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A new mechanism of formation of topological defects

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Abstract. In this talk we discuss a new mechanism of formation of topological defects due to enhanced magnitude oscillations of a complex scalar order-parameter (OP) field during bubble collisions in a first order phase transition.

Keywords. Phase transitions; topological defects.

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1. Introduction

Topological defects such as cosmic strings and textures are believed to play a very important role in structure formation in the early Universe; on the other hand, topological defects such as monopoles which are believed to be produced in copious amounts during GUT phase transitions, are in conflict with observation and some mechanism such as inflation must be invoked to get rid of these defects [1]. Cosmic strings have also been used to generate the observed baryon asymmetry of the Universe in certain models of Baryogenesis. In view of their important cosmological consequences, it is necessary to understand the various mechanisms by which these defects can be formed.

The plan of the talk is as follows. We first discuss the physical picture of the new mechanism (which we call the '*flipping*' mechanism) and then discuss the results of numerical simulations in (2+1) dimensions [2]. This work was done in collaboration with S Digal and A M Srivastava.

2. The Kibble mechanism of topological defect formation

Conventionally, formation of topological defects is thought to occur either via thermal fluctuations or via the so-called 'Kibble mechanism' which has been described in detail in the talk by Rajarshi Ray in this conference.

An important aspect of Kibble mechanism is that the dynamics of the field does not play an important role in the determination of the probability of defect per domain. We now describe a new mechanism where the dynamics of fields plays a very crucial role in defect formation.

3. Physical picture of the new mechanism and results of numerical simulations

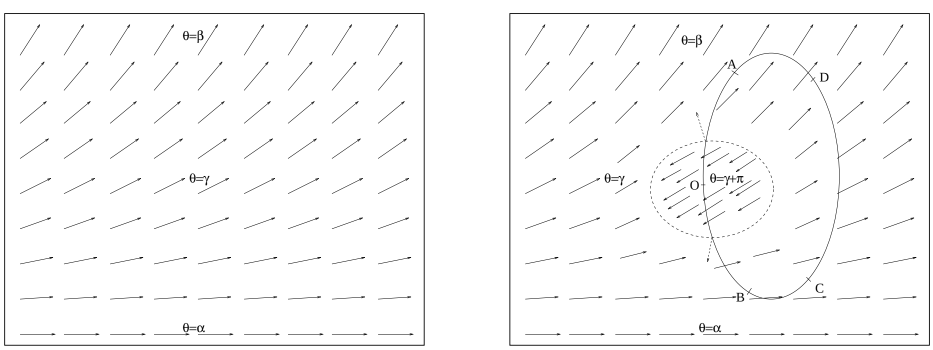
The mechanism of flipping can be easily understood from the two figures shown below. Figure 1a shows a region of physical space with spatially varying OP field Φ. The length of the arrow indicates the field *magnitude* while the direction (measured w.r.t. the X-axis) indicates the *phase* of the OP field Φ with the phase varying from $\theta = \alpha$ to $\theta = \beta$ as shown. Now suppose large magnitude oscillation of the OP field leads to flipping of the field in the central region(within the dotted loop) causing Φ to pass once through $\Phi = 0$; as shown in figure 1b. (Large magnitude oscillations can arise during highly energetic collision of bubbles during a first order phase transition and also during a *quench* form very high temperatures.) It is clear that when Φ passes through 0, it amounts to discontinuous change in θ by π, as shown in figure 1b. We call it the flipping of Φ. (For simplicity, we take θ to be uniform inside the flipped region.) Now consider the variation of θ along the closed path AOBCD (shown by the solid curve in figure 1b). On moving along this solid curve, we take θ to vary smoothly (as shown by the dotted arrows) as we cross the dotted curve. It is then easy to see that θ winds by 2π as we go around this closed path implying that a vortex has formed inside it. Similarly, we can conclude that an antivortex has formed in the other half of this region.

One can easily generalize this picture for the formation of other defects such as monopoles and textures [2].

We now describe the results of numerical simulation of vortex formation (in 2+1 dimensions) in a system having a global $U(1)$ symmetry and undergoing a first order phase transition. The model Lagrangian which describes the system in which the global $U(1)$ symmetry is spontaneously broken (expressed in terms of a dimensionless field Φ and appropriately scaled coordinates) is

$$\mathcal{L} = (1/2)(\partial_\mu \Phi^\dagger)(\partial^\mu \Phi) - (1/4)\phi^2(\phi - 1)^2 + \epsilon\phi^3 \tag{1}$$

where $\Phi = \phi_1 + i\phi_2$.



(a) (b)

Figure 1. (**a**) A region of space with θ varying uniformly from α at the bottom to some value β at the top. (**b**) Flipping of Φ in the center (enclosed by the dotted loop) has changed $\theta = \gamma$ to $\theta = \gamma + \pi$ resulting in a pair production.

