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Bags vs. Strings: Hadrons in Type I and Type II Superconducting Vacua

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Bags vs. Strings: Hadrons in Type I and Type II Superconducting Vacua

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Abstract

Two popular models for hadronic structure are bags and strings. Both involve analogies with superconductivity. We claim that the most appropriate analogies are type I superconductors for bags and type II superconductors for strings. The structures of hadrons is somewhat different for the two situations. In principle, and in practice in the real world, it is the similarities which are most important. These include linear confining potentials, linearly rising Regge trajectories and short distance Coulomb potentials. These are all generic properties of bound states in a superconductor and the main distinctions between bags and strings is under what circumstances these limiting behaviors set in.

1. Introduction

Despite the intractability of the confinement problem in QCD several, QCD inspired, models for hadrons have proven useful. Prominent among these are string [1] and bag models [2]. In pristine form these two descriptions are extremely different. One has quarks bound together by a string whose thickness, if not actually infinitesimal, is much smaller than the separation between the quarks. The meson is a one dimensional system characterized by the string tension $\frac{1}{2\pi\alpha'}$. In the bag picture quarks are confined inside a spherical bubble of perturbative medium embedded in a non-perturbative vacuum. Hadrons are three dimensional systems characterized by a uniform bag pressure B.

At first blush these models are vastly different and it is surprising that adherents of these competing descriptions invoke the same imagery of superconductivity for motivation, justification and productive insight. How can two such diverse pictures emerge from the same physical analog system? It is our purpose to answer this question and to clarify the similarities, parallels and distinctions between bags and strings.

The general analogy with superconductivity is valid and immediately implies strong similarities between bags and strings. We understand their distinction as being related to the differences between type I and type II superconductors. Bags find their natural habitat in type I media while strings exist most comfortably in type II.

The most dramatic distinctions between types I and II superconductors arise in their bulk properties [3]. For our purposes a more microscopic, or local, distinction is relevant. At the interface between a normal metal and a superconductor a surface develops. The energy associated with this surface is positive for type I, and negative for type II. Herein lies the clue for a discrimination between bags and strings. A monopole anti-monopole ($m\bar{m}$) embedded in a superconductor will form a normal fissure in the superconductor and compromise a bound state of confined monopoles. (In this paper we will always deal with a U(1) superconductor and so our discussion concerns itself with bag and string models for monopole confinement in electric superconductors. The analogy with colored quark confinement in a chromomagnetic superconducting vacuum [4] is immediate and direct even if incomplete. We shall refer to confined $m\bar{m}$ systems as hadrons). If our $m\bar{m}$ pair finds itself in a type I superconductor the positive surface tension will tend to make the fissure spherical and will produce a three dimensional, almost spherical bag. If, on the other hand, the $m\bar{m}$ is in a type II superconductor the negative surface energy will cause the configuration to minimize total energy by maximizing surface. A string, which is all surface, develops. A more refined, less intuitive, but more quantitative argument will be given in Section III which is based on a discussion of vortex solutions in Higgs Ginzburg Landau theory presented in Section II. We shall continue our heuristic discussion in Section I and summarize in Section IV.

Having, starkly, distinguished between the two models for hadrons we hasten to remind the reader that realistic bag and string models have strong similarities. The most celebrated of these are the appearance [5] in bag models, in suitable limits, of linearly rising Regge trajectories and linear confining potentials, archtypical string properties. Physical strings have finite width. When the $m\bar{m}$ separation is comparable to this width, the potential will not be linear (for sufficiently small separation it must be Coulombic) and the geometry will be three dimensional. The hadron will resemble a small bag.

