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PHENOMENOLOGICAL THEORY OF SUPERCONDUCTIVITY THROUGH GENERALIZED MEISSNER EFFECT

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Constructing the effective action for fields associated with monopoles and dyons separately, in the Abelian projection of *QCD*, it has been demonstrated that any charge (electrical or magnetic) screens its own direct potential to which it minimally couples and anti-screens the dual potential leading to dual superconductivity in accordance with generalized Meissner effect. It has been demonstrated that monopole loops produce screening effects for magnetic propagator and anti-screening effect for dual electric propagator (Aμ-propagator), which excludes electric field from inside the magnitude superconductor in accordance with dual Meissner effect. It has also been shown, in this case that the magnetic superconductivity is the Higgs phase of magneto-dynamics and the electrically charged particles are confined by a linear potential in magnetic superconductor. The duality of Higgs phase and confinement phase has also been established and it has been shown that the interactions of chromomagnetic monopoles are saturated by this duality.

INTRODUCTION

Physicists were fascinated by magnetic monopole since its ingenious idea was given by Dirac[1,2] and also by Saha[3,4] by showing that the mere existence of monopole implies the quantization of electric charge in the Abelian theory. In the mean time, it became clear[5-7] that monopole and dyon[8-9] (a particle carrying electric and magnetic charges) can be understood better in non-Abelian gauge theories. Such non-Abelian monopoles are known to arise as classical solutions in field theoretical models like the Georgi-Glashow model and also in pure Yang-Mills theories where the role of fundamental Higgs scalars could eventually be played by some composite fields. In any case, these non-Abelian monopoles can be understood, in the framework of these models, as defects in space-time of $U(1)$ gauge fields which arise once the unitary gauge is chosen[10-11]. Julia and Zee[8] extended the idea of non-Abelian monopole proposed by t' Hooft[5] and Polyakov[6] and constructed classical solutions for non-Abelian dyons. Now it is widely recognized[12] that SU(5) grand unified model is a gauge theory that contains monopole solution and it has been demonstrated by Witten[13] that non-Abelian monopoles are necessarily dyons which arise as quantum mechanical excitation of fundamental monopoles. Thus monopoles and dyons became intrinsic part of all current grand unified theories (GUT's) and super symmetrical models[14-19]. Perhaps the most important aspect of monopoles and dyons in physics is their role in the mechanism of quark confinement[20-25] along the lines of dual Meissner effects[26-30] leading to dual superconductivity as discussed in some recent papers[31-37] by employing dual gauge potential where magnetic degree of freedom manifestly appears in the partition function. However, the crucial ingredient for condensation in a chromo-magnetic superconductor would be the non-Abelian force in contrast to the Abelian ones in ordinary superconductivity. Topologically, a non-Abelian gauge theory is equivalent to a set of Abelian gauge theories supplemented by monopoles [38]. The method of Abelian projection is one of the popular approaches to confinement problem, together with dual superconductivity [39,40] picture, in non-Abelian gauge theories. Monopole condensation mechanism of confinement (together with dual superconductivity) implies that long-range physics is dominated by Abelian degrees of freedom [41,42] (Abelian dominance). The conjecture that the dual Meissner effect is the color confinement mechanism is realized if we perform Abelian projection in the maximal gauge where the Abelian component of gluon field and Abelian monopoles are found to be dominant[43-44]. Then the Abelian electric field is squeezed by solenoidal monopole current [45].

