String Flip-Flop and Quark Matter^{*}

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8 references

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Abstract

Quarks are bound by strings attached to them. When two strings come close, a rearrangement of connections takes place. This effect plays an important role in a dense ensemble of quarks, quark matter. A phase transition from nuclear matter to quark matter occurs at the nucleon density $\rho < 5\rho_0$ where ρ_0 is the density of the ordinary nuclear matter.

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1. Introduction.

Since 1932 when the nucleons were discovered, a nucleus has been regarded as made of nucleons and possibly a few number of pions. Actually, however, nucleons and pions are composed of quarks and probably strings that bind them, and a nucleus must be looked at as an ensemble of quarks and strings. In ordinary nuclei or in normal nuclear matter, nucleons are well-separated and it is a fair approximation to regard them as a set of nucleons.

When nuclear matter is compressed, the quark wave functions of nucleons overlap and rearrangement of string connections takes place. In this case it is no longer possible to think in terms of nucleons. The system must be described by quarks and strings joining them. In the present paper this state, the quark matter state,¹ will be investigated. It turns out that phase transition from nuclear matter to quark matter takes place at a density less than five times the density of normal nuclear matter.

The Yukawa potential, the one-pion-exchange potential, is no longer applicable in quark matter. Instead, the reconnection of strings, the string flip-flop, acts as an agent to bind the multiquark system. Thus there will be (metastable) quark matter: a dibaryon resonance is an example. This mechanism is also responsible for exotic states like dimeson resonances.

In the following section, § 2, we summarize the interaction of quarks and strings. In § 4 we investigate the quark matter state, and the string flip-flop interaction will be discussed in § 5.

2. Quarks and Strings.

From the linearity of Regge trajectories we conclude that the potential energy acting on a quark is linear in the distance r . As the origin of this linear potential, we assume strings attached to quarks.² An example of such string is provided by a flux of magnetic lines of force in a type II superconductor, which forms a string of constant line density. In QCD, color is a source of lines of force and lines emitted from a color end on its complementary color. Red, blue and green form a colorless system, so lines of force close in this three quark system.

The vacuum in QCD is a superstate and squeezes the lines to form strings. From a colored system a string or strings must extend to somewhere. Only a colorless group of quarks can form a closed system disconnected from others. Strings are formed so that the length of strings is as short as possible. Accordingly the string of a R-B-G system is Y-shaped, with two strings making an angle 120° each, if the three quarks are placed in a sharp triangle. Here we are fixing the position of quarks, i.e., we are considering adiabatic potential. Although this is not a good approximation for ordinary quarks which have a small rest mass, we shall see later that quarks have an effective mass and the velocity is not extremely relativistic.

Regarding the thickness of the string, following facts are noted: In a nucleon the string potential dominates over the one-gluon-exchange potential (see the end of this section), so the strings are certainly there. On the other hand, in the pion which is much smaller than the proton strings are not noticeable. This is reflected in the very small mass of the pion which implies that here the attractive gluon potential is the dominant one. A string loses its meaning at the dimension of the pion size. We conclude that the

diameter of the string is of the order of pion size, which is, from the observed electromagnetic form factor,

$$d \text{ string} \approx 0.4 \text{ fm.}$$

For interquark distance less than this value, not the string potential but the normal one-gluon-exchange potential must be used.

So far strings were treated classically. There are two-quantum mechanical effects that are important to us:

1) Tearing of string.

A stretched string is torn, i.e., it makes a transition to a state of a meson and string. This is an emission of a meson and is described by the Yukawa interaction.

Figure 1.

2) Flip-flop of strings.

Strings can make a transition to another configuration provided the latter is a possible one consistent with the color condition. This is a kind of tunneling effect: the strings stretch themselves, violating the energy conservation, and when they touch each other, they switch to the other configuration (Fig. 2). As we shall see in § 5, the transition amplitude is proportional to

Figure 2.

$$T \propto e^{-a' A},$$

where A is the area the strings have to sweep in making this transition.

