Instanton Model of QCD Phase Transition Bubble Walls

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Using the liquid instanton model continued into Minkowski space and modified for finite temperature, the energy momentum tensor and the surface tension for bubble walls during the QCD phase transition are derived. The resulting surface tension of bubble walls is in agreement with lattice calculations. Application to bubble collisions is discussed.

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I. INTRODUCTION

At the time $10^{-5}$ s the temperature ($T$) of the universe was approximately 300 MeV. During the time interval between $10^{-5}$-$10^{-4}$s the universe passed through the temperature $T_c \approx 150$ MeV, the critical temperature for the chiral phase transition from the quark-gluon plasma (QGP) to the hadronic phase (HP), the quark-hadron phase transition (QHT). There have been many numerical studies of the QHT. Some lattice gauge calculations indicate the the transition is weakly first order \cite{1}, which would imply bubble formation during the QHT. At the present time lattice calculations cannot determine the order of the transition \cite{2}. Recent numerical calculations in the MIT Bag model \cite{3} find a first order transition with hadronic bubbles stable for nucleation at a scale of 1 fm.

Assuming that the QHT is first-order there have been a number of studies of the bubble nucleation \cite{4} and of possible observational effects of such a phase transition. The latter include the possibility of large scale density perturbations \cite{5} and the seeding of primary magnetic fields \cite{6} that could lead to observational effects in the Cosmic Microwave Background Radiation (CMBR), or large scale galactic or extra-galactic structure.

The essential property of the bubbles needed to study the nucleation is the surface tension \cite{4,7}, $\sigma$. The most recent lattice calculations give a value of $\sigma \approx 0.015 T_c^3$ \cite{8}, while earlier studies \cite{9} find a larger value. In our present work we wish to estimate $\sigma$ from the QCD Lagrangian, with the result that we obtain the energy momentum tensor that can be used in future work on bubble collisions. For the electroweak phase transition bubble collisions have been studied and interesting estimates of magnetic fields formed during the collisions have been made \cite{10,11} using an abelian Higgs model plus the QED Lagrangian \cite{12}. However, because of the complexity of nonperturbative QCD, a reliable model of the bubble walls formed in the QHT has not been formulated. It is the goal of the present work to formulate such a model.

Since the main structure of the bubble walls must be gluonic in nature we use pure gluodynamics. Noting that the walls separate the hadronic from the quark/gluon plasma regions of the universe, it is natural to consider an instanton picture of the walls. The QCD instantons are classical solutions for the color field, which were derived in Euclidean space \cite{13,14}. They connect points in two vacua with different winding numbers. In analogy with Coleman’s model \cite{15} of regions of true and false vacua, we consider the instantons connecting vacua with different winding numbers in the quark-gluon region and the hadronic region on the opposite sides of the bubble. The Euclidean instanton model cannot be used for the treatment of bubble nucleation and collisions (in fact the energy density and surface tension vanish in this picture), but the model must be continued to Minkowski space \cite{15}. In brief, our picture is a Minkowski space analytic continuation of the instanton model for the bubble walls separating the quark/gluon from the hadronic regions during the QHT.
It is well known that the instantons of the instanton liquid model [16] can provide the essential nonperturbative gluonic effects of QCD at the medium length scale of 0.3-0.5 fm, although instantons do not provide confinement. As we show below, this seems to be the crucial length scale needed for QCD bubble walls. In recent work an effective Lagrangian was used to estimate domain wall formation possibly associated with the QCD phase transition [17]. Although the resulting domain wall is within the hadronic bubble it resembles the bubble wall that we obtain with the instanton model in the present work. That model has also been used to examine the possibility of magnetic walls formed during the QHT seeding galactic magnetic structure [18]. Also, there are recent numerical investigations of the T-dependence of the properties of the QCD instantons [20,21], which we need in the present investigation.

In Sec. II we review the instanton liquid model at T=0 and discuss the energy density and equation of motion in Minkowski space. In Sec. III we use recent lattice results for instantons at finite temperature [20] as well as our own recent work on glueballs [22] to estimate the surface tension. The surface tension is derived at time t=0, and serves as an initial condition for bubble nucleation and collisions in Minkowski space. In Sec. IV we discuss the energy momentum tensor for gluonic QCD in Minkowski space and possible applications based on the instanton model for bubble collisions and cosmological observations.