Analogously the distinctions between superconductors of type I and II becomes blurred under some circumstances. It is a common misperception that the vortex lines of Abrikosov exist only in type II superconductors. This is false. Flux quantization and the existence of a stable vortex line in a superconductor is a topological property which is the same for any superconductor. The Ginzburg-Landau equations will always have a stable single vortex solution whether its parameters are in type I or type II regime. The existence of type I vortices is experimentally well established [5]. The striking differences between types I and II superconductors is evident in the dramatically different <u>interactions</u> between vortices and to a lesser extent in the vortex structure (see III) in the two species of superconductors. Type I vortices attract, type II vortices repel. This is consistent with our above remarks on surface energy. In large magnetic fields with very many vortex units the type I vortices will coalesce into a bulk, macroscopic field while the type II vortices remain separated into very many vortices with microscopic fields. This accounts for the different bulk behavior of type I and type II. By contrast in microscopic fields of one or two flux units the similarities are more evident than the differences.

Hadrons contain one unit of flux and we therefore expect individual hadrons to be somewhat insensitive to the type I or type II nature of their surrounding superconducting vacuum medium. If the $m\bar{m}$ pair are widely separated they will be connected by a flux tube which is the distinctive, characteristic container for magnetic field lines in any superconducting medium. Linearly rising Regge trajectories and linear confining potentials are thus intrinsic properties of hadrons existing in a superconducting vacuum. What distinguishes between type I and type II is the limits under which such behavior breaks down. For an ideal string (0 thickness) they will be true always, whereas for bags they will be true only beyond some minimal monopole separation. The experimental validity of asymptotic flux tube behavior is direct evidence for the superconducting nature of the QCD vacuum. Similarly, except for zero width strings, when the $m\bar{m}$ are brought close enough together they will "forget" that they are in a superconductor and interact through a Coulomb potential.

In passing we remark that interesting differences in bulk hadronic matter should be manifest between type I and II. This should be relevant in the transition from nuclear matter to a quark-gluon plasma.

In summary, the distinction between bags and strings is related to the distinction between type I and type II superconductors. In "idealized" models the distinctions are sharp. In the real world it is the similarities which are more apparent. The beautiful and overwhelming evidence for linearly rising Regge trajectories and the almost universal acceptance of linear confining potentials with short range Coulomb parts are strong evidence for the superconducting nature of the QCD vacuum. These properties are intrinsic to both types of superconductors and are generic results in both bag and string models. The two models will differ in their deviations from these characteristic properties.

II. Vortex Lines in Higgs-Ginzburg Landau Theory

The Ginzburg-Landau equations describing a superconductor are well-known to particle physicists, in their relativistic generalization, as the Higgs model.

$$\mathcal{L} = -\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + (D^{\mu}\phi)^*(D_{\mu}\phi) - g(\phi^*\phi-\phi_o^2)^2 \qquad (2.1)$$

$$D_{\mu}\phi = (\partial_{\mu}+ieA_{\mu})\phi \qquad (2.2)$$

The standard Higgs mechanism application highlights the appearance of two massive particles. The vector particle has mass $m_V^2=2e^2\phi_o^2$, and the scalar has mass $m_H^2=4g\phi_o^2$. Ginzburg-Landau theory highlights two lengths which are the inverse of the above masses. The London penetration depth $\lambda_L=1/m_V$ measures how sharply magnetic fields die off in superconductors while $\xi_{GL}=1/m_H$ measures the distance over which superconductivity becomes established. An important dimensionless parameter is κ_{GL} the ratio of these lengths. We collect the above relations in (2.3)

$$m_V^2 = \frac{1}{\lambda_L^2} = 2e^2\phi_o^2 \qquad\qquad m_H^2 = 1/\xi_{GL}^2 = 4g\phi_o^2$$

$$\kappa_{GL} = \frac{\lambda_L}{\xi_{GL}} = \frac{m_H}{m_V} = \sqrt{\frac{2g}{e^2}} \qquad (2.3)$$