In the present paper the effective action has been constructed for purely magnetic charges (only monopoles) in the Abelian version of *QCD* and it has been demonstrated that monopole loops produce screening effects for magnetic propagator (B_μ- propagator) and anti-screening effect for dual electric propagator (A_μ- propagator), which excludes electric field from inside the magnitude superconductor in accordance with dual Meissner effect. It has also been shown, in this case, that the magnetic superconductivity is the Higgs phase of magnetodynamics and the electrically charged particles are confined by a linear potential in magnetic superconductor. The duality of Higgs phase and confinement phase has also been established and it has been shown that the interactions of chromomagnetic monopoles are saturated by this duality. $\frac{1}{k^4}$ −behaviour of gluon propagator, in this case, has been shown to lead to condensation of monopoles and the resulting state of chromomagnetic superconductivity. In the Abelian projection of QCD with the simultaneous existence of electric charges and monopoles also, the effective action and current correlators have been constructed and it has been shown that any particle (electrically charged or monopole) screens its own direct potential to which it minimally couples and anti-screens the dual potential (B_μ for electric charges and A_μ for monopoles). It has been demonstrated that this dual anti-screening effect leads to dual superconductivity in accordance with generalized Meissner effect. It has also been shown that the duality of Higgs phase and confinement in this case is a strong guide to the description of confinement and it saturates the interactions of chromomagnetic monopoles. Finally, constructing the effective action for dyonic field in Abelian projection of *QCD* in terms of electric and magnetic constituents, A_μ and B_μ, of the generalized four-potential, the dyonic current correlators have been derived and it has been demonstrated that the dyonic electric charge produces screening effect for A_μ-propagator and anti-screening effect for B_μ-propagator while the dyonic magnetic charge produces screening effect for B_μ-propagator and anti-screening effect for $A\mu$-propagator. These anti-screening effects have been shown to lead to dyonic condensation and dual superconductivity and also to maintain the asymptotic freedom of non-Abelian gauge theory (*QCD*) in its Abelian version.

MAGNETIC SUPERCONDUCTIVITY THROUGH DUAL MEISSNER EFFECT

For purely magnetic charge source (i.e. only monopoles), the field equations may be written as

$$H_{\mu\nu,\nu} = k_\mu \qquad \text{... (2.1)}$$

$$H^d_{\mu\nu,\nu} = 0$$

and

$$B_\mu = k_\mu \qquad \text{... (2.2)}$$

where B_μ is the magnetic four potential, k_μ is the magnetic four-current density and magnetic field tensorfield tensor $H_{\mu\nu}$ is given by

$$H_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \qquad \text{... (2.3)}$$

with $H^d_{\mu\nu}$ as its dual tensor given by

$$H^d_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\alpha\beta}\, H^{\alpha\beta} \qquad \text{... (2.4)}$$

The Lagrangian density for spin-1 monopole (*i.e.*, bosonic dyon) of rest mass m_o may be written as follows in the Abelian theory;

$$L = \frac{1}{4}(B_{\nu,\mu} - B_{\mu,\nu})^2 - k_\mu B^\mu \qquad \text{... (2.5)}$$

where the constant term m_0 has been ignored. It leads to field equations (2.2) upon variation with respect to B_μ.

With the development of non-Abelian gauge theories, Dirac monopole has mutated in another way as we have to take into account not only electromagnetic $U(1)$ gauge group but also the color gauge group $SU(3)_C$ describing strong interaction. At energy around 100 GeV electromagnetism merges in the electroweak interaction with the gauge group $SU(2)\ XU(1)$. These gauge theories still have monopoles of Dirac type, but the ordinary magnetic fields of the monopoles, in general, will be accompanied by color magnetic or magneto weak fields. The results of usual gauge group $U(1)$ may be generalized to an ordinary gauge group H when potentials are defined in the Lie algebra of H, *i.e.*,

$$B_\mu = B^a_\mu t_a, \qquad \text{... (2.6)}$$

where t_a are generators of H. To avoid unnecessary factors of i, the t_a are taken to be anti-Hermitian and the coupling derivative is

$$D_\mu = \partial_\mu - B_\mu$$

where the minimal coupling has been absorbed into B_{μ}. Each matter field belongs to some unitary representation of *H* and the potential acts on it according to this representation of the generator t_a. When one specializes again to the case $H = U$ (1), one has to reintroduce the factor i_g to make contact with the old notation. Topologically, the most important difference between a non-Abelian gauge theory and a set of Abelian (*QED* type) gauge fields is the compactness of the non-Abelian gauge group *H*. Thus in *QCD*, because *SU*(3) is compact, the color electric charges defined with respect to any maximal Abelian subgroup are quantized. It implies that we can write down gauge field configurations that asymptotically look like magnetic monopole of any chosen Abelian direction. The spherically symmetric monopoles have the magnetic field.

$$\vec{B}^a = \frac{1}{2} Q^a \frac{\hat{r}}{r^2} \qquad \text{... (2.8)}$$

where Q^a is a generator of *H*. They can be considered as *U*(1) monopoles where *U*(1) is the subgroup of *H* generated by Q^a.

