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# Phase Imprinting in Equilibrating Fermi Gases: The Transience of Vortex Rings and Other Defects

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We present numerical simulations of phase imprinting experiments in ultracold trapped Fermi gases which were obtained independently and are in good agreement with recent experimental results. Our focus is on the sequence and evolution of defects using the fermionic time-dependent Ginzburg-Landau equation, which contains dissipation necessary for equilibration. In contrast to other simulations we introduce small, experimentally unavoidable symmetry breaking, particularly that associated with thermal fluctuations and with the phase imprinting tilt angle, and illustrate their dramatic effects. As appears consistent with experiment, the former causes vortex rings in confined geometries to move to the trap surface and rapidly decay into more stable vortex lines. The latter aligns the precessing and relatively long-lived vortex filaments, rendering them difficult to distinguish from solitons.

*Introduction.* The evolution of defects (solitons or domain walls, vortices, cosmic strings, monopoles, and other topological structures) is central to many sub-disciplines in physics, including cosmology, as well as condensed matter and fluid dynamics. An issue of broad interest is the way in which the nature of the defects changes as equilibration ensues, reflecting the specifics of the initial perturbation as well as the boundary conditions. In trapped superfluid atomic gases one has access to real time dynamics. Here, rapid cooling from the normal phase [1, 2], sudden density cuts [3] and phase imprinting all have led to a sequence of defects which may, in some cases, be relevant to the Kibble-Zurek mechanism in cosmology as well as to superfluid turbulence. Phase imprinting is a quite violent alteration of the superfluid in which part of the superfluid experiences a phase shift close to  $\pi$ . This perturbation has attracted recent attention in trapped Fermi gas superfluids because of reports of rather long-lived solitons having anomalously large effective masses and oscillation periods [4]. These dark solitons are planar density depletions which maintain their shape and are associated with phase changes, near  $\pi$ .

In this paper we present numerical simulations which relate to these phase imprinting experiments. Our work anticipated [5] what was observed in even more recent experiments [6] which re-examined the earlier reports of heavy solitons [4]. Consistent with our numerical findings, the apparent solitons are actually [6] long-lived line or “solitonic” vortices, which are vortex filaments in an anisotropic trap. There is another class of separate, concurrent experiments which have recently observed solitonic vortices. These were also previously misidentified as solitons [7, 8]. Our numerical findings give insight into the instabilities that lead to the formation of vortices in both sets of experiments.

Our paper supports the notion of a natural hierarchy towards less extended and less complex defects (soliton to vortex ring to single vortex) during the processes of equilibration. One might similarly expect that the simplest defects are often the most difficult to relax; indeed, we find that the residual filamentary vortices continue for some time to precess around the atomic cloud. Additionally we find that a very small tilt of the phase imprinting angle is sufficient to consistently align this line vortex in the trapped gas. This picture appears generally consistent with experiment [6]. The above observations underline a key contribution of this paper: to show how simulations of defect evolution require one to subject the numerics to checks for robustness against unavoidable broken spatial symmetries in the experiment.

Our work should be contrasted with previous numerical simulations of the Gross-Pitaevskii (GP) and Bogoliubov-de Gennes (BdG) equations which addressed the previously claimed solitonic stability and attributed it instead to vortex rings (that is, vortex lines which are closed into a loop) [9, 10]. These past claims of stable vortex rings [9] appear inconsistent with experiment [6]. They omitted noise, broken symmetries, and in many cases dissipation and thus do not exhibit all the transitions necessary for the full equilibration of the cloud. This literature [9, 10] has focused instead on symmetric vortex rings which maintain inversion symmetry about the  $z$ -axis [parity transformation  $(x, y)$  to  $(-x, -y)$ ] and often apply initial conditions specifically designed to produce a stable vortex ring. In recent work which introduced a small trap anisotropy [10], there were reports of a vortex ring breaking into two vortex lines. However, in this work reflection symmetries were still maintained, so that the two lines of opposite vorticity perpetually move along the longitudinal axis, and after nearing the edge re-