T is not large so the mixture of ψ_2 in ψ_1 , which is given by

$$\frac{T}{E_1 - E_2},$$

is in general small. However, when E_2 becomes equal to E_1 , a resonance takes place and the state is a mixture of equal amount of ψ_1 and ψ_2 , irrespective of the magnitude of T . After passing the resonance and E_2 becomes less than E_1 , the state turns to ψ_2 . As a result, for a given configuration, strings are formed so that the total length of the strings is the minimum,

$$V_{\text{str}} = a_{\text{min}} \sum r_i, \quad (1)$$

subject to the color condition that any colored system must be attached to a string and must not be left disconnected. The potential energy is not a simple sum of two-body or three-body potentials: it depends on the configuration of all quarks.

Up to now quarks were held fixed. If they are allowed to move, eq. (1) is not a correct expression of the potential energy. The confining potential must be a Lorentz scalar rather than the fourth component of a vector. To see this let us consider a simple case, the individual particle approximation. The Y-shaped string is very suitable for this, since the center of the Y is almost equal to the center of gravity. The Hartree potential is (almost) a linear one proportional to the distance from the center to the quark. The total energy is the sum of individual energy:

$$H^{(1)} = \alpha p + V, \quad (2)$$

$$E_{\text{tot}} = \sum E_i^{(1)}. \quad (3)$$

In eq. (2) the rest mass of the ordinary quark is neglected. The equation (3) does not hold if the one-gluon-exchange force between quarks is not negligible.

If the potential is of vector type, the single-body equation is

$$(\alpha p + ar) \psi = E \psi,$$

which gives

$$p^2 \psi = (E - ar)^2 \psi \approx a^2 r^2 \psi, \quad r \rightarrow \infty$$

The wave is traveling with real momentum at $r \rightarrow \infty$, so no bound state exists in this case.³ On the contrary, if the potential is a scalar,

$$(\alpha p + ar\beta) \psi = E \psi, \quad (4)$$

gives second order equation

$$(p^2 + a^2 r^2 + \{\alpha p, ar\beta\}) \psi = E^2 \psi.$$

This is of harmonic oscillator type and certainly gives bound states. The rising potential must be a scalar in order to produce bound states.

Another nice feature of the scalar type potential is the magnetic moment. From eq. (4), we have for the electromagnetic interaction,

$$\{\psi^*(\alpha A)\psi\} = \{\psi^*(\frac{p}{E}A + \frac{\sigma B}{2E})\psi\},$$

where A and B are the vector potential and magnetic field, respectively. This shows that a quark with charge $Q_q e$ has a magnetic moment $Q_q e/2E$.⁴

For the proton, eq. (3) gives $E = M_p/3$, and the quark magnetic moment is

$$\mu_q = Q_q \cdot 3 \cdot \frac{e}{2M_p},$$

which is the amount needed for the nucleon magnetic moments.

The conclusion is that in the nucleon the string potential dominates and it is a Lorentz scalar. The potential energy of a multiquark system, in a Hartree approximation, is given by

$$V = a \min \sum r_i \beta^{(i)} \quad (5)$$

where r_i is the distance from the center. The value of the constant a is taken as $0.15 \sim 0.2$ in meson spectroscopy.⁵ We shall see that in a single particle approximation we are taking, $a = 0.1$ is the correct choice.

3. Multinucleon System.

Consider two nucleons, each having an extension of the order $r_p = 0.8$ fm.

I. $r_{NN} > 1.6$ fm. When the nucleon-nucleon distance r_{NN} is larger than $2 r_p$, there is no overlap of wave functions. The system can be described by two nucleons and the one-pion-exchange potential:

$$\text{System} = \sum N + V_{\text{Yukawa}}. \quad (\text{I})$$

II. $r_{NN} < 1.6$ fm. The wave functions overlap. It happens that a quark of the other nucleon is nearer to the center and string flip-flop occurs (Fig. 3).

