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Intrinsic and extrinsic vortex nucleation mechanisms in the flow

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Abstract

We propose very general vortex nucleation mechanisms[1] analogous to a hydrodynamic instability and calculate associated critical velocity in agreement with experiments. The creation of vortices via extrinsic mechanism is driven by a formation of the surface vorticity sheet created by the flow, which reaches a critical size. Such a sheet screens an attraction of a half-vortex ring to the wall, the barrier for the vortex nucleation disappears and the vortex nucleation is started. In the intrinsic mechanism the creation of a big vortex ring, which transforms into the vortex, is driven by a fluctuative generation of small vortex rings.

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Numerous experiments in superfluid ^{3}He and ^{4}He show that critical velocity of the superflow is described by the scaling expression $V_c = V_0(1-T/T_c)^p$ with the scaling exponent p[2, 3]. This universality can not be described in the framework Iordanskii- Langer- Fisher activational nucleation theory (see, also, references in[3]). To remove this discrepancy we propose new type of vortex nucleation mechanisms[1] relevant both for superfluids and for superconductors which may be both *intrinsic and extrinsic*. The mechanisms are based on the creation of the stochastic regions with fluctuative vorticity [1]. The vortex penetrates the nucleation barrier with the aid of critical fluctuations via a creation of the fluctuative vorticity regions. The size of the regions depends on the *flow velocity*. When the size of these regions reaches a critical value a barrierless vortex nucleation is started. The critical size depends only on the temperature.

The vortex nucleates in a process similar to the Berezinskii-Kosterlitz-Thouless (BKT) phase transition [4], where instead of vortex-antivortex (V-A) pairs in the nucleation region a fluctuative vorticity liquid is generated. A similar situation occurs in the Williams-Shenoy(WS) [5] model of the λ-phase transition where the role of V-A pairs of the BKT transition is played by the vortex rings. In the same spirit taking into account the vorticity fluctuations on smaller scale in the nucleation region, with the aid of renormalization group we obtain the scaling universality for the critical velocity of the form [1]:

$$V_c = V_0(1 - T/T_c)^p, \tag{1}$$

where the value $V_0 = \hbar/ma_c$ and a_c is a vortex core radius at zero temperature. For ^{4}He it is $a_c = 2.0 - 2.3$Å[6]. The critical exponent p depends on the type of a vortex nucleation or on the dominating shape of the vorticity fluctuations. We derived the renormalization group taking into account both the vortex loops and the half-loops fluctuations. The derivation of scaling relations is associated with the problem of two relevant operators: the temperature and the flow velocity. This problem is solved due to a finite size of the critical fluctuation regions. That is the scaling associated with the flow velocity and temperature is stopped when the size of the nucleation center reaches the critical value, at which the barrier for the vortex nucleation disappears. The nucleation centers are generated by the flow and characterize *a hydrodynamic threshold instability*.

The extrinsic mechanism is related to some centers of nucleation around

which a surface vorticity sheet is created. Such centers of nucleations may be both extended and pointlike. In the first case it is a smooth surface of the rotating bucket or smooth walls in small apertures, in orifices or in narrow channels of Vycor glasses. The pointlike centers of nucleation may be a surface asperity on smooth walls or impurity atoms like ^{3}He impurities in ^{4}He.

For *the superflow near a smooth surface* there occurs a hydrodynamic instability analogous to a surface phase transition, in which *the width of the surface vorticity sheet reaches a critical size* R_c, the barrier for the vortex nucleation disappears and the vortex generation is started. As the flow velocity increases the energy of the pinned half-vortex ring decreases. This stimulates their activation through thermal fluctuations. In their turn the fluctuational half-vortex rings of a small radius assist in the creation of half-vortex rings of larger radius and so on. The picture is reminiscent of the scaling in BKT transition, where the coupling between the vortex and antivortex decreases as the temperature and the flow rise. The scaling relation for critical velocity again takes the derived universal form (1) with $p = 1$.

In Vycor glasses, where one has narrow channels instead of the half-vortex rings for the plane geometry, the optimal shape of fluctuations will be small segments of the vortex rings. This shape depends on the curvature, i.e. on the radius of the narrow channel. Because of this the critical temperature of the phase transition decreases while the critical indices i.e. the universality class of the phase transition remains the same and the critical velocity is described by the same critical exponent with $p = 1$.