In a realistic theory with electromagnetic and quark matter fields, Q^a may be diagonalized by a global gauge transformation and thus the solution of quantization condition

$$\exp (2\pi\, Q) = 1, \qquad \text{... (2.9)}$$

may be written as

$$Q = i\,(mQ_e + nQ'_{3c} + nQ'_c) \qquad \text{... (2.10)}$$

where Q_e is the electric *U*(1) generator normalized to unity, Q_{3c} acts on the color states of the quark fields as the diagonal matrix-diag (–1/3, –1/3, 2/3) and Q'_c acts as (1, – 1, 0). Moreover, the integers *m* and *n* have to satisfy additional condition

$$m + n = 0 \bmod 3 \qquad \text{... (2.11)}$$

Taking into account the existence of quarks we find that for monopole with ordinary magnetic charge only, *m* must be multiple of 3. The monopoles with *m* =1 are possible but they must have a color magnetic field in addition.

For non-Abelian H, the spherically symmetric ansatz (2.19) can only be valid for a limited range of distances. The confinement of color electric charge corresponds to the screening of color magnetic charge[54]. In particular, for distances beyond 1 Fm the energy of the color magnetic field drops exponentially and not as r^{-2} as one would obtain from equation (2.19). This means that beyond 1Fm one can neglect the difference between realistic monopoles and Dirac ones. Thus there are monopole field configurations in any non-Abelian gauge theory. To prove the phase structure of the theory, we can add a scalar field (*i.e.,* Higg's field) in the adjoint representation so long as this does not change the nature of flow of the coupling constant with energy. For asymptotically free theories, the low energy behaviour is dominated by the Abelian monopoles of zero mass which are almost point-like. The interaction of point-like monopoles with gluons and charged particles can be studied as a dual analog of point-like charged particle interactions. It leads to condensation of monopole[15]. Topologically, a non-Abelian gauge theory is equivalent to a set of Abelian gauge theories supplemented by monopoles which undergo condensation. This condensation leads to confinement. The scalar fields (*i.e.*, Higg's fields) have all decoupled by now and hence this field ϕ plays a role of a regulator only. This theory also has massless gluons denoted by A_μ, charged massive gluons W_μ and monopoles which are coupled minimally to massles B_μ and electrically charged particle W_μ. These Abelian monopoles play the key role in the dual superconductor model of the QCD vacuum. In this process of Abelianization (*i.e.* the Abelian projection) the quark are electrically charged particles and if the monopoles are condensed the dual Abrikosov string carrying the electric flux is formed between quarks and antiquark. Due to a non-zero string tension the quarks are confined by the linear potential.

The effective action for monopole field in this Abelian projection of *QCD* may be written in the following manner from this Lagrangian density given by eqn. (2.5):

$$S = -\frac{1}{4}\int H_{\mu\nu}(x)\, \mu(x-y)\, H^{\mu\nu}(y)\, d^4x d^4y + k_\mu B^\mu \qquad \text{... (2.12)}$$

where $\mu\ (x-y)$ as magnetic permeability and the magnetic four-current k_μ couples to the field B_μ and the magnetic current correlations may be written in the following form;

$$\langle k_\mu \rangle = \frac{\delta S}{\delta B_\mu} \qquad \text{... (2.13)}$$

$$\langle k_\mu(x) k_\nu(x)\rangle = \frac{\delta^2 S}{\delta B_\nu(x)\, \delta B_\mu(x)} \qquad \text{... (2.14)}$$

From equations (2.12) and (2.14), we get

$$\langle k_\mu(x) k_\nu(y)\rangle = -\int \frac{d^4k}{(2\pi)^4}\, e^{ik(x-y)}[k^2\delta_{\mu\nu} - k_\mu k_\nu]\, \mu(k^2) \qquad \text{... (2.15)}$$

where $\mu\ (k^2)$ is the Fourier transform of $\mu(x\text{-}y)$ and k_μ and k_ν on the right hand side are the components of four-propagation-vector k while $k_\mu(x)$ and $k_\nu(y)$ on the left hand side are the components of magnetic four-current density at the points x and y respectively.