In a more symmetrical way, transitions as given in Fig. 4 will take place. The system must be described by six quarks and the string potentials:

Figure 3.

$$\text{System} = \sum q + V_{\text{string}}. \quad (\text{II})$$

III. $r_{NN} < 0.6$ fm or $r_{qq} < 0.4$ fm. Here the string loses its meaning and the one-gluon-exchange potential prevails.

All quarks are in one bag⁶ of normal phase surrounded by the superstate vacuum:

Figure 4.

$$\text{System} = \sum q + V_{\text{normal}} \quad (\text{III})$$

In the present paper we are concerned with the intermediate region II.

4. Quark Matter.

In ordinary nuclei the nuclear density is such that $\rho_0^{-1/3} = 1.9 \text{ fm}$ and nucleons can be said to be mostly in region I. However, as it is compressed, the string flip-flop begins to be important. In a highly compressed state a quark is no longer confined to a nucleon. It can travel within the whole volume by reconnecting strings. It feels an averaged constant potential and can be treated as a free particle. The system can be described by a Fermi gas of quarks. This is called quark matter.

At low compression only ordinary quarks come in. There are six kinds, u and d each in three hues. The Fermi gas to be considered contains equal number of each kind.

$$\begin{aligned} n(u_R) &= n(u_B) = n(u_G) = n(d_R) = n(d_B) = n(d_G) \\ &= \frac{A}{2} (= n(p) = n(n)), \end{aligned} \quad (6)$$

where $n(p)$ and $n(n)$ are numbers of proton and neutron of the system when it is regarded as a nuclear matter. The Fermi momentum is given by

$$P_F = (3\pi^2 \rho)^{1/3} = \left(\frac{3\pi^2}{2} \frac{A}{V} \right)^{1/3}, \quad \rho = \frac{n}{V}, \quad (7)$$

where V is the volume of the Fermi gas. The equality $n(q) = n(N)$, eq. (6), tells us that the Fermi momentum calculated as a nuclear matter is the same as that calculated as a quark matter.

First we calculate the potential energy in the individual particle

approximation. From a center we look for the nearest, say, red quark and draw a string. Stated in the other way, a red quark searches for the nearest center ^{which can} accept it. Since centers are uniformly distributed, we take the average. When particles (centers) are uniformly distributed with a density ρ ($= A/V$), the average of the distance to the nearest particle is given by

$$\bar{r} = \Gamma\left(\frac{4}{3}\right) \left(\rho \frac{4\pi}{3}\right)^{-1/3},$$

where Γ is the gamma function. In our case, the average of the string length is

$$\begin{aligned} \bar{r} &= \Gamma\left(\frac{4}{3}\right) \left(\frac{A}{V} \frac{4\pi}{3}\right)^{-1/3} = 0.89 \left(\frac{8}{9\pi}\right)^{-1/3} P_F^{-1} \\ &= 1.36 / P_F, \quad (\text{in units GeV} = 1) \end{aligned} \quad (8)$$

The potential energy per quark is

$$\langle V \rangle_{\text{per } q} = a \bar{r} \beta = \frac{1.36 a}{P_F} \beta \equiv M(P_F) \beta.$$

The quantity multiplying β can be called the effective mass. The total energy of the quark matter is

$$E_{\text{tot}} = \sum_{|p| < P_F} \sqrt{p^2 + M^2(P_F)},$$

and the energy per quark is

$$E_{\text{per } q} = \int \sqrt{p^2 + M^2(P_F)} d^3p / \int d^3p \equiv I(P_F).$$

In the two extreme cases,

$$I(P_F) = M(P_F) = \frac{1.36 a}{P_F}, \quad P_F \ll M(P_F),$$

$$= \frac{3}{4} P_F, \quad P_F \gg M(P_F).$$

$I(P_F) = E \text{ per } q$ is plotted as a function of P_F in Figure 5. (a is taken as 0.1). It has a minimum at

$$P_F = 0.42 \text{ GeV} \equiv P_F^C, \quad (9)$$

and

$$E \text{ per } q = 0.46 \text{ GeV}, \quad (10)$$

$$\rho = 4.9 \rho_0,$$

where ρ_0 is the ordinary

nuclear matter density

(corresponding to $P_F = 0.25 \text{ GeV}$).