II. INSTANTON MODEL AT T=0, CONTINUATION TO MINKOWSKI SPACE, AND QCD CHIRQAL PHASE TRANSITION BUBBLES

In this section we review the instanton model of QCD at T=0, and the extension of the model to treat the bubble walls in the QCD chiral phase transition. Instantons are obtained and studied in Euclidean space. As described in early work on the application of instantons to bubble nucleation and collisions [15] in formulating the instanton bubble itself one proceeds in Euclidean space, while for the study of collisions of nucleating bubbles one must work in Minkowski space. This will be discussed further in Sec. IV.

A. T=0 Instanton Model in Minkowski Space

The Lagrangian density for pure glue is

$$\mathcal{L}^{\text{glue}} = -\frac{1}{4} G \cdot G,$$

where

$$G_{\mu\nu}^n = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu],$$

$$A_\mu = A_\mu^n \lambda^n / 2,$$

with $\lambda^n$ the eight SU(3) Gell-Mann matrices. The instantons are the classical solutions of the gauge fields for a pure SU(2) gauge theory. I.e., writing $A_\mu^n = A^{\text{inst}}_\mu^n + A^{\text{qu}}_\mu^n$, where $A^{\text{inst}}_\mu^n$ is a pure gauge classical field, if one keeps only the instanton gluonic field, and solves the equation of motion obtained by minimizing the classical action in Euclidean space

$$\delta[\int G^{\text{inst}} \cdot G^{\text{inst}}] = 0,$$

one obtains the solution [15]

$$A^{\text{inst}}_\mu^n(x) = \frac{2\eta_{\mu\nu} x^\nu}{(x^2 + \rho^2)},$$

$$G^{\text{inst}}_{\mu\nu}^n(x) = -\frac{\eta_{\mu\nu} A^2}{(x^2 + \rho^2)^2}. $$
for the instanton and a similar expression with -n for the anti-instanton, where $\rho$ is the instanton size and the $\eta^a_{\mu\nu}$, are [14]: $\eta^a_{\mu\nu} = \epsilon_{abc} \eta^c_{\mu4} = \delta_{\mu4}; \eta^a_{\mu\nu} = -\delta_{\mu\nu}$, with (a,b,c) = (1,2,3) and ($\mu, \nu$) = (1...4). The instanton connects points in two QCD vacua which differ by one unit of winding number. The instanton contribution to the Lagrangian density is

$$\frac{1}{4} G^{\text{inst}} \cdot G^{\text{inst}} = 48 \frac{\rho^4}{(x^2 + \rho^2)^4}.$$  \hspace{1cm} (5)

The energy momentum tensor, $T^{\mu\nu}$, can be obtained from the Lagrangian, and in Minkowski space is given by (see, e.g., Ref [23])

$$T^{\mu\nu} = \sum_a (G^{\mu\alpha}_a G^{\nu\alpha}_a - \frac{1}{4} g^{\mu\nu} G^{\alpha\beta}_a G_{\alpha\beta a}).$$  \hspace{1cm} (6)

To get the Euclidean space expression for the energy density, $T_{44}$, one carries out the analytic continuation giving $x^2 = x^\mu x_\mu = \vec{x}^2 + x_0^2$ in Euclidean space, while it is $\vec{x}^2 - x_0^2$ in Minkowski space. From this one see that $g_{44} = -g^{00}$. Therefore in Euclidean space the energy density in the instanton model is

$$T^{\text{inst}}_{44} = G_{a4\alpha} G_{a\alpha4} + \frac{1}{4} G_{a\alpha\beta} G_{a\alpha\beta} = 0.$$  \hspace{1cm} (7)

The result shown in Eq.(7) follows from Eq.(4) and the properties of the $\eta^a_{\mu\nu}$ given in Ref [14].