In the perturbation theory, the deviation of $\mu(k^2)$ from unity can be interpreted as the vacuum polarization due to monopole loops. For small penetration $\chi(k^2)$, we have

$$\mu(k^2) = 1 + \chi_g(k^2) \qquad \text{... (2.16)}$$

Equations (2.13), (2.14) and (2.15) show that the monopole loops [*i.e.*, $\chi_g(k^2) > 0$], produce screening effects for B_μ-propagator ($\mu > 1$) and anti-screening effect for the dual A_μ-

propagator. This ant-screening effect excludes electric field from inside the magnetic superconductor in accordance with dual Meissner effect. However, in magnetic superconductivity the electric field can penetrate the magnetic superconductor up to London penetration depth

$$|\lambda_L| = \lambda_g$$

For small k^2, we have

$$\in = \frac{k^2}{m_{Lg}^2} \quad \text{... (2.17)}$$

where $$m_{L_g} = \frac{1}{\lambda_g}$$

Thus we get $$\mu\,(k^2) = \frac{1}{\in} = \frac{m_{L_g}^2}{k^2} = \frac{1}{\lambda_g^2 k^2} \quad \text{... (2.18)}$$

Then equation (2.15) may be written as follows

$$< k_\mu(x) k_\nu(y) = -\int \frac{d^4k}{(2\pi)^4}\left[\delta_{\mu\nu} - \frac{j_\mu j_\nu}{k^2}\right] m_{L_g^2} \quad \text{... (2.19)}$$

Thus the quanta of field B_μ acquire a mass m_{L_g} through summation of bubbles. It shows that the magnetic superconductivity is the Higg's phase of magnetodynamics. This relation also shows that the dual potential A_μ associated with magnetic current density k_μ has a propagator that goes like $\frac{1}{k^4}$ since the free field part of the action (2.12) (*i.e.*, effective action) may be written as

$$S_p = \frac{1}{4}\int F_{\mu\nu} \frac{\cdot}{m_{L_g}^2} F^{\mu\nu} d^4x \quad \text{... (2.20)}$$

where the field tensor $F_{\mu\nu}$ is given as follows in terms of dual potential A_μ:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad \text{... (2.21)}$$

Thus the magnetic superconductivity involves the massive quanta of field B_μ (mass equal to m_{L_g}) and *a* $\frac{1}{k^4}$ – propagator for dual potential A_μ.

The $\frac{1}{k^4}$ – behaviour of gluon propagator, described by equations (2.19) and (2.20), is equivalent to the condensation of monopoles and the resulting state of chromo-magnetic superconductivity[46-50].

DUAL SUPER CONDUCTIVITY THROUGH GENERALIZED MEISSNER EFFECT

Let us now consider the dynamics allowed to simultaneously incorporate electric and magnetic charges on different particles (*i.e.*, allowing the simultaneous existence of electric charges and monopole but not the dyons). An Abelian monopole of monopole, moving in the field of electric charge *e*, carries the following residual angular momentum (field contribution) besides its orbital and spin angular moment :

$$\vec{J}_{res} = eg\frac{\vec{r}}{r} \qquad \text{... (3.1)}$$

which when quantized leads to

$$eg = \frac{1}{2}n \ \text{(in the units of } \hbar \text{)} \qquad \text{... (3.2)}$$

where n is an integer. It is celebrated Dirac's quantization condition which shows that the mere existence of an isolated magnetic charge implies the quantization of electric charge.

In this case the field equations (2.1) may be generalized to the following symmetric form:

$$F_{\mu\nu,\nu} = j_\mu \ ; \quad H_{\mu\nu,\nu} = k_\mu \qquad \text{... (3.3)}$$

$$F^d_{\mu\nu,\nu} = 0 \ ; \quad H^d_{\mu\nu,\nu} = 0$$

where $F_{\mu\nu}$ and $H_{\mu\nu}$ are given by equations (2.15) and (2.3) respectively. Similarly, the equation (2.2) may be generalized into following form

$$A_\mu = j_\mu;$$

$$B_\mu = k_\mu \qquad \text{... (3.4)}$$

All these equations are dual invariant under the duality transformations

$$F_{\mu\nu} \to H_{\mu\nu}; \qquad H_{\mu\nu} \to -F_{\mu\nu};$$

$$j_\mu \to k_\mu; \ k_\mu \to j_\mu \qquad \text{... (3.5)}$$

The effective action in the Abelian projection of *QCD*, described by eqns. (2.9), (2.10) and (2.11), may be written as follows in this case;