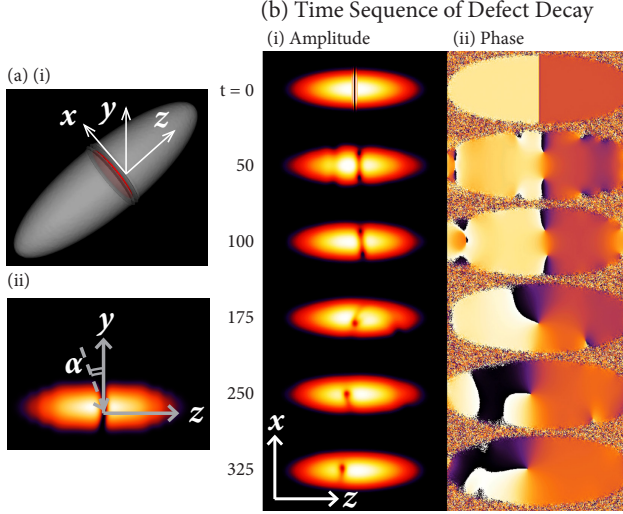


FIG. 1. (Color online) (a) Depictions of axes used. (i) 3D rendering of initial depletion plane (red) with axes used in the paper:  $y$  is vertical, and  $z$  is the long axis of the trap. (ii) Side view of axes at  $t = 20$  after phase imprinting for the run in (b), along with the tilt of the imaging beam,  $\alpha$ , considered later in this work. (b) TDGL simulation results for one time sequence, focusing on the vortex ring decay, of a phase imprinting applied at  $t = 0$  with  $\lambda = 3.3$  and parameters as in the text. (i) shows the cloud density integrated along  $y$  and (ii) the phase in the  $y = 0$  plane [from 0 (black) to  $2\pi$  (white)]. Here phase imprinting has formed a ring ( $t = 50$ ), which is just slightly off center. The ring moves toward the cloud edge ( $t = 100$ ), then impacts the edge and decays to a vortex line ( $t = 175$ ).

combine into a ring moving in the opposite direction. We show that these complex processes, which do not bring the system closer to equilibration, are not found here and are overwhelmed by other symmetry breaking features.

*Our approach.* In contrast to the bosonic GP dynamics, we use the complex time-dependent Ginzburg-Landau (TDGL) equation [11] appropriate for fermionic superfluids (discussed in the Supplemental Material (SM) [12]), to address three-dimensional (3D) anisotropic trapped Fermi gases subjected to a near- $\pi$  phase imprinting quench [4]. We consider a harmonic confining potential  $V(\mathbf{x}) = (\omega_{\perp}^2(x^2 + y^2) + \omega_z z^2)/2$ , where  $\omega_{\perp}$  and  $\omega_z$  define how tightly confining the trap is in comparison to the chemical potential, as well as the trap ratio  $\lambda = \omega_{\perp}/\omega_z$ . Our central TDGL equation is  $e^{-i\theta} \partial_t \psi(\mathbf{x}, t) =$

$$\left\{ [1 - V(\mathbf{x})] + \frac{1}{2} \nabla^2 - |\psi(\mathbf{x}, t)|^2 \right\} \psi(\mathbf{x}, t) + \chi(\mathbf{x}, t), \quad (1)$$

where  $\chi$  is uniformly distributed thermal noise. Equation (1) contains two parameters, in addition to the trap frequencies. First,  $\theta$  controls the amount of dissipation, effectively moving from BCS ( $\theta = 0$ , dissipative) to BEC ( $\theta = \pi/2$ , reducing to the time-dependent GP equation, or equivalently the nonlinear Schrödinger equation). Sec-

ond, through  $\langle \chi(\mathbf{x}, t) \chi^*(\mathbf{x}', t') \rangle = 2\gamma T_{\chi} \delta(\mathbf{x} - \mathbf{x}') \delta(t - t')$ , a fluctuation temperature can be set [1, 13–15]. In this work the dimensionless fluctuation temperature is chosen to be very close to the zero-temperature limit, with  $\gamma T_{\chi} = 2 \times 10^{-9}$  [1]. Beyond these parameters, the rescaling to this normalized form follows from Ref. [11].

A TDGL approach [16–18] can be viewed as a dissipative GP simulation where the dissipation becomes progressively stronger as the dynamics changes from propagating (in BEC) to diffusive (in BCS), reflecting the fact that pairs are in equilibrium with the underlying fermions. Along with this dissipation is a stochastic contribution required to simulate finite temperatures or experimental imperfections [1]. Higher levels of microscopic self consistency lead to longer-lived pairs in the intermediate (near-unitary) regime [17, 18], as compared to earlier estimates of the TDGL coefficients. This effectively reduces the dissipation (increases  $\theta$ ). We use  $\theta = 88^\circ$  for simulations here, with the amount of dissipation primarily affecting the lifetime of the resulting vortex line described below. (See SM for more details [12].)