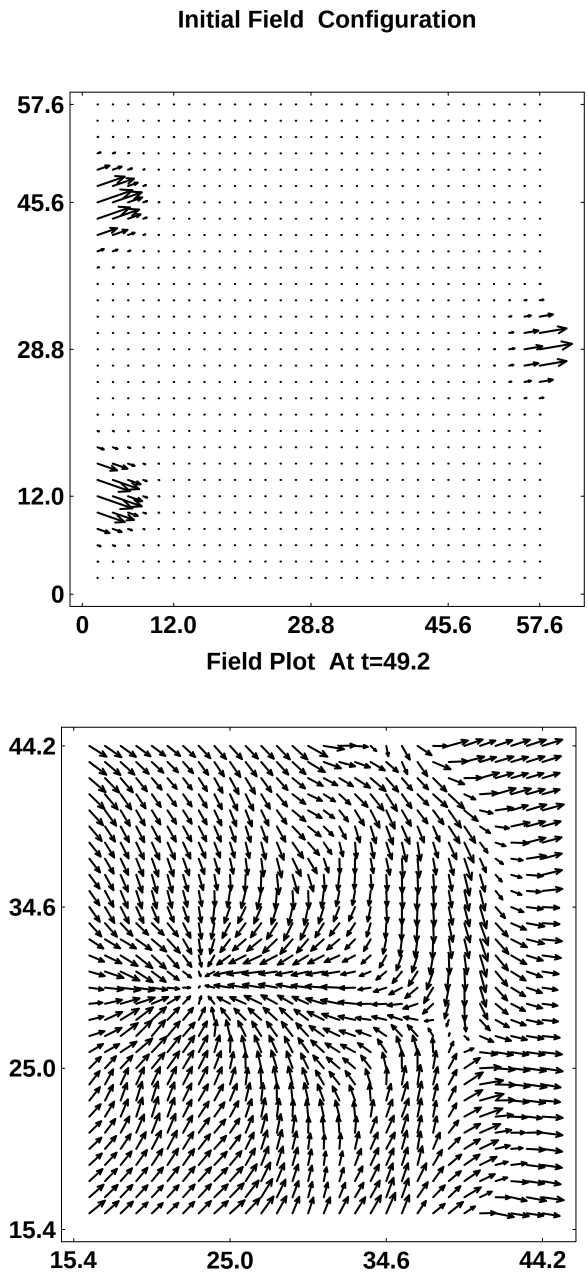


Figure 2. (**a**) Initial field configuration. (**b**) Field configuration at $t = 49.2$ showing a vortex-antivortex pair.

This is the form of the Lagrangian used in our numerical simulations. Note that the presence of the cubic term in ϕ indicates that the phase transition (in this case ocurring at zero temperature) is of *first order*. There exists a local minimum of the potential at $\phi = 0$ and phase transition occurs because of tunneling of the field (originally trapped in the local minimum due to supercooling) from the false vacuum (local minimum) to true vacuum (global minimum). The tunneling process manifests itself through nucleation of bubbles of true vacuum in a false vacuum background. If the nucleated bubbles are greater than some critical radius, then it is energetically favourable for them to grow. The growing bubbles ultimately coalesce and phase transition is complete when the fraction of volume in true vacuum approaches unity.

As discussed earlier, flipping of the OP field can occur during higly energetic bubble collisions. Bubbles grow by converting false vacuum to true vacuum. During the process of bubble growth, the energy difference between false and true vacuum is converted to the kinetic energy of the bubble walls. When the bubbles collide, this kinetic energy is dissipated into magnitude oscillations and phase waves. The conditions necessary for sufficiently energetic field oscillations leading to flipping of Φ and formation of a vortex-antivortex pair are:

1. Large initial bubble separation.
2. Region of spatially varying phase.
3. Small phase difference between the colliding bubbles.

Figure 2a shows the initial field configuration containing 3 half-bubbles with phases as indicated. Note, that the choice of phases are such that *no* vortices can form via Kibble mechanism. Figure 2b shows the field configuration at some later time after bubble collision. One can clearly see that the field in the central region (region in between the colliding bubbles) has ‘flipped’ leading to the formation of a vortex-antivortex pair.

To ascertain the relative importance of the flipping mechanism it is necessary to simulate a realistic phase transition in which bubbles are *randomly* nucleated with *random choice of phases* inside them. Results of such simulations show that due to the requirement of strong field oscillations,

1. Formation of vortices by flipping mechanism is suppressed for large bubble nucleation rate. We found that for very small nucleation rates, this mechanism is the most dominant.
2. Damping suppresses this mode of defect formation by suppressing field oscillations.

We have also studied defect formation in systems where the symmetry is spontaneously as well as *explicitly* broken. In that case, the flipping mechanism is the dominant mode of vortex formation [3].

In conclusion we have demonstrated a novel mechanism of topological defect formation in which field oscillations brought about by bubble collisions may lead to flipping of the field resulting in the formation of a vortex-antivortex pair. This mechanism of defect formation should also be valid in second order transitions brought about by *quenching* the system from very high temperatures. This mechanism is also applicable to formation of other defects such as monopoles and textures.

References

[1] A Vilenkin and E P S Shellard, *Cosmic strings and other topological defects* (Cambridge University Press, Cambridge, 1994)
[2] S Digal, S Sengupta and A M Srivastava, *Phys. Rev.* **D55**, 3824 (1997); *Phys. Rev.* **D56**, 2035 (1997)
[3] S Digal and A M Srivastava, *Phys. Rev. Lett.* **76**, 583 (1996); *Phys. Rev.* **D58**, 103510 (1998)