$$S = -\frac{1}{4}\int F_{\mu\nu}(r) \in (x-y) F^{\mu\nu} d^4x d^4y - \frac{1}{4}\int H_{\mu\nu}(x) \mu(x-y) H^{\mu\nu} d^4x d^4y$$

$$+ j_\mu A^\mu + k_\mu B^\mu \quad \text{... (3.6)}$$

with $\in (x-y)$ as ordinary dielectric constant and μ $(x-y)$ as magnetic permeability such that

$$\int \in (x-y)\,\mu(y-z)\, d^4y = \delta(x-z) \quad \text{... (3.7)}$$

where δ (x) is Dirac-Delta function.

The current correlations (2.7) and (2.8) may be generalized into the following form in the in the present case;

$$\left\langle j_\mu \right\rangle = \frac{\delta S}{\delta A_\mu}$$

$$\left\langle k_\mu \right\rangle = \frac{\delta S}{\delta B_\mu}$$

$$\left\langle j_\mu(x)\, j_\nu(y) \right\rangle = \frac{\delta^2 S}{\delta A_\nu(y) \delta A_\mu(x)}$$

$$\left\langle k_\mu(x) k_\nu(y) \right\rangle = \frac{\delta^2 S}{\delta B_\nu(y) \delta B_\mu(x)} \quad \text{... (3.8)}$$

For the action given by eqn (3.6), these relations lead to the following generalization of eqn. (2.9):

$$\left\langle j_\mu(x)\, j_\nu(y) \right\rangle = -\int \frac{d^4k}{(2\pi)^4} [k^2 \delta_{\mu\nu} - k_\mu k_\nu] \in (k^2) \quad \text{... (3.9)}$$

and

$$\langle k_\mu(x) k_\nu(y) \rangle = -\int \frac{d^4k}{(2\pi)^4} e^{ik(x-y)} [k^2 \delta_{\mu\nu} - k_\mu k_\nu]\, \mu(k^2) \quad \text{... (3.10)}$$

For small perturbations we have

$$\in (k^2) = 1 \pm \chi_e(k^2) \quad \text{... (3.11)}$$

$$\mu(k^2) = 1 \pm \chi_g(k^2) \quad \text{... (3.12)}$$

where the upper signs in the right hand sides correspond to vacuum polarization due to charge particle loops and the lower sign corresponds to that due to monopole loops. Relations (2.13) may also be generalized as

$$\left\langle j_\mu(x) j_\nu(y) \right\rangle = -\int \frac{d^4k}{(2\pi)^4}[\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}]\, m_{L_e}^2 \quad \text{... (3.14)}$$

and $$< k_\mu(x) k_\nu(y) >= \; -\int \frac{d^4k}{(2\pi)^4}\left[\delta_{\mu\nu} - \frac{j_\mu j_\nu}{k^2}\right] m_{L_g^2}$$

where the quanta of field A_μ(photon) acquires a mass m_{L_e} through summation of bubbles

These relations show that charged particles $[\chi_\in(k^2) > 1]$ produce screening effect for the A_μ- propagator with the corresponding photon acquiring the mass m_{L_e} (through summation of bubbles), and ant-screening effect for the B_μ- propagator. On the other hand, the monopole loops produce screening effect for B_μ with corresponding photon acquiring the mass m_{Lg}, and anti-screening effect for A_μ-propagator. Thus any particle (electrically charged or monopole) screens its own direct potential to which it minimally couples, and anti-screens the dual potential (B_μ for electric charges and A_μ for monopoles). This dual anti-screening effect leads to dual superconductivity in accordance with generalized Meissner effect (usual one and the dual Miessner effect).

When all the dual charges (electric as well as magnetic) appear in loops, then the anti-screening effect provides the prescription that the magnetic photon (B_μ)-charged particle vertex is identical to the A_μ-charge particle vertex with the coupling constant e replaced by *i.e.*, Similarly, the usual photon (A_μ) – monopole vertex is identical to B_μ-monopole vertex with the coupling constant g replaced by i_g.

An interesting logical consequence of this prescription is that the monopole-A_μ contribution is given by $e^2 \to -g^2$ in the charged particle – A_μ vertices and the magnetic photon (B_μ) couples to charges with $-e^2$.