In this section we are interested in the static finite energy solutions of the equations of motion which follow from (2.1). We follow the notation of [7]. We expect these solutions to be vortex lines. In cylindrical coordinates (z,ρ,θ), Coulomb gauge $\nabla\cdot\vec{A}=0$, with $A_o=0$, the static equations of motion read

$$(\nabla^2-2e^2|\phi|^2)\vec{A} = -i\phi^*\vec{\nabla}\phi$$

$$(\vec{\nabla}-ie\vec{A})^2\phi = 2g\phi(|\phi|^2-\phi_o^2) \tag{2.4}$$

choose

$$\vec{A}(\rho,\theta) = \hat{\theta}\,A(\rho) \quad \phi(\rho,\theta) = \phi(\rho)e^{in\theta} \tag{2.5}$$

with

$$A(\rho) = \frac{n}{e\rho}[1-F(\rho)] \tag{2.6}$$

so

$$\vec{B} = \vec{\nabla}\otimes\vec{A} = \hat{z}\ \frac{1}{\rho}\frac{d}{d\rho}[\rho A(\rho)] = \hat{z}\ \frac{n}{e\rho}F'(\rho) \tag{2.7}$$

The integer n will turn out to be the number of flux quanta contained in the vortex. Finally the equations of motion read

$$F''-F'/\rho - 2e^2\phi^2F = 0$$

$$\phi'' + \frac{\phi'}{\rho} - \frac{n^2F^2}{\rho^2}\phi - 2g\phi(\phi^2-\phi_o^2) = 0 \tag{2.8}$$

Since our primary objective is a semi-quantitative analysis of the important features of the vortices and not detailed numerical profiles the strategy we adopt is a variational approach rather than a direct solution of (2.8). The energy per unit length of the static solutions is

$$E = 2\pi\int_0^\infty \rho d\rho\{\tfrac{1}{2}(\tfrac{n}{e\rho})^2(F')^2 + (\tfrac{n}{\rho})^2F^2\phi^2 + \phi'^2 + g(\phi^2-\phi_o^2)^2\} \tag{2.9}$$

The test functions for F and ϕ should be consistent with the flux quantization condition

$$2\pi\int_0^\infty \rho d\rho\ \beta(\rho) = \frac{2\pi n}{e} \quad \text{or } F(0) = 1 \tag{2.10}$$

and the boundary conditions imposed by (2.8)

$$F(\rho) \xrightarrow[\rho\to 0]{} 1-\rho^2/\lambda^2$$

$$\phi(\rho) \xrightarrow[\rho\to 0]{} C\rho^n \qquad (2.11)$$

and

$$F(\infty) = B(\infty) = 0 \qquad \phi(\infty) = \phi_o \qquad (2.12)$$

The test functions we employ consistent with the general form discussed above are

$$\begin{aligned} F(\rho) &= 1-\rho^2/\lambda^2 && \rho<\lambda \\ &= 0 && \rho>\lambda \\ \phi(\rho) &= \phi_o(\rho/\xi)^n && \rho<\xi \\ &= \phi_o && \rho>\xi \end{aligned} \qquad (2.13)$$

This choice makes the math tractable and the physics transparent. The parameter λ is obviously related to the London penetration depth and gives the distance over which the magnetic fields extend in the superconductor (see Fig. 1). The parameter ξ (Fig. 2) is obviously related to the Ginzburg-Landau coherence length and measures the distance necessary for the superconducting state to restore itself from the "normal" state present at $\rho=0$.

Minimization of (2.9) involves competition between a) the second and last terms which want $\phi=\phi_o$, $F=0$; b) the boundary conditions (2.11); and c) the derivatives which want changes in F and ϕ to be gradual. It is intuitively clear that functions F and ϕ with qualitative similarities to (2.13) exist which will perform this minimization. The existence of a solution is independent of the values of g and e and hence the type of superconductor.