For the nucleation of QCD bubbles and for bubble collisions one must work in Minkowski space. From Eqs.(6,4) one finds for the energy density in Minkowski space

$$T_{\text{inst}}^{00} = \frac{1}{2} G^{\text{inst}} \cdot G^{\text{inst}}$$

$$= 96 \frac{\rho^4}{(x^2 + \rho^2)^4}.$$  \hspace{1cm} (8)

Eq.(8) gives the energy density for an instanton. To complete the instanton model for $T^{00}$ one must find the instanton density, $n$, for the particular system in question. Evaluation of the instanton density is reviewed for both $T=0$ and finite $T$ in Ref [16]. In the instanton model the density is easily evaluated in terms of the gluon condensate, which is proportional to the vacuum matrix element $<G \cdot G>$. Thus the instanton value for $n$, $n(\text{inst})$, is given by

$$n(\text{inst}) = \frac{<G \cdot G>}{\int d^4x G^{\text{inst}} \cdot G^{\text{inst}}}.$$  \hspace{1cm} (9)

From Eq.(8) and the phenomenological value for the quark constant $<G \cdot G> \simeq 1.0 GeV^4$, one finds that

$$n(\text{inst}) \simeq 1.0 fm^{-4}.$$  \hspace{1cm} (10)

This value is consistent with that determined by the tunneling amplitude [14,16]. Another evaluation of $n$ can be obtained from the QCD sum rule evaluation of scalar glueballs. Since the correlator for scalar glueballs is given by the Fourier transform of $<G(x) \cdot G(x') G(0) \cdot G(0)>$, the pole term in the dispersion relation for the correlator has a factor of $n$. By comparing to the 1.5 GeV candidate for a scalar glueball, the best fits were found [22] for values up to about twice the instanton value. Also, some lattice calculations [20] have found larger values.

To evaluate the surface tension of the bubble walls we must also consider instantons at finite temperature during bubble nucleation, which we do in the next section.
B. QCD Chiral Phase Transition Bubble Walls

The equations of motion for pure glue QCD are obtained from the Lagrangian given by Eq.(1). Using
\[ \delta \int G \cdot G = 0, \]
(11)
and working in a SU(2) version of QCD, with \( A_\mu = A_a^a \sigma^a / 2 \), \( \sigma^a \) being the Pauli spin matrices, and \([A_\mu, A_\nu] = i \epsilon^{abc} A_b^a A_c^\nu \sigma^a / 2\), the equations of motion are
\[ \partial_\mu \partial_\mu A_a^\nu + g \epsilon^{abc} (2 A_b^a \partial_\mu A_c^\nu - A_b^a \partial_\nu A_c^\mu) + g^2 \epsilon^{abc} \epsilon^{eef} A_b^a A_c^e A_f^\nu = 0. \]
(12)
Recognizing that the instanton form of Eq.(11) is a classical solution to these equations of motion, we try the form
\[ A_{\mu, \text{inst}}^a (x) = 2 \eta^{-a} x^\nu F(x^2), \]
(13)
and substituting in Eq.(12) find that \( F(x^2) \) satisfies
\[ \partial^2 F = -4 \frac{\partial F}{\partial x^2} - 12 F^2 + 8 x^2 F^3 \]
(14)
in the Lorentz gauge, with the gauge condition \( \partial_\mu A_\mu^a = 0 \). By using the initial condition
\[ F(x, t = 0) = \frac{1}{(x^2 - \bar{x}_0)^2 + \rho^2}, \]
(15)
one finds that the instanton form is indeed an approximate solution. This is discussed further in Section IV, where collisions of QCD bubbles are discussed.

From the phenomenological applications the instanton liquid model was developed, with \( \rho = 0.33 \) fm.

This gives the thickness of the instanton wall at temperature \( T=0 \). To complete our model we need the instanton density at \( T=T_c \), as well as the value of the instanton size at that temperature. This is discussed in the next section.

III. BUBBLE WALL SURFACE TENSION

In this section we evaluate the surface tension in the instanton model. In order to do this we must consider the dependence of the instanton size and density on the temperature. We start with calculating the surface tension for an instanton wall.

The surface tension is the essential parameter for classical bubble nucleation. For the treatment of nucleation one must work in Minkowski space. As discussed in detail in Ref. \[ \text{Ref.} \]
to treat nucleation and collisions with instanton input one makes an analytic continuation from Euclidean to Minkowski space at the initial time, \( t=0 \). For our problem this is achieved by replacing \( t \) by it, or in Minkowski space \( x_\mu x^\mu = \bar{x}^2 - t^2 \). In the present section we study the surface tension at \( t=0 \); and the energy density in Minkowski space derived in the previous section from the instanton solutions can be used for the derivation of the surface tension. The results at \( t=0 \) which we find will serve as part of the initial conditions for the study of nucleation and collisions, as discussed in Sec. IV.