DYONIC SUPERCONDUCTIVITY THROUGH GENERALIZED MEISSNER EFFECT

Let us now consider the system of dyons, each carrying the generalized charge q, generalized four-current J_μ and generalized potential V_μ as complex quantities consisting of electric and magnetic components as rear and imaginary parts in the following manner respectively :

$$q = e - i\text{g},$$

$$J_\mu = j_\mu - i k_\mu$$

and $$V_\mu = A_\mu - iB_\mu \quad \text{... (4.1)}$$

For the self- dual fields the Abelian monopoles become Abelian dyons[51]. These dyons are coupled minimally to the massless V_μ and electrically charged particles W_μ. In *QCD* for low energy the dyons interactions are saturated by duality. Thus the infrared properties of the *QCD* in the Abelian projection can be described by the Abelian Higgs Model (AHM) where dyons are condensed leading to confinement. As such, the non-Abelian confinement of dyonic charge is related to linear Abelian theory in a dyonic superconductor.

The effective action for dyonic field in this Abelian projection of *QCD* may be written in the following manner [33] as the generalization of eqns. (2.12) and (3.6);

$$S = -\frac{1}{4}\int G_{\mu\nu} \notin (x-y) G^{\mu\nu}(y) d^4x d^4y + J_\mu V^\mu \qquad \text{... (4.2)}$$

where $\notin (x-y)$ is the generalized dielectric constant defined as

$$\notin (x-y) = \in (x-y) - i\mu(x-y) \qquad \text{... (4.3)}$$

with $\in (x-y)$ as ordinary dielectric constant and μ(x-y) as magnetic permeability satisfying eqn. (3.7).

In equation (2.23) the generalized field tensor $G_{\mu\nu}(x)$ is given by

$$G_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

or

$$G_{\mu\nu} = F_{\mu\nu} - iH_{\mu\nu} \qquad \text{... (4.4)}$$

which satify the dual symmetric generalized field equations

$$G_{\mu\nu,\nu} = J_\mu$$

and

$$G^d_{\mu\nu,\nu} = 0 \qquad \text{... (4.5)}$$

Then the current-correlations are given by

$$\langle J_\mu \rangle = \frac{\delta S}{\delta V_\mu} \qquad \text{... (4.6)}$$

and

$$\langle J_\mu(x) J_\nu(y) \rangle = \frac{\delta^2 S}{\delta V_\nu(y)\, \delta V_\mu(x)} \qquad \text{... (4.7)}$$

Which lead to the following generalization[33] of eqns. (3.9) and (3.10):

$$\langle J_\mu(x) J_\nu(y) \rangle = -\int \frac{d^4k}{(2\pi)^4} e^{ik(x-y)} [k^2 \delta_{\mu\nu} - k_\mu k_\nu] \notin (k^2) \qquad \text{... (4.8)}$$

where $\notin (k^2)$ is Fourier transform of $\notin (x-y)$. For free generalized fields in vacuum $\notin (k^2) = 1$. In the perturbation theory the deviation of $\notin (k^2)$ from 1 can be interpreted as the vacuum polarization due to dyon loops. For peturbationally small $\chi(k^2)$, we have

$$\notin (k^2) = 1 + \chi(k^2) \qquad \text{... (4.9)}$$

where

$$\chi(k^2) = \chi_e(k^2) - i\chi_g(k^2) \qquad \text{... (4.10)}$$

with $\chi_e(k^2)$ as peturbation related with electric charge loop and χ_g as the peturbation related with magnetic charge loop. These equations show that the dyonic electric charge produces screening effect for A_μ-propagator $(\in > 1)$ and anti-screening effect for B_μ-propagator. Similarly, the dyonic magnetic charge $[\chi_g(k^2) > 0]$ produces screening effect for B_μ - propagator (μ > 1) and anti-screening effect for A_μ - propagator. Let us apply equation (2.27) to the case of dual superconductivity. $\notin$ in this case, includes fully non-peturbative effects. This rigidly excludes generalized electromagnetic field inside the dual superconductor in conformity with the generalized Meissner effect with its real and imaginary constituents as the strict Meissner effect and dual Meissner effect respectively.