Our studies are based on numerical simulations discretized in  $512^3$  grid points designed to solve Equation (1) using a quasi-spectral split-step method. The simulations are performed on a GPU computing cluster, allowing relatively large simulation sizes. The initial condition is found using a heat diffusion equation to cool the system to equilibrium before the phase imprinting is applied, as in Ref. [1]. Within this TDGL approach for Fermi gases, the form and rescaling of the trap potential is inserted via the local density approximation,  $\mu \rightarrow \mu - V(\mathbf{x})$ , where  $\mu$  is the chemical potential [normalized to 1 in Eq. (1)]. In the bosonic TDGL limit, this trap potential form is identical to that used in GP [19], and away from this limit, it is slightly rescaled.

*Our detailed findings: Transience of defects.* We investigated a system with axial ( $xy$ ) symmetry,  $\omega_z = 0.038\mu/\hbar$ , and a variable trap ratio  $\lambda = \omega_{\perp}/\omega_z$ . The parameters used here match the trap ratios and symmetries in Ref. [4], but with a somewhat larger  $\omega/\mu$  which provides more fine-grained computational resolution of the defects. We will focus on the case  $\lambda = 3.3$ . In more anisotropic traps with  $\lambda = 6.2$ , we find the vortex ring is even more transient, immediately colliding with the cloud edge to leave a line vortex. Finally, in quasi-1D clouds with  $\lambda = 15.0$ , the system cannot nucleate vortices and a reasonably stable soliton appears which oscillates along the axial direction of the trap, in agreement with 1D predictions.

After the cloud has reached equilibrium, we imprint a  $175^\circ$  phase shift in the middle of the cloud [in a plane perpendicular to  $z$ , with axes shown in Fig. 1(a)], and observe the evolution. Images from a typical run are displayed in Figure 1(b) (see also SM [12]). Immediately after the imprint, a planar density depletion forms [first frame in Fig. 1(b)]. However, the plane rapidly deforms

along the axial direction (see SM [12]), and a vortex ring forms. This initial formation of the vortex ring, similar to the snake instability [10, 20–24], appears in the second frame of Figure 1(b) [25]. In the absence of noise and dissipation, this ring is stable and oscillates in the trap, as observed in other simulations [9, 10]. The presence of noise perturbs part of the ring, moving it closer to the boundary. The third and fourth frames illustrate the ring collision with the boundary.

The observed tilting and attraction of the vortex ring to the boundary can be qualitatively understood by applying the method of images [26] to vortex dynamics. (See SM for more details [12].) By considering the simplified case of the ring’s interaction with a hard planar boundary, an image vortex ring can be introduced to satisfy the boundary conditions [26]. This approximation still captures the main dynamics of the trapped vortex ring [27, 28]. In this approximation the ring propagates along the boundary due to advection by supercurrents, but the image vortex retards that part nearest the boundary leading to a tilt [29, 30]. Finally, the tilted ring is attracted to the boundary, and “reconnects” with the image ring, resulting in a vortex line attached to the boundary [see Figure 1(b)]. The reconnection dynamics are essentially the same as that of the reconnection between two vortex lines [26, 31, 32].

The stability of these line and ring defects, and their robustness to unavoidable noise and broken symmetries, are critical to properly compare simulations to experiment. In Figure 2(a) we plot the defect lifetime as a function of the initial phase imprinting angle applied. The vortex ring always decays relatively rapidly, through shrinking to zero radius at small imprinting angles or from impacting the trap edge at larger angles. However, at the large phase imprinting angles appropriate to experiment, the vortex line that remains after ring decay can persist for a relatively long time, as in Figure 2(b-c), where multiple cycles of the vortex line precession are observed. These lifetimes are controlled by the advection of the defects, which in turn depends on both the local phase gradient and the superfluid density depletion. Similar to solitonic behavior [33], small phase shifts lead to large defect velocities, while phase shifts close to  $\pi$  cause large density depletions and apply very little momentum to the defects. These low velocities significantly contribute to the long vortex lifetime in this regime [34].

A more detailed view of this precessing trajectory is shown in Figure 2(b). At the earliest times, when the vortex is near the cloud center, it has a smaller-scale rotation in the counterclockwise direction in addition to the main precession of the vortex in the clockwise direction. This smaller-scale rotation, seemingly due to the decay of the other portion of the ring, gradually subsides, and the remaining precession and outward movement of the vortex are typical in the presence of dissipation (see also SM [12]) [30, 35]. The precession of this line vortex could ap-

pear as a traveling density depletion. This is illustrated in Figure 2(c), under the assumption that the vortex line was precessing in a plane that is nearly orthogonal to the one observed.