At this point a stable quark matter is formed. However, this matter has zero surface tension.

Indeed, the average distance $\bar{r}$,

eq. (8), which gives the potential

Figure 5.

energy of a quark, is unchanged even if the quark is near the surface or well deeply in the quark matter. Below $P_F < P_F^c$, i.e., if the volume is larger than the critical volume, the quark matter splits into pieces and finally reaches to $3q$ objects which cannot be broken further. Below the critical point, the system is an ensemble of baryons, and the minimum (9), (10) is the critical point of the phase transition

$$\sum B \text{ (baryon matter)} \leftrightarrow \sum q \text{ (quark matter)}.$$

Here we used the word baryon matter rather than nuclear matter since in a slightly compressed nuclear matter, there may be some Δ resonances beside nucleons. $P_F = 0.7$ GeV corresponds to $r_{qq} = 0.4$ fm where string loses its meaning. The phase transition takes place at a density well below that for bag formation.

5. String Flip-Flop.

We shall now give a slightly more detailed discussion of these matters. The string flip-flop causes an attractive interaction among quark and string system. If a state ψ_1 is connected to another state ψ_2 by a transition matrix element T , the energy is lowered by

$$\Delta E = \frac{E_2 - E_1}{2} - \sqrt{\left(\frac{E_2 - E_1}{2}\right)^2 + T^2}, \quad (11)$$

where E_i is the (unperturbed) energy of the state ψ_i . In the two extreme cases,

$$\begin{aligned} \Delta E &= -|T|, & E_2 - E_1 &\ll 2T, \\ &= -\frac{T^2}{E_2 - E_1}, & E_2 - E_1 &\gg 2T. \end{aligned}$$

The second expression is the second order perturbation expansion term.

Two strings acquire an attractive interaction by flip-flop. This is the interaction among quarks in region II to play a role of the Yukawa interaction in region I. The case $E_2 = E_1$ is most favorable since the energy is linear in T rather than quadratic in it. The state is said to form a resonating group structure.

Lacking the correct theory to describe quarks and strings, the flip-flop interaction should be determined phenomenologically, in a similar way as the tearing of strings is described by the Yukawa coupling. Here we take the lattice gauge theory and estimate the order of magnitude of T .

In the lattice gauge theory the Hamiltonian consists of an unperturbed term which is the string energy and an interaction term of order $1/g^4$ that creates (or annihilates) a tiny closed loop of string on a plaquette of lattice space. If one side of the plaquette (anti) coincide with the original string, the string is deformed through an area d^2 , d being the lattice constant. The whole transition is an A/d^2 - step process, where A is the area the strings sweep in making the flip-flop. The transition amplitude is therefore proportional to

$$T \propto \left(\frac{1}{g^4}\right)^{A/d^2} = e^{-a'A}, \quad a' = \frac{1}{d^2} \ln g^4.$$

This is the most important factor in T .⁷ The rest is due to quantum mechanical fluctuation and is difficult to evaluate exactly. The transition amplitude is given by

$$T = a c l e^{-a'A}, \quad c = O\left(\frac{1}{g^6}\right), \quad a' = a O\left(\frac{1}{g^2} \ln g^4\right), \quad (12)$$

where ℓ is the sum of the lengths of strings making the flip-flop and c is a small constant of the order $1/g^6$. a' is written in terms of a and g rather than the lattice constant.