The surface energy is the surface tension \( \times \) the area of the wall for a thin wall. Note that the wall thickness is of the order of \( \rho \), the instanton size, which is a fraction of a fermi, so that a thin-wall formalism is appropriate. Therefore the surface tension with one instanton at \( t=0 \) is
\[ \sigma^{\text{inst}} = \int dx T^{00,\text{inst}}(x, 0, 0) \]
\[ = \int dx \frac{1}{2} \mathbf{G} \cdot \mathbf{G}. \]  
(16)

From Eqs.(5,16)

\[ \sigma^{\text{inst}} = 3 \cdot 2^5 \int dx \frac{\rho^4}{(x^2 + \rho^2)^4} \]
\[ = 6 \cdot 2^5 \frac{5! \pi}{6! \rho^3}. \]  
(17)

In order to complete our model, we must work with instantons at the temperature \( T = T_c \), which means using a modified instanton size and density. Moreover, since we are dealing with a gluonic wall separating the two phases, the QGP and the HP, the number density is quite different from the result given in Eqs.(9,10) for the \( T=0 \) system. We use the model applied for the lattice calculations [8], and described in detail in Ref. [9]. In this picture the free energy is calculated using two peaks for the two phases on the two sides of the bubble, separated by a mixed quark/gluon-hadronic phase. There will be a factor of the instanton number density, i.e., the instanton density times the effective four-volume, for each peak. Therefore, from from Eq.(17) the resulting surface tension in our instanton model is

\[ \sigma = 6 \cdot 5 \frac{\pi \overline{N}^2}{\overline{\rho}^3}, \]  
(18)

where \( \overline{N} \) is the instanton number density at the surface and \( \overline{\rho} \) is the instanton size at \( T = T_c \). We obtain \( \overline{N} \) from the \( T = 0 \) instanton number per four-volume, \( n = (N/V) \) of Eq.(1). Defining \( n = \overline{\pi} \text{ GeV}^4 \) at finite \( T \) and using \( V=\overline{\rho}^4, \overline{N}^2 = 5.96 \pi^2 \), where we use \( \overline{\rho} = 0.25 \text{ fm} \), as discussed next.

At \( T=0 \) \( \rho = 0.33 \text{ fm} \) in the liquid instanton model [16]. This has also been found in lattice calculations [24]. There have been a number of numerical investigations on the modification of the instanton system at finite \( T \). Based on these calculation [20,21] we take \( \overline{\rho} = 0.25 \text{ fm} \). There is uncertainty in the value of the instanton density, \( n \), at \( T=0 \). In our work on scalar mesons/glueballs [22] we found values of \( \overline{\pi} = 0.0008-0.0015 \), with 0.0008 used in the instanton liquid model. These values also cover the range of values of lattice gauge calculations over the past decade. From the results of the finite \( T \) calculations the \( n \) seems to decrease by about a factor of 2 at \( T_c \), so we use the range \( \overline{\pi} = 0.0004-0.00075 \). This gives us the result

\[ \sigma = (0.013 \rightarrow 0.046) T_c^3, \]  
(19)

compared to the value \( \sigma = 0.015 T_c^3 \) in the most recent lattice calculation [8]. We note that the instanton liquid model of the QCD bubble wall gives a value \( \sigma = 0.013 T_c^3 \) in very good agreement with the lattice calculation, and that our model for the bubble wall is quite promising.

IV. DISCUSSION OF APPLICATIONS TO COLLISIONS

Although the knowledge of the surface tension is essential for studying the nucleation and collisions of bubbles during the QCD chiral phase transition, there is no observable directly related to these bubbles, so the challenge is to find observable effects related to these bubbles. In our recent work we have investigated the possibility of a magnetic walls being formed by interactions of hadrons with an internal gluon instanton wall which might be formed within the hadronic phase during the QCD chiral phase transition. In this section we discuss this possibility and the relationship to the wall surface tension that has been derived above.
As was discussed in Sec. II the instanton model itself describes a static bubble. For the study of bubble nucleation and collisions one works in Minkowski space. Starting from the instanton Lagrangian and using standard field theory methods one obtains the color $E$ and $B$ fields,

\begin{align*}
E_n^i &= G_n^i \\
B_n^i &= -\frac{1}{2} \epsilon^{ijk} G_n^j,
\end{align*}