The Ansätz (2.13) is a mild caricature of the true solution. λ and ξ, and hence the properties of the vortex, are obtained by minimizing the action with respect to λ and ξ. Qualitatively different behavior arises depending on whether λ is smaller or larger than ξ. This corresponds to the difference between type I and type II superconductors. For type I ($\lambda<\xi$) we find, for n=1,

$$E = \pi\phi_o^2\left(1+\left(\frac{3g}{e^2}\right)^{1/3}\right) \tag{2.14}$$

with

$$\lambda^2 = \frac{1}{e^2\phi_o^2}\left(\frac{9e^2}{g}\right)^{1/3} \qquad \xi^2 = \frac{1}{g\phi_o^2}\left(\frac{3g}{e^2}\right)^{1/3} \tag{2.15}$$

With n>1 the expressions become more complicated but simplify for n>>1

$$E_n \simeq n\pi\phi_o^2 \tag{2.16}$$

$$\lambda^2 \simeq \frac{n}{\sqrt{ge^2}\,\phi_o^2} \simeq \xi^2 \tag{2.17}$$

For type II ($\lambda>\xi$)

$$E = \pi\phi_o^2\left[\frac{5}{2}-(\xi/\lambda)^2 + \frac{1}{2}(\xi/\lambda)^4 + 2\ell n(\lambda/\xi)\right]. \tag{2.18}$$

In the extreme limit $\lambda>>\xi$

$$\lambda^2 = \frac{1}{e^2\phi_o^2} \qquad \xi^2 = \frac{3}{g\phi_o^2} \tag{2.19}$$

while E, for n>1, $\lambda>>\xi$, becomes

$$E_n = 2n^2\pi\phi_o^2\ \ell n\ \lambda/\xi \tag{2.20}$$

a well-known result in the theory of type II superconductors [3]. It will be of note in the following section that the limiting contribution (2.20), characteristic of type II superconductivity comes entirely from the $F^2\phi^2$ term in (2.9).

Equations (2.16) and (2.20) provide the key for distinguishing between the varieties of superconductors. As the amount of flux increases the total energy for eq. (2.16) type I superconductor increases at most linearly with the flux (n). This is a rigorous result of the variational procedures. If we trust the energy estimates for $n \geq 1$ including non-leading terms (e.g. $(\frac{eg}{e^2})^{1/3}$) we find

$$E_n < nE_1 \tag{2.21}$$

In type I superconductors, therefore, vortices tend to coalesce into macroscopic regions of magnetic field. Vortices attract each other [8]. (In particular language we can think of the dominance of scalar, attractive forces over repulsive vector ones since $m_H < m_V$.)

A very different behavior emerges for type II superconductors. Equation (2.20) implies that the energy of a multi-flux ($n>1$) vortex is larger than that of n single flux lines. The stable n flux configuration is n single flux lines [8,9]. The energetics translates, in force language, to repulsive forces between type II vortices. From the viewpoint of the particle spectrum in the Higgs model, $m_V << m_H$ means vector particle exchange forces, which can be repulsive, will dominate over scalar forces.

The transition between the two types of superconductors takes place when $\lambda \equiv \xi$, which as determined by (2.15), is

$$\tilde{\kappa}^2 \equiv \frac{3g}{e^2} = 1 \quad \text{or} \quad \kappa_{GL} = \sqrt{2/3} \tag{2.22}$$

This is to be compared to the exact result $\kappa_{GL} = 1/\sqrt{2}$ from which it differs by 15%. This accuracy gives us confidence that the crude trial functions (2.13) lead to results which are, at least, semi-quantitatively reliable. This accuracy is typical of our results [10]. For $\tilde{\kappa}<1$ (see (2.22)) the medium is type I, for $\tilde{\kappa}>1$ it is type II.

III. Confined $m\bar{m}$ Systems in Type I and Type II Superconductors: Bags and Strings

The association of string models with vortex lines in type II superconductors is well-known since the classic work of Nielsen and Olesen [11]. Let us therefore explore the bag model in the language of the theory of Higgs-Ginzburg and Landau (HGL) for superconductivity. Since we have discussed only vortex lines we consider the cylindrical bag which results with widely separated $m\bar{m}$ [5]. The bag model has a uniform distribution of magnetic field spread over a completely "normal" perturbative vacuum ($\phi\equiv 0$) ending abruptly at a sharp boundary. The corresponding test functions would then be

$$\begin{aligned} F(\rho) &= (1-\rho^2/\lambda^2) \qquad && \rho<\lambda \\ &= 0 && \rho>\lambda \\ \phi(\rho) &= 0 && \rho<\lambda \\ &= \phi_o && \rho>\lambda \end{aligned} \tag{3.1}$$