One $\frac{c}{\Lambda}$ T is given we can calculate the string flip-flop energy of a quark matter. The exact evaluation is difficult and not worth pursuing since the original interaction was not defined with any precision. We shall make a rough estimate of an interaction energy between two centers separated by R . This energy corresponds to a nuclear potential between nucleons. It has a range of order $\bar{r}$ since for $R > 2\bar{r}$ there is no overlap of quark wave functions. For $R \approx \bar{r}$, a flip-flop takes place when the configuration of quarks and strings are such that $E_2 - E_1$ is not large compared with T and the area A is not large compared with $1/a'$. This gives

$$V_{cc}(R \approx \bar{r}) \approx - \frac{c^2}{aa'} \frac{1}{\bar{r}}.$$

The interaction energy per center or per nucleon is

$$E_N = \frac{1}{2} \rho_N \int V_{cc}(R) d^3R \approx - \frac{c^2}{aa'} P_F. \quad (13)$$

The interaction V_{cc} is of Wigner type which shows no saturation character and gives a positive surface tension of the quark matter. So with this interaction the quark matter is stable against separation into pieces. However, no such stable object is observed. Perhaps the binding energy (13) is not sufficient to hold a nucleon from evaporation. In the quark matter if regarded as a Fermi gas of nucleons, the top nucleon has a kinetic energy

$$K.E._N = \frac{P_F^2}{2M_p} = 0.1 \text{ GeV}, \quad (P_F = P_F^c).$$

The instability condition puts an upper limit of the constant c .

Quark matter will be formed when two nuclei collide and local high density is attained. The translational degrees of freedom is tripled by the phase transition and results in a change of some statistical properties, like the compressibility or the sound velocity.

A simplest yet nontrivial quark matter is the nucleon-nucleon resonant state formed by six quarks. Some such resonances have been observed⁸. They can be either bound states of two baryons or states of six quarks (Table I). At present it is not clear which assignment is more appropriate.

Table I

	Bound by	Binding energy	Size
Di baryon	OPEP	tens MeV	$\sim 1/m_\pi = 1.4 \text{ fm}$
Hexaquark	String f-f	$\sim 100 \text{ MeV}$	$\sim r_p = 0.8 \text{ fm}$

6. Baryons.

A baryon made of three quarks is the simplest quark matter. From eq. (10) a baryon has an energy

$$E_B = 1.44 \text{ GeV}, \quad (\text{quark matter})$$

although treating the three-body state as a Fermi gas is not reasonable.

From the Hartree equation (4), we have an energy of a baryon

$$E_B = 3 \sqrt{2.6a} = 1.53 \text{ GeV. (Hartree)} \quad (14)$$

So by an accident these two values are fairly close.

There are several corrections to the baryon energy.

1) One-gluon-exchange potential. This vanishes for a heavy quark matter due to the saturation character. For a baryon it gives an energy

$$\Delta E_g = -2 \alpha_s \langle \frac{1}{r} \rangle \approx -0.5 \alpha_s \approx -0.2 \text{ GeV}, \quad (15)$$

where α_s is the strong fine structure constant.

2) Pion-emission-reabsorption. With the (pseudovector) Yukawa coupling constant f , the self-energy of a nucleon due to pions is

$$\Delta E_\pi = -\frac{f^2}{4\pi} \frac{3}{\pi} \frac{1}{m_\pi^2} \int \frac{k^4}{k^2 + m_\pi^2} G^2(k) d^3k,$$

where $G(k)$ is the form factor of a nucleon emitting a pion. If it is taken equal to the proton electric form factor,

$$\Delta E_\pi \approx -0.2 \text{ GeV}. \quad (16)$$

Incidentally, the magnetic moment of the proton due to the pion cloud is

$$\mu_{p,\pi} = \frac{f^2}{4\pi} \frac{4}{3\pi} \frac{M_p}{m_\pi} \int \left\{ \frac{4k^4}{(k^2 + m_\pi^2)^2} - \frac{3k^2}{k^2 + m_\pi^2} \right\} G^2(k) dk = 0.05 \text{ N.M.},$$

and very small. The nucleon magnetic moments are mostly due to the quark configuration as was discussed in § 2.