(20)

with the i,j,k indices running 1,2,3. From this the energy-momentum tensor, $T$ for an instanton in Minkowski space is given as

\begin{align*}
T_{00,\text{inst}} &= \frac{1}{2} (E_n \cdot E_n + B_n \cdot B_n) \\
T_{0i,\text{inst}} &= \epsilon^{ijk} E_n^j B_n^k \\
T_{ij,\text{inst}} &= (E_n^i E_n^j + B_n^i B_n^j) - T_{00,\text{inst}} \delta_{ij}
\end{align*}

(21)

(22)

(23)

From the results of Sec. II and with a straightforward calculation we obtain for the stress energy tensor in the instanton model from Eq.(23)

\begin{align*}
T_{ij,\text{inst}} &= -\left( \frac{4\rho^2}{(x^2 + \rho^2)^2} \right)^2 \delta_{ij}.
\end{align*}

(24)

To obtain the color $E$ and $B$ fields one must solve the QCD equations of motion. Solutions to the equations of motion with an effective Lagrangian have been found for a pure SU(2) gauge theory in Minkowski space [26]. Using the general picture of Coleman [15] in which one sets the instanton initial conditions at time $t=0$ and then uses the equations of motion in Minkowski space for the evolution, a SU(2) model of QCD instantons has been developed and applied to heavy relativistic heavy ion collisions [27].

We are developing a similar program for our cosmological studies of the QCD chiral phase transition in the early universe based on QCD field theory. During the collision of two bubbles the colliding walls might form an internal wall within the merged bubbles. In classical nucleation theory when two identical bubbles collide they merge to form a bubble with the same surface tension as the original bubble walls. In our case the result would be instanton walls described in the previous sections. Note that in Ref. [17] an estimate of the lifetime of the gluonic domain walls in their model was $10^{-5}$s, which allows magnetic walls to be formed [18]. Although the present theory is quite different, a two-dimensional model of bubble collisions starting from the gluonic QCD Lagrangian finds that an internal gluonic wall is formed [28], and this suggests that magnetic structures could form. Using the standard evolution methods as used for tangled magnetic fields for the scattering [25], or for metric perturbations [29] one can investigate possible observational effects in the CMBR. A preliminary investigation of this has been carried out [19] assuming the interior instanton wall is formed, which is shown to lead to an interior magnetic wall, and CMBR polarization correlations are found that could be observed in the next few years.

The crucial question is whether an internal wall is formed with the properties of the nucleating QCD bubbles. In a 1+1 dimensional study in pure QCD, the equations of motion of Eq.(14) were solved. This corresponds physically to very large bubbles colliding, as illustrated in Fig.1.
Fig. 1  QCD bubble walls colliding

To model collisions one takes an initial condition with two walls, such as

$$F(x, t = 0) = \frac{1}{(x - x_0)^2 + \rho^2} + \frac{1}{(x + x_0)^2 + \rho^2},$$

with $2x_0$ the separation between the two bubble walls at time $t=0$, and follows the evolution. In Ref [28] it was found that an interior wall is indeed formed, which seems to be similar to the initial walls. Fig.1 illustrates the process at the instant when the walls are overlapping, and the calculation shows the two bubbles separating with an internal instanton-like structure remaining at the collision region. From this one would conclude that the interior wall would have approximately the same surface tension as discussed in the previous sections, and could result in the magnetic wall of Ref [19]. Moreover, the studies of the QCD chiral phase transition [4,5] find that in contrast to the electroweak phase transition where many bubbles nucleate, the QCD chiral phase transition seems to proceed via inhomogeneous nucleation, with larger distance between bubbles and few nucleating bubbles involved in the transition to the hadronic phase. Thus the large bubble collision of Fig.1 and Ref [28] is well-founded.

To investigate the nucleation and collision of bubbles during the QCD chiral phase transition one must include quark and hadronic degrees of freedom, since they play a major role in the free energy difference between the hadronic and quark/gluon phases. With Eq.(12), however, one can learn a great deal about the bubble walls, and our results for the surface tension in the present paper are quite promising. The full 3+1 dimensional treatment of nucleating QCD bubbles is a subject of future research.

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