DISCUSSION

For purely magnetic charge source (*i.e.*, only monopoles) the Langrangian density of the field is given by equation (2.5) with effective action of equation (2.12). In this case the magnetic four-current k_μ couples to the filed B_μ and the magnetic current correlation is given by equation (2.15). This equation, along with equation (2.14), shows that monopole loops produce screening effects for B_μ–propagator and anti-screening effect for dual A_μ-propagator. This anti-screening effect excludes electric field from inside the magnetic superconductor in accordance with dual Meissner effect. Equations (2.19) and (2.20) show that the quanta of the field B_μ (to which monopole couples) acquire the mass m_{L_g} leading to the conclusion that magnetic superconductivity is the Higgs phase of magnetodynamics. These relations also show that the dual potential A_μ associated with magnetic current density k_μ has a propagator that goes like $\frac{1}{k^4}$. This behaviour of potential A_μ shows that electrically charged particle pairs would be confined by a linear potential in magnetic superconductor. Thus the Higgs phase, in terms of B_μ and the monopoles, is the confinement phase here. Thisleads to the duality of Higgs phase and confinement phase. This duality appears to be a strong guide to the description of confinement. At least for low k^2, the interactions of chromomagnetic monopoles can be saturated by the duality. It is concluded that the $\frac{1}{k^4}$ – behaviour of gluon propagator, described by equations (2.19) and (2.20), is equivalent to the condensation of monopoles and the resulting state of chromomagnetic super conductivity[46-50]. A Simple $U(1)$ standard electrodynamics with monopoles cannot yield condensation of monopoles. In the non-Abelian case we further have charged gluons W_μ whose interactions are determined by symmetry and which lead to instability of monopoles and their condensation.

In the Abelian projection of *QCD* with the simultaneous existence of electric charges and monopoles (but not dyons) the effective action is given by equation (3, 6) and the current correlations are given by equations (3,8), (3.9) and (3.10) which reduce to equations (3.14) under the small perturbations given by equations (3.11) and (3.12). These relations demonstrate that charged particles produce screening effect for A_μ- propagator, with the corresponding photon acquiring the mass m_{L_e} and anti-screening effect for B_μ- propagator while the monopole loops produce screening effect for B_μ, with corresponding photon acquiring the mass m_{L_g} and anti-screening effect for A_μ- propagator. Thus any particle (electrically charged or monopole) screens its own direct potential to which it minimally couples, and anti-screens the dual potential (B_μ for electric charges and A_μ for monopoles). This dual anti-screening effect leads to dual superconductivity in accordance with gereralized Meissner effect. This dual superconductivity is the Higgs phase of *QCD* in its Abelian projection. These anti-screening effects also show that monopoles can maintain asymptotic freedom of the non-Abelian gauge theory (*QCD*) in its Abelian projection. The most convenient microscopic description of the low energy *QCD* is thus provided by the chromomagnetic monopoles.

The anti-screening effect described by equations (2.10) to (2.14) provides the prescription that the magnetic photon B_μ-charge particle vertex is identical to the A_μ- charge particle vertex with the coupling constant e replaced by ie. Such prescription of coupling of a gauge particle to its dual charge must be used only when all dual charges appear in loops. An interesting logical consequence of this prescription is that the monopole- A_μ contribution is given by $e^2 \to -g^2$ in the charged particle A_μ-vertices and the magnetic photon (B_μ) couples to charges with $-e^2$. If in a theory all the monopole interactions are given by this prescription, then it is saturated by duality. The duality of Higgs phase and confinement, prescribed by equations (3.14), suggests that the duality should be a strong guide to the description of confinement and also that the interactions of chromagnetic monopoles should be saturated by duality, at least for low k^2.

Equation (4.2) gives the effective action for dyonic field in Abelian projection of *QCD*, which leads to the dyonic current correlations given by equations (4.6), (4.7) and (4.8). These relations show that the dyonic electric charge produces screening effect for $A_{\mu\text{-}}$propagator and anti-screening effect for $B_{\mu\text{-}}$ propagator. Similarly, the dyonic magnetic charge produces screening effect for B_μ–propagator and anti-screening effect for A_μ – propagator. This anti-screening effect maintains asymptotic freedom of non-Abelian gauge theory (*QCD*) in the Abelian version. In *QCD*, because of asymptotic freedom, the Landau singularity (led by charged particles in ordinary electrodynamics) is in the infrared regime and hence the most convenient microscopic theory of low energy *QCD* is produced by the chromodynamic dyons.

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