Are spin-mass vortices nucleated in normal-superfluid interface of ^{3}He?

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(July 5, 2000)

In a recent manuscript Eltsov, Kibble, Krusius, Ruutu and Volovik [1] report observations of spin-mass vortices in an experiment where superfluid ^{3}He was locally heated above its T_c by absorption of a neutron. They interpret this finding as evidence of Kibble-Zurek mechanism of defect creation. The purpose of this note is to show that under the experimental conditions the spin-mass vortices can be created also by a different mechanism. Therefore it seems premature to conclude that "composite defect reinforces cosmology–^{3}He analogy" as claimed in the title of Ref. [1].

The superfluid order parameter in the neighborhood of a normal–superfluid interface caused by a temperature gradient was studied in Ref. [2]. Aranson, Kopnin, and Vinokur went a step further and considered a superflow parallel to the interface [3]. They found that there is an instability in the flow that takes place at smaller flow velocity than in bulk superfluid. The process of nucleation of vortices is quite conventional, and is schematically presented in Fig. 1. The coordinate axis x is parallel to the external superflow and is placed near the N-S interface on the superfluid side. The solid and dashed lines represent the real and imaginary parts of the order parameter A. Figure 1a represents uniform flow where $A \propto \exp(\mathrm{i}\phi)$ with $\phi = kx$. If the flow exceeds a critical value, the phase $\phi(x)$ is no more linear and its change becomes concentrated at some points (at x_0 in Fig. 1b). This suppresses the amplitude of the imaginary component (Fig. 1c). It goes to zero and then grows negative (Figs. 1d…g). A one-quantum (mass) vortex is nucleated in this process.

The discussion above assumed a single-component order parameter. For real ^{3}He we consider the simplest case where no A phase appears near the N-S boundary. (If there were A phase, the nucleation of spin-mass vortices would be natural since they have been observed previously in experiments where the A-B interface has gone through the experimental cell [4].) The simplest order parameter would be $\overleftrightarrow{A} \propto \hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{y}}\hat{\mathbf{y}} + \hat{\mathbf{z}}\hat{\mathbf{z}}$. However, the components whose orbital part (latter index of the tensor $\overleftrightarrow{A}$) is perpendicular to the interface (here $\hat{\mathbf{z}}\hat{\mathbf{z}}$) are more suppressed than the others because their gradient coefficient in the Ginzburg-Landau free energy is three times as large as for the others. Let us for the moment neglect the z component completely. Then we can reinterpret the solid and dashed curves in Fig. 1 as the real and imaginary parts of the amplitude of $\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{y}}\hat{\mathbf{y}}$. That process leads to formation of usual mass vortices. However, there is another possibility: once the imaginary component has disappeared (Fig. 1d), it may stay zero and there is another component that grows instead of it in Figs. 1e…g. Here it can be the real amplitude of $\pm(\hat{\mathbf{y}}\hat{\mathbf{x}} - \hat{\mathbf{x}}\hat{\mathbf{y}})$ because then the energies of the following states (Fig. 1e…g) are unchanged. Therefore it should be equally likely to nucleate this component. A half-quantum spin-mass vortex is nucleated in this process. More precisely, the vortex has a half-quantum circulation of both spin and mass.

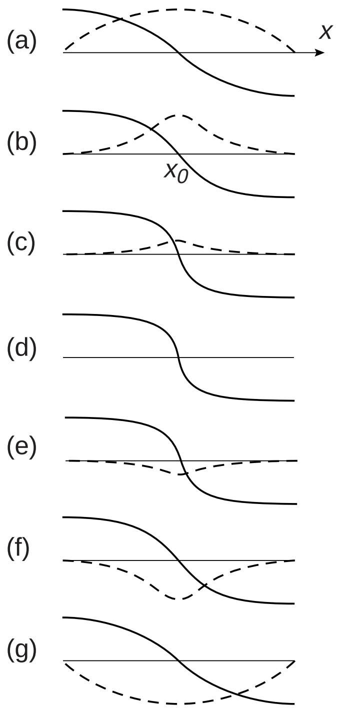

FIG. 1. This figure illustrates the development of instability of flow in the x direction, but the interpretation of the solid and dashed lines depend on the order parameter.

The presence of the third component in the B-phase order parameter causes that there are no free half-quantum vortices. But we may still think that the initial nucleation process generates half-quantum vortices as described above. When they penetrate deeper into the superfluid, they have to form pairs. Two half quantum spin-mass vortices form a usual double-core mass vortex if the spin quanta are opposite. If the spin-quanta are the same, they form a one-quantum spin-mass vortex. In fact, the double-core structure of this object was found already in the first paper where spin-mass vortices were considered, and their stability against dissociation into separate spin and mass vortices was shown [5].

In conclusion, we have sketched a mechanism to create spin-mass vortices that is quite conventional flow instability applied to the case of many-component order parameter near thermal N-S boundary.

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