*Comparison to Experiment.* The results and interpretations of recent experiments [6] agree well with the vortex line observations described above. What remains to be understood, then, is what determines the line vortex orientation. As demonstrated by the results of multiple runs in Figure 2(d.i), without further symmetry breaking, our simulations produce vortex lines with random orientations. (Similarly, note that the run used in Figs. 1(b) and 2(b-c) has a random vortex orientation which does not match experiment.) In order for the lines to have robust alignment, as has been found in the most recent experimental analysis [6], other symmetry-breaking features must be present. One proposed possibility is that asymmetries in the perpendicular trap frequencies  $\omega_x$  and  $\omega_y$  govern the vortex orientation [6]. Another alternative is a slightly tilted phase-imprinting beam. With the inclusion of noise in our simulations, we have found that small trap anisotropies, as are reported experimentally [6], do not produce reliable vortex orientations in contrast to recent claims [36]. (It should be noted that in our earlier simulations we were inclined to believe in this mechanism as well, but have since rejected it.) The lack of consistency we find reflects the possibility of reconnection between the two vortices that form, and the relatively chaotic vortex behavior that follows (see SM for details [12]). This is in contrast to the simulations [10, 36] which maintain a reflection symmetry about the  $yz$  plane ( $x \rightarrow -x$ ), thus leading to vortex alignments which do not otherwise seem to be stable [37].

A more satisfactory alternative is to include the effects of very small tilts in the phase-imprinting beam, so that it is offset from the vertical axis by an angle  $\alpha$  [see Fig. 1(a.ii)] and no longer perpendicular to the long  $z$  axis, while remaining perpendicular to the  $x$  axis. We find this can reliably determine the vortex orientation, and agrees with the orientation observed in experiment. As this imaging beam cannot be placed perfectly, we believe this is a plausible mechanism for determining the orientation of the vortex line. This is shown in Figure 2(d.ii). As noted in Ref. [6], slight tilts of the initial planar depletion can lead to different effects. Here, we find that for tilts in the imprinting beam of  $\alpha = 1^\circ$  or smaller, a vortex ring is produced which quickly decays to a vortex line, as in the absence of this symmetry breaking. The degree of tilt needed to orient the line is dependent on the magnitude of the noise introduced. For typical values of our small noise prefactor, an  $\alpha \approx 0.05^\circ$  tilt is adequate. Furthermore, for a  $1^\circ$  tilt we find that moderate anisotropies have no discernible influence upon the ultimate orientation of the vortex line, though it may add an additional decay step (see SM [12]).

Our simulations (with these small broken symmetries)