The original bag model neglected the surface energy, which appears in (2.9) as $(\phi')^2$, coming from the (assumed) small region near $\rho\approx\lambda$ where ϕ goes from 0 to ϕ_o. This surface term, which would actually dominate if (2.9) is the correct expression for the bag energy, has been incorporated into the MIT bag [2] model, and is the sole contribution to the SLAC bag model [12]. With (3.1) the $F^2 \phi^2$ term makes no contribution to the energy and $\xi = \lambda$.

It is straightforward to see that (3.1) does not minimize (2.9) (for any physically imperative smoothing of the ϕ transition from 0 to ϕ_o) and that (2.13) is a superior solution. It also appears that the bag model is (with surface energy) a better approximation to the type I vortex than to the type II. The major component of energy in type II vortices (2.20) comes from the $F^2\phi^2$ term, which contributes little to the type I vortex (κ<<1). Further, type I superconductors have a tendency to equilibrate the values of ξ and λ, whereas type II vortices readily develope two distinct regions. This can be seen from the ratio λ/ξ evaluated in the two situations

$$\lambda/\xi \Big|_{I} = (\tilde{\kappa})^{\frac{1}{3}} \qquad \lambda/\xi \Big|_{II} \simeq \frac{\tilde{\kappa}}{3} \qquad (3.2)$$

Because of the small fractional power, λ and ξ will be comparable for all but extreme values of $\tilde{\kappa}$ ($\tilde{\kappa}^{1/3}$<<1) in type I superconductors.

The strongest clue for the tendency of bags to prefer type I media comes from a comparison of the diameter of a flux tube (widely separated m and $\bar{m}$) embedded in a material which is gradually changed from one type to the other. Two of our three parameters (e,g,ϕ_o) must be fixed as we make the transition. The natural choice is to hold fixed the monopole charge or amount of flux, measured by 1/e. A physically important and well measured parameter is the linear energy density of the vortex. This is equivalent to the string tension $\frac{1}{2\pi\alpha'}$ or the universal Regge slope α' and should be fixed as the medium changes so as to keep the known physics constant. From (2.16) and (2.20) we have (n=1)

$$\frac{1}{2\pi\alpha'} = \pi\phi_o^2 \Big|_{I} = \pi\phi_o^2 \, \ell n\tilde{\kappa} \Big|_{II} \qquad (3.3)$$

The nature of the medium is altered by changing $\tilde{\kappa}$. Starting in a type I medium ($\tilde{\kappa}_I$<<1) we go over to a type II ($\tilde{\kappa}_{II}$>>1) by increasing g. As we do so the dimensions characteristic of the type I vortex (2.15) shrink, and it approaches the ideal (zero thickness) string limit. The diameter of the type I flux tube is

$$d_I \equiv \xi_I = \frac{\pi}{e} \sqrt{6\alpha'} \, \tilde{\kappa}^{-1/3} \qquad (3.4)$$

while that of the type II flux tube is

$$d_{II} \equiv \lambda_{II} = \frac{\pi}{e} \sqrt{2\alpha' \, \ell n\tilde{\kappa}_{II}} \qquad (3.5)$$

implying

$$d_I/d_{II} = \frac{\sqrt{3}\, \tilde{\kappa}_I^{-2/3}}{\sqrt{\ell n \, \tilde{\kappa}_{II}}} \qquad (3.6)$$

which for $\tilde{\kappa}_I$ <<1 and $\tilde{\kappa}_{II}$>1 is much larger than 1. We thus see how the width of the flux tube decreases as we change the material from type I to type II. The core of the tube which has dimension ξ_{II}, and carries the major contributions to E also continues to shrink as g increases (2.19) The implications of this for a non-asymptotic separation of m and $\bar{m}$ is illustrated schematically in fig. 3. An $m\bar{m}$ is shown in fig.3a in a type I material, with a separation $\gtrsim \xi$. The nature of the medium is changed, keeping α' and the monopole charge fixed, to a type II medium. The spatial extension of both the magnetic field and the perturbative vacuum contract with the result 3b. The characteristic transverse distances have shrunk and a bag like configuration has been converted into a string like one.