If there is *a microscopic surface asperity* (a small mountain peak) on a smooth surface it may play the most important role in the nucleation of vortices, since in its neighborhood the flow is the greatest. On this site the surface vorticity cloud is created more efficiently and it has bigger radius than the surface vorticity sheet on a smooth surface. This surface vorticity cloud screens locally (in the region of the surface asperity) the attraction of the half-vortex ring to the wall. When the size of this vorticity cloud reaches the critical value the vortex barrierless nucleation is started. This is described by the same universal scaling relation, eq.(1) with $p = 1$ [1, 2]. The scaling exponent has not been changed due to the universal character of the creation of critical stochastic regions. In this case the role of aperture size is played by the size of the surface asperity. In the rotating bucket experiments the nucleation mechanism is identical to the aperture experiments.

The role of the impurity atoms (like ^{3}He in the ^{4}He) or clusters of impurity atoms (if any exist) in the vortex nucleation is similar to a surface asperity, i.e. they serve as centers of the stochastic regions filled with the surface vorticity. That is any inhomogeneity in the bulk similar to the surface asperity stimulates locally the vorticity cloud and serves as a vortex nucleation center. Such situations occur only if there are very rare density of surface asperities or a very low density of surface inhomogeneities. If the density of such inhomogeneities increases and will create some random potential, then the correlations of this random potential may, in principle, change the value of the scaling exponent p. This may be relevant for Aerogel and Xerogel glasses [2].

In the intrinsic mechanism the vortices are created in a flow of superfluid with the aid of nucleation of droplets filled with a fluctuative vorticity liquid. The optimal dominating shape of vorticity fluctuations is a vortex ring. Taking into account such vorticity fluctuations we got the critical exponent $p = 1$, which is in a poor agreement with experiments in ^{4}He [3]. If one considers the bending of the fluctuative vortex rings in the droplets one must use Flory arguments about self-avoiding walk exponent, i.e., to take into account the vortex tangle or bending of the loops. This may change the value of p.

All these arguments with scaling do work in ^{3}He: where, however, the thermal fluctuation region is very close to T_c. But since the vortices are created due to hydrodynamic flow instability[1], the critical exponent $p = 1/2$, (the surface roughness changes this to $p = 1/4$ [3]) is valid not too close to T_c.

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References

[1] F.V.Kusmartsev, Phys. Rev. Lett. **76**, 1880 (1996)

[2] R.E.Packard and T.M.Sanders, Jr., Phys. Rev. Lett. 22, 823(1969);Phys.Rev.**A 6**, 799 (1972); D.D.Awshalom and K.W.Schwarz, Phys. Rev. Lett. 52,49(1984); E.Varoquaux, M.W. Meisel and A. Avenal, Phys. Rev. Lett. **57**,2291 (1986); G.Ihas et al, Phys. Rev. Lett. **69**, 327 (1992) ; J.Davis et al, Phys. Rev. Lett. **69**, 323 (1992); E.Varoquaux et al Phys. Rev. Lett. **70**, 2114 (1993); G.G.Ihas et al Physica **B 194-196**, 583 (1994); A.Tyler, H.A.Cho and J.D. Reppy, Phys. Rev. Lett. **73**, 987 (1994); J. D. Reppy, J. of Low Temp. Phys. **87**, 205 (1992)

[3] S. Godner et al, J. Low. Temp. Phys. **93** 131 (1993) (see, Sec.6.2). G.M. Shifflett and G.B. Hess , J. Low. Temp. Phys. **98** 591 (1995); U.Parts et al, Europhys. Lett.**31**, 449 (1995)

[4] V. Berezinskiĭ, Sov. Phys. JETP **32**, 493 (1971), and J. M. Kosterlitz and D. J. Thouless, J. Phys. C **6**, 1181 (1973).

[5] G.A.Williams, Phys.Rev.Lett. **59**, 1926 (1987), S.R. Shenoy, Phys. Rev. **B40**, 5056 (1989)

[6] M. Saarela et al, J. Low Temp. Phys. **93**, 971 (1993); Phys. Lett. A **202**, 317 (1995).