective modes than in superconductors, but again their masses are simply related to the fermion mass parameter.³⁵ Theory and experiment seem to be in fairly good accord.

This brings up another domain where the BCS theory is effective, namely nuclear physics, where the nuclear pairing has been interpreted as a Cooper pairing. Thus one would expect existence of bosonic excitations which are simply related to fermionic (single particle) ones. In other words, there will be simple relations among bosonic excitations of an even-even nucleus and those of an even-odd nucleus differing by a nucleon. The result may be construed as a kind of (broken) supersymmetry between even-even and even-odd nuclei, giving a possible theoretical explanation³⁶ to the empirical supersymmetry in nuclear physics observed by Iachello et al.³⁷

2.6 Looking Toward the Immediate Future

The above discussion immediately brings us back to high energy physics: what about the Higgs bosons in the Weinberg-Salam theory? Are

they not actually collective modes (or bound states) in the same sense that the bosons in superconductors are?

The technicolor models have been proposed exactly from this point of view.³⁸ One first imagines that there are massive fermions (technifermions) of 100 GeV to 1 TeV scale with their own strong gauge interactions, and then essentially repeats the hadron physics at this thousand times larger energy scale. Thus the Higgs boson would be a scalar bound state, like the sigma meson, of technifermions. (Would that have twice the mass of the constituent fermions?) But there should also be a host of other particles. Even the W and Z could be of this kind.

Such a scenario, although outside of the current standard model, probably will look natural to those who have been following the development of particle physics. As a matter of fact, there are already several experimental signals from CERN and DESY hinting at a rich spectrum of new physics.

On the other hand, the WS theory is also working extremely well as far as its predictions about the structure of weak interactions are concerned. Why should this be so if the compositeness shows up at these energies?

We shall see.

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Addendum after the last sentence in 2.2: [Chiral transition depends strongly on the quark representation. For the fundamental representation, the two temperatures seem to be the same. See J. Polonyi et al., Phys. Rev. Lett. 53 (1984) 644.]