A proper study of an $m\bar{m}$ in a superconductor would require extension of the HGL theory to include sources. We know of only one such, numerical study, over a limited range of values of κ[13]. Our analytic study of the vortex tube can, however, give us qualitative insight into the patterns to be expected.

For an $m\bar{m}$ pair embedded in a superconductor we have four relevant distance scales. Three of these $\sqrt{\alpha^{\prime}}, \lambda, \xi$ are characteristic of the medium, while the fourth we denote r is the $m\bar{m}$ separation. $\sqrt{\alpha^{\prime}}$ is the incremental extension of the vortex as we climb a Regge trajectory.If $\sqrt{\alpha^{\prime}} >> \lambda, \xi$ the string limit is applicable. For $\sqrt{\alpha^{\prime}} << \lambda, \xi$ we expect the string limit to be reached only asymptotically. Empirically hadronic sizes are $\sim \sqrt{\alpha^{\prime}}$.

For the exploration of hadronic properties for various values of λ, ξ, we study the static potential of heavy monopoles. When $r >> \lambda, \xi$ the unversal flux tube dictates a linear potential. When $r << \lambda$ the magnetic field is essentially oblivious to the existence of the superconductor and is given by the standard dipole form . The magnetic field energy no longer contributes to the linear potential, but rather establishes a Coulomb interaction. When $r<<\xi$ the major contribution to the linear part of the potential disappears and a contribution proportional to r^3 (volume) appears. When $r<<\lambda,\xi$, the Coulomb interaction is the only relevant one.

The interesting intermediate cases are $\lambda<<r<<\xi$ for $\tilde{\kappa}<<1$ and $\xi<<r<<\lambda$ for $\tilde{\kappa}>>1$. The first case, for type I materials has a non-dominant linear potential piece from the magnetic field energy which is still concentrated in a thin tube between the monopoles. The bulk of the linear vortex energy is replaced by an r^3 volume term. There is no Coulomb term.

For $\xi<<r<<\lambda$ the potential has both a Coulomb piece and a linear piece coming from the tube (of diameter ξ) of perturbative vacuum running between the monopoles. In this region, for type II materials, the well known Cornell Ansätz $V = -\frac{4}{3}\frac{\alpha_s}{r} + \frac{1}{2\pi\alpha'}r$, for the potential is valid. The $m\bar{m}$ energy is actually falling somewhat faster with decreasing r than implied by $\frac{1}{2\pi\alpha'}$ r term since the energy density is losing the contribution from the magnetic field energy. (We expect the $r \ln \lambda/\xi$ implied to become $r \ln (r/\xi.)$ Thus we expect fits utilizing the Cornell Ansatz to produce a value for the phenomenological string tension $\frac{1}{2\pi\alpha'}$, somewhat larger than that implied by using values of α' obtained from truely asymptotic behavior such as from Regge trajectories. This is in fact what is observed [14]. The Richardson [15] potential automatically provides this type of interpolation.

Can we, from our knowledge of the actual $q\bar{q}$ potential, derive limits on the values of λ and ξ? The heavy $q\bar{q}$ potential has been determined [16] for $\frac{1}{2}$ (GeV)$^{-1} \lesssim r \lesssim 5$ (GeV)$^{-1}$. There is no question but that for $r \gtrsim 5$(GeV)$^{-1}$ strong deviations from the asymptotic linear potential are present. Therefore at least one of λ, and ξ must be $\gtrsim 5$(GeV)$^{-1}$. For $r \lesssim 2$(GeV)$^{-1}$ the potential is dropping off faster than can be explained by the <u>total</u> disappearance of the $\frac{r}{2\pi\alpha'}$ linear term. A Coulomb component must be present at these distances, $\lambda \gtrsim 2$ (GeV)$^{-1}$.