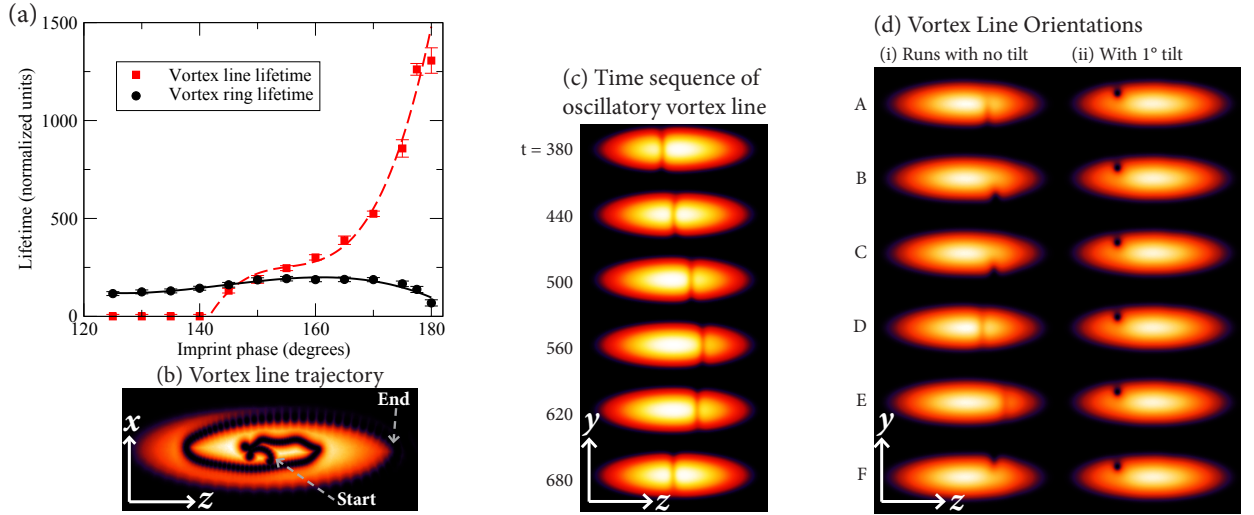


FIG. 2. (Color online) (a) Lifetimes of defects as a function of the imprinting phase, using the same parameters as in Figure 1(b). Red squares indicate lifetimes of vortex lines, which are substantially longer than those of vortex rings (black circles). Error bars reflect run-to-run variations and limitations on time estimates. Lines are cubic polynomial fits provided as a guide to the eye. (b) Plots of the trajectory of the precessing single vortex near the end-stage of equilibration for the same run. Here frames (cuts of  $|\psi|^2$  along the  $y = 0$  plane) with  $\Delta t = 5$  were combined and the minimum density among all frames selected, displaying the vortex trajectory during  $t = [180, 1160]$ . (c) A series of density plots for the  $\lambda = 3.3$  run in Figure 1(b), integrated along the  $x$  axis, during the interval in which only one vortex is present. The density effectively shows a line depletion due to the orientation of the vortex, which oscillates along the cloud. (d) Comparison of a (d.i) perfectly orthogonal phase imprinting and (d.ii) phase imprinting with a beam tilted by  $1^\circ$  relative to the vertical axis, leaving it orthogonal to the  $x$  (short horizontal) axis but not to the  $z$  (loosely confined horizontal) axis. Each cell is integrated along  $x$  at  $t = 400$  for a run with different random noise, but conditions otherwise unchanged. This shows that without a tilt the vortex can be oriented many different directions (d.i), but a small tilt stabilizes the orientation in different runs (d.ii).

led us to believe that what was observed experimentally [4] was not a long-lived soliton but rather this residual precessing vortex filament which can be imaged as in Figure 2(c). However, in order to fully compare with experiments, one needs to address the period of oscillations and the associated trends from the BCS to BEC sides of unitarity. In general, we expect that for constant trap parameters, the period of the precession of a vortex line will follow the size of the superfluid cloud. This means that as the system approaches unitarity from the BEC side, the increase in interaction strength will expand the cloud and lead to a longer precession period. Similarly, if  $\omega_\perp$  is kept constant and  $\lambda$  decreased, the weaker  $z$ -axis confinement will increase the cloud size and lead to a longer precession period. Both of these trends match the BCS-BEC variation observed experimentally [4]. These predictions can be quantified using the Thomas-Fermi (TF) approximation. In this case the precession frequency has been derived as [38–40]

$$\omega_p = \frac{3\hbar\omega_z\omega_\perp}{M(\omega_z^2 + \omega_\perp^2)R_{xz}^2} \log\left(\frac{R_{xz}}{\xi}\right) \frac{1}{1 - r_0^2}, \quad (2)$$

where  $\xi$  is the healing length,  $R_{xz}^2 = 4\mu/[M(\omega_z^2 + \omega_\perp^2)]$  defines an effective trap radius, and  $r_0 = (x/R_x, z/R_z)$  is the dimensionless vortex position. Using the TF approximation [19] for the parameters  $\mu$  and  $\omega_\perp$  given in

Ref. [4] at unitarity, we obtain a very rough estimate of the ratio of the vortex period to the trap period as  $T_v/T_z = 10.2/(1 - r_0^2)$ , in reasonable agreement with the reported results near unitarity. Our simulations also agree with Equation (2) (see SM [12]).

*Conclusion.* These simulations strongly support the conclusion that earlier experimental observations [4], which reported stable solitons, were in fact observing precessing vortex lines. We note that our simulation-based observation, attributing the experimental observations to vortex lines, preceded more recent experiments [6]. Adding to the support for our physical picture is the fact that the oscillation period associated with the precessing vortex filament [Eq. (2)] depends directly on the cloud size squared, and that this period will be longest in the BCS and shortest in the BEC regimes. Finally, important is the rather robust vortex line alignment we find with a very small tilt of the phase imprinting angle.

This work demonstrates that in future simulations of superfluid dynamics, the stability of the results should be established in the presence of imperfections (*i.e.*, thermal fluctuations, small anisotropies, misalignments, etc.). These processes are necessary for simulations to mimic real-world experiments, and to properly model the dynamics which lead to ultimate equilibration.

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