Physica C 479 (2012) 15–18

Contents lists available at SciVerse ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

The effect of pinning on vortex states with attractive and repulsive interactions

C. Reichhardt, J. Drocco, C.J. Olson Reichhardt *, A.R. Bishop

Center for Nonlinear Studies and Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

ARTICLE INFO

Article history:
Accepted 27 December 2011
Available online 5 January 2012

Keywords:
Superconducting vortex
Pinning
Clumps

ABSTRACT

Recently there has been renewed interest in understanding vortex patterns in superconductors and Bose–Einstein condensates, where the repulsive vortex–vortex interactions have an additional intermediate or long range attractive component. These states can arise in low-κ materials and may occur in multi-band superconductors. A combination of repulsive and attractive pairwise interactions can also occur in certain types of Bose–Einstein condensates and in magnetic superconductors. We show that when the pairwise interaction includes a long range attractive term, the ground state consists of a single vortex cluster. In the presence of pinning there is a well defined transition to a fragmented state as a function of pinning strength and density. We also demonstrate that in systems with intermediate range attraction and long range repulsion, ordered stripe and bubble phases occur.

1. Introduction

A rich variety of patterns can arise in systems where collections of particles interact with competing repulsive and attractive interactions. These patterns include stripes, clumps, bubbles, and novel crystal phases [1]. In general vortices in superconductors predominantly interact only via a repulsive force and form a triangular lattice in the absence of pinning; however, there are a variety of systems in which the vortex interactions can have an additional attractive component [2–14]. The effects of these more complex vortex interactions have recently gained renewed attention after experiments in MgB_2 revealed evidence of vortex cluster states that can be interpreted as forming due to additional attractive vortex interactions [15]. The modified vortex attraction was proposed to arise due to the fact that MgB_2 is a two-band superconductor containing one type-II band and one type-I band. This interpretation has been strongly challenged since longer range attraction between vortices can also arise in single band superconductors and calculations show that two-band systems have a single order parameter [2,11]. Calculations using an extended Ginsburg–Landau formalism for two-band superconductors indicate that the condensate can exhibit two different length scales leading to non-monotonic vortex interactions [11,12]. Even for strictly repulsive vortex interactions, pattern formation is still possible if two distinct length scales appear in the interaction potential. This has been demonstrated in studies of other pattern forming systems, where stripe or clump type patterns can arise in general for potentials with two length scales even if there is no attractive component in the interaction [16]. Attractive vortex interactions are known to arise in low κ superconductors [2] and it is also possible to engineer vortex systems with short range repulsion and long range attraction by creating hybrid samples in which a type-I superconductor is layered with a type-II superconductor [6]. Attraction between vortices may arise in magnetic superconductors, where the attraction is mediated by the underlying magnetic substrate [8]. There are also observations in certain superconductors that may have exotic order parameters, where some form of attraction between the vortices appears to be present, leading to a coalescence of vortices [7]. For vortex matter in Bose–Einstein condensates, there are predictions that in certain regimes the vortices will have non-monotonic interactions [17].

In addition to vortices, many other condensed matter systems have a combination of attractive and repulsive interactions between particles, such as electrons at certain fillings in the quantum Hall state [18], colloidal assemblies [19], and stripes in high-temperature superconductors [20]. In spite of the large number of systems in which competing interactions between particles can arise, there is very little understanding of what effects quenched disorder would have on such states. Vortices in the presence of quenched disorder may be an ideal system in which to study this issue, since tailored pinning arrays can be readily fabricated and have been well studied in systems with monotonic, strictly repulsive vortex interactions [21–26]. In this work we study a model for vortices with an intermediate range repulsion and a long range attraction inspired by the recent imaging experiments of Ref. [15]. We show that for long annealing times, a single vortex cluster is the generic ground state, while for short annealing times or fast quenches the system forms metastable fragmented bubble like states. We then add a periodic array of pinning sites and show that at a well defined pinning strength, the vortex configuration changes from a single clump to a fragmented state of smaller clumps. We also demonstrate that

* Corresponding author.
E-mail address: cjrx@lanl.gov (C.J. Olson Reichhardt).