The foregoing is not sufficiently precise to distinguish between a type I or type II superconducting vacuum . The success of the Cornell potential speaks in favor of a type II vacuum, but this potential is hardly unique. Similarly the precocity of linearly rising Regge trajectories and the existence of a hard core repulsive potential between nucleons seem to favor a type II vacuum. This evidence too is suggestive, but hardly conclusive. Bag models have repulsive cores because of quark-quark interactions which we have completely neglected. Although linear Regge trajectories are expected asymptotically in bag (and type I) models we do not understand them sufficiently well to predict when such behavior sets in. Our own prejudice is that we are more likely to live in a type II vacuum.

IV. CONCLUSIONS

We have examined the structure of vortices in type I and type II superconductors and extrapolated this information to learn something about monopole-anti-monopole bound states in such environments. The existence of a vortex and hence a string or tube connecting the widely separated m and $\bar{m}$ is a characteristic property of any type of superconductor or any medium describable by a Higgs, Ginzburg, Landau model. Consequently, linear confining potentials and asymptotically linearly rising Regge trajectories are expected [17]. At sufficiently small separations, smaller then typical length scales of the medium (λ,ξ), the $m\bar{m}$ interactions should be dominated by Coulombic forces. Since these three properties are widely accepted properties of QCD confinement we find strong support for the idea that quarks find themselves in a chromomagnetic superconducting vacuum.

If we construct models for $m\bar{m}$ confinement a bag model will be more apt if the $m\bar{m}$ are embedded in type I materials. A string model seems more appropariate for type II environments. This is because, for given monopole charge and fixed asymptotic string tension $\frac{1}{2\pi\alpha'}$, the $m\bar{m}$ system will be thicker, or fatter in type I materials and hence more three dimensional. The relation $\lambda \simeq \xi$ is more likely to be approximated in a type I material and the energy contribution of the $F^2\phi^2$ term in equation (2.9), which is neglected in bag models, is of much less significance in type I than type II.

The distinction between the two types of superconductors is subtle and we cannot determine which type better corresponds to the QCD vacuum. The coexistence for 10 years of string and bag models is an indication of the difficulty of making distinctions. What is of most importance is that the superconductivity analogy is pertinent and fruitful.

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Figure Captions

Fig. 1 The Ansatz (2.13) for the function F, and the magnetic field H inside the vortex.

Fig. 2 The order parameter ϕ inside the vortex.

Fig. 3 Static configuration for an $m\bar{m}$ embedded in a moderate ($\tilde{\kappa} \lesssim 1$) type I superconductor. The $m\bar{m}$ separation is $\approx \xi$. Horizontal lines indicate regions of non-zero H, vertical lines indicate regions of non-superconductivity.

Fig. 4 The same situation as 3 except that the nature of the medium has been changed by altering $\tilde{\kappa}$, so $\tilde{\kappa} \gtrsim 1$. The configuration looks much more stringlike.