Collecting eqs. (14), (15) and (16), the energy of a baryon is

$$M_B = 1.5 - 0.2 - 0.2 = 1.1 \text{ GeV.} \quad (17)$$

We have been neglecting the spin dependence of the interaction. Eq. (17) should be compared with the average of ordinary baryons, N and Δ , which is

$$\frac{2M_N + 4M_\Delta}{6} = 1.13 \text{ GeV.}$$

This justifies the choice $a = 0.1 \text{ GeV.}^2$

7. Conclusion and Discussions.

Introducing the notion of the string flip-flop which takes place when two nucleons come close, the energy of the quark matter was calculated. The phase transition from baryon (nuclear) matter to quark matter will occur at a density less than $5 \rho_0$, well before the formation of a bag. The attractive string flip-flop interaction is expected to lower this critical point.

The string flip-flop interaction acts as a major agent to hold a dense

multi-quark system. It will produce metastable quark matter, the simplest example being the dibaryon resonant state. In a similar way ^{we can think of} a quarkonium matter, that consists of high density quarks and antiquarks bound by the string flip-flop. The simplest nontrivial one is made of $qq\bar{q}\bar{q}$ making a resonating group structure as given in Figure 2. It decays into two mesons with a wide width. If the flip-flop attraction is sufficiently strong to form a stable multi-quark-antiquark system, it corresponds to the "pion condensation". For quantitative arguments, the precise form of the flip-flop interaction must be specified, either phenomenologically or from more fundamental interaction.

The form (12) suggested by the lattice gauge theory cannot be taken as it stands. When two strings are aligned on a line, the area A is zero no matter how the two are separated. This produces a long range potential of the form $1/R^n$ between hadrons in contradiction to observation. Actually the expression (12) no longer holds when the width of the area A is less than the lattice constant d . A linear term in the string length is needed in the exponent beside the term proportional to the area.

In the present paper the Hartree approximation was introduced and the problem was reduced to a single-quark problem. It is possible to evaluate the potential energy in a more exact way. However, the form of the interaction energy for two or more quark system in a relativistic theory is somewhat ambiguous.

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References

1. For earlier discussions of quark matter; D. Ivanenko and D. F. Kurdgelaidze, Indian J. Pure Appl. Phys. 7, 585 (1969); N. Itoh, Progr. Theor. Phys. 44, 291 (1970).
2. Y. Nambu, Proc. Int. Conf. Symmetry and Quark Models, Detroit, 1969 (Gordon and Breach) p. 269.
3. Sauter, Zs. f. Phys. 69, 742 (1931).
4. H. J. Lipkin and A. Tavkhelidze, Phys. Lett. 17, 331 (1965).
5. See, e.g., J. D. Jackson, C. Quigg and J. L. Rosner, Proc. 19th Int. Conf. on High Energy Phys., Tokyo, 1978, p. 391, Y. Hara, *ibid.* 825.
6. Quark matter in a bag model has been discussed by: G. Baym and S. A. Chin, Phys. Lett. 62B, 241 (1976), G. Chapline and M. Nauenberg, Nature 264, 235 (1976).
7. K. Kikkawa pointed out that the Wilson's area law can be applied to this problem.
8. For a summary and references, see Y. Hara, *loc. cit.*, p. 835.
9. The self-energy due to pions, eq. (16), may depend on the baryon spin.

Figure Captions

Figure 1: Emission of a meson from a string. Open and solid circles represent quarks and antiquarks, respectively.

Figure 2: Flip-flop of strings.

Figure 3: Flip-flop of strings of two nucleons.

Figure 4: Resonating group structure in six-quark system.

Figure 5: Energy per quark as a function of Fermi momentum P_F . The minimum is given in the figure. $P_F > 0.7$ GeV correspond to region III and the present calculation is inapplicable. $P_F = 0.25$ GeV is that of ordinary nuclear matter. Below the critical point P_F^C the system is an ensemble of baryons.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5