0921-4534/$ - see front matter
doi:10.1016/j.physc.2011.12.029

ordered stripes and clump crystals can be stabilized if a longer range repulsion is added to the attractive part of the interaction. In this case, the presence of strong pinning causes the clusters or stripes to gradually break up into smaller fragments; however, under an applied external drive, the size of the clumps or stripes grows when the effectiveness of the pinning is reduced in the moving state. Our results suggest that vortex matter with competing interactions represents an outstanding system in which to address many issues of pattern formation that are of general interest for systems with competing interactions.

2. Simulation

We consider a two-dimensional system of N_v vortices. The dynamics of vortex i arise from integrating the following overdamped equation of motion

$$\eta \frac{d\mathbf{R}_i}{dt} = \mathbf{F}_i^{vv} + \mathbf{F}_i^{p} + \mathbf{F}^{T}. \tag{1}$$

Here η is the damping constant and $\mathbf{R}_i$ is the position of vortex i. In previous studies of purely repulsive vortices we used the vortex–vortex interaction force $\mathbf{F}_i^{vv} = \sum_{i \neq j}^{N_v} f_0 K_1(R_{ij}/\lambda)\widehat{\mathbf{R}}_{ij}$, where $K_1(r)$ is the modified Bessel function, $f_0 = \phi_0^2/2\pi\mu_0\lambda^3$, ϕ_0 is the flux quantum, λ is the London penetration depth, $R_{ij} = |\mathbf{R}_i - \mathbf{R}_j|$, and $\widehat{\mathbf{R}}_{ij} = (\mathbf{R}_i - \mathbf{R}_j)/R_{ij}$ [22,23]. In this work we consider the recently proposed non-monotonic vortex–vortex interaction force [27] $\mathbf{F}_{ij}^{vv} = (aK_1(bR_{ij}/\lambda) - K_1(R_{ij}/\lambda))\widehat{\mathbf{R}}_{ij}$, where a and b are positive constants that determine the magnitude of the interaction. Here there is both a repulsive and an attractive term. We consider $a > b$ and $b > 1.0$, corresponding to the repulsive core and attractive tail predicted to occur in certain vortex systems. We use $a = K_1(r_c)/K_1(br_c)$ with $r_c = 2.1$ and take $b = 1.1$ as in [27]. We cut off the exponentially decaying interaction for $R_{ij} > 8\lambda$. The pinning force $\mathbf{F}_i^p$ arises from attractive short range parabolic pinning sites, as modeled previously [24,25], with radius $r_p = 0.6\lambda$ and a maximum pinning force of F_p. Here we consider a square arrangement of pinning sites which can be readily experimentally realized. The term $\mathbf{F}^T$ represents a thermal force with the following properties: $\left\langle F_i^T(t) \right\rangle = 0.0$ and $\left\langle F_i^T(t) F_i^T(t') \right\rangle = 2\eta k_B T \delta_{ij}\delta(t - t')$. We also consider a phenomenological model for the pairwise interactions as in [28], where the particles have a long range repulsion and a short range attraction. We compare the resulting patterns to those obtained in the system with long range attraction.