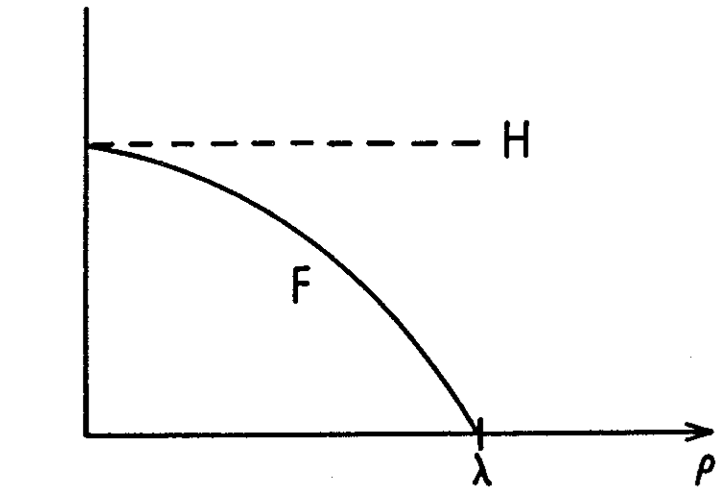

Fig. 1

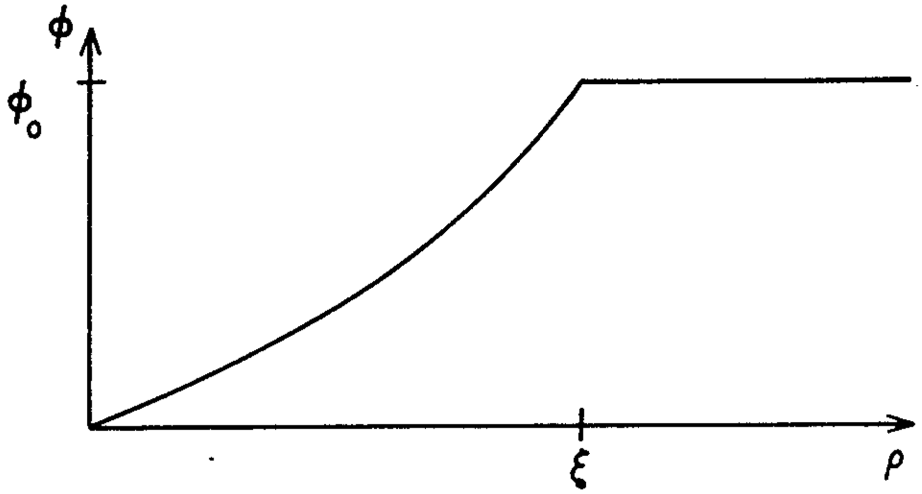

Fig. 2

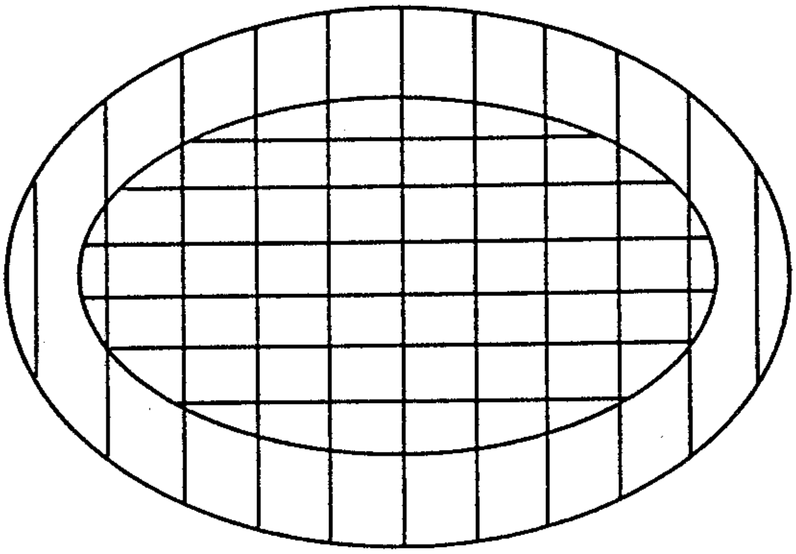

Fig. 3

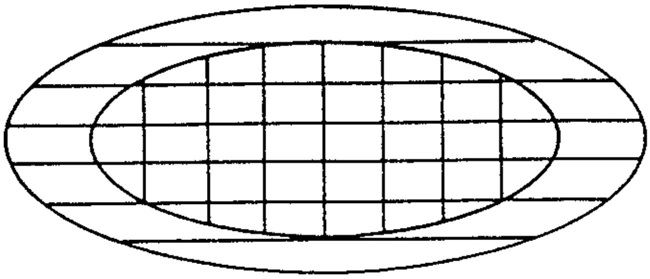

Fig. 4