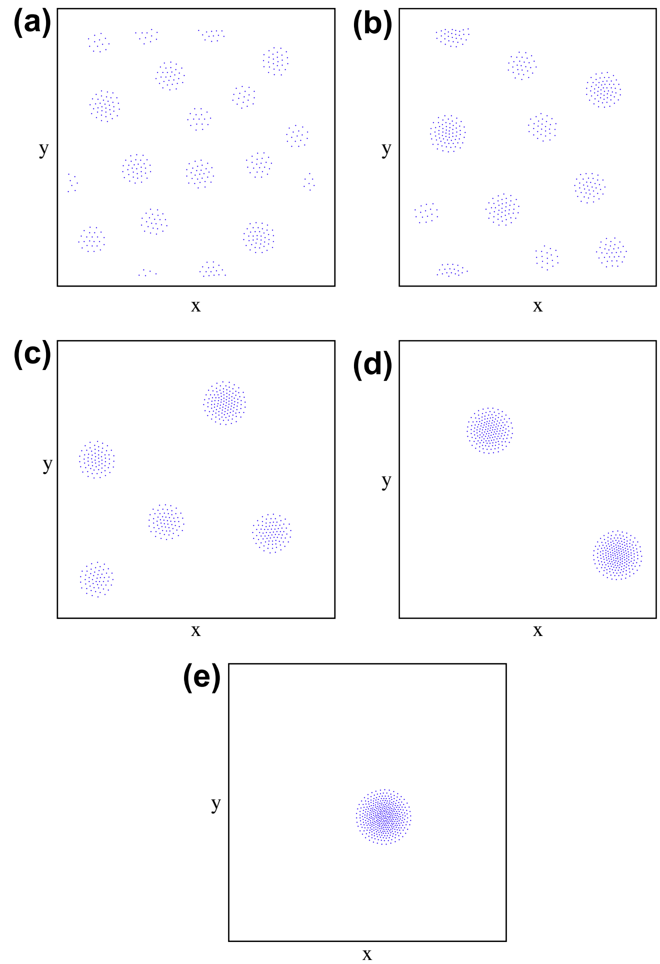

Fig. 1. Vortex positions (dots) for a $64\lambda \times 64\lambda$ sample with short range repulsion and longer range attraction after the system is quenched from an initially triangular lattice. The vortex density is $n_v = 0.083\phi_0/\lambda^2$. The temperature is lowered from $F^T = 2.3$ in increments of $\delta F^T = 0.005$ to $F^T = 0.0$. We spend δt simulation time steps at each temperature increment. (a) In an instantaneous quench with $\delta t = 1$, separate clumps form with different numbers of particles in each clump. (b) For $\delta t = 500$ there are fewer, larger clumps. (c) At $\delta\ t = 25{,}000$ even fewer clumps appear. (d) There are only two clumps for $\delta t = 250{,}000$. (e) At $\delta t = 1{,}000{,}000$, all the vortices condense into a single large circular clump. For $\delta t > 1{,}000{,}000$, only a single clump forms.

3. Configurations for varied quench times

We consider a vortex density of $n_v = 0.083\phi_0/\lambda^2$. We place the vortices in a triangular lattice at a temperature of $F^T = 2.3$ and cool to $F^T = 0.0$ in increments of $\delta F^T = 0.005$. We spend δt simulation time steps at each temperature increment. Fig. 1a shows the final configuration for a sample with an instantaneous quench of $\delta t = 1$. The system forms separated clusters of vortices of varied sizes. Once the clumps form, any clumps separated by more than 8λ cannot coalesce at $F^T = 0.0$. We note that if we had used an infinite range attractive interaction, even at $T = 0$ the clumps would slowly come together over time to form a single large clump. Fig. 1b shows the same system for annealing with $\delta t = 500$. There are fewer clumps with larger average size, indicating that during the annealing time the smaller clumps are mobile and wander around the sample until they collide with another clump to form a larger clump. For longer annealing times, even fewer clumps form and the average clump size increases, as shown in Fig. 1c for $\delta t = 25{,}000$. In Fig. 1d for $\delta t = 250{,}000$ there are only two clumps, while in Fig. 1e for $\delta t = 1{,}000{,}000$ only a single large cluster forms. Increasing δt above $\delta\ t = 1{,}000{,}000$ still produces only a single clump. These results indicate that the ground state for vortices with attractive longer range interactions is a single clump rather than multiple isolated clumps, labyrinths or stripes. We note that in real superconductors the vortex states do not form under the thermal annealing procedure considered here. Thus the experimental systems may effectively be in the instantaneous or fast quench regime so that separated clusters could form. Studies of this same model under rapid annealing show that as the vortex density is varied, other states such as labyrinths and bubbles form [27]. If pinning is present, these metastable states may become the dominant states that would be observed. It may be possible to perform a dynamic annealing of the cluster states by applying an ac or dc driving current to the system. This will force the vortices to enter a fluctuating state and will reduce the effectiveness of the pinning, which may permit the clumps to become mobile and condense into fewer larger clumps. Simulations of driven pattern forming systems have previously shown that a pattern that has been fragmented by pinning can be dynamically driven into a more ordered state with larger clumps or stripes when the effect of the pinning is reduced [14,28–30].