Free vortex-antivortex states in hollow cylindrical Josephson tunnel junction

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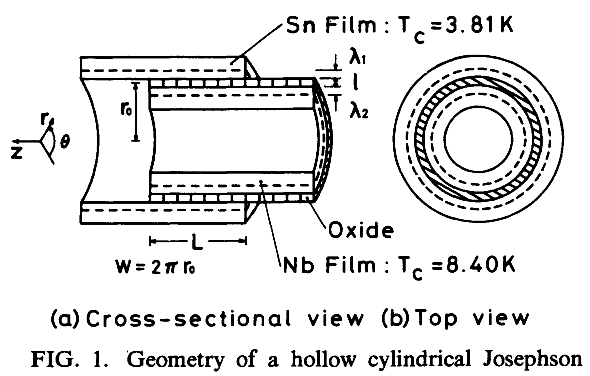
With the use of a hollow cylindrical Nb-Nb_x-Sn Josephson tunneling junction, dynamic vortex motion was studied by the flux-flow voltage across the junction. The junction voltage versus applied axial magnetic field characteristics in the presence of the axial trapped flux in the junction showed the first evidence for the free vortex and antivortex trains moving in opposite directions and passing through each other.

Systems including vortices and antivortices have attracted many physicists in connection to Kosteritz-Thouless transition.[1] Particularly, the condition for a vortex and an antivortex to form a bound state or to annihilate each other is not known at present. It was shown by computer simulation that in one-dimensional dissipative sine-Gordon systems solitary waves of opposite sense propagating in opposite directions pass through each other when they meet, if their relative speed is high enough.[2] There has been, however, no experimental evidence to demonstrate this solitonlike behavior in real systems.

In this paper we show a first evidence that a vortex train and an antivortex train moving in opposite directions pass through each other in a cylindrical Josephson junction.

Several cylindrical Nb—Nb_x-Sn Josephson tunnel junctions shown in Fig. 1 have been fabricated on the substrate of Pyrex glass by means of rf sputtering, vacuum deposition, and photolithographic techniques as endless Josephson junction systems for the propagation of axial flux quanta. The surface of the Nb film was oxidized in air of atmospheric pressure at 80 °C for a few minutes in order to make the tunnel barrier. The dimension of a typical junction thus fabricated is shown in Table I. Our junction is much shorter than the radius in contrast to the previous work.[3]



(a) Cross-sectional view (b) Top view

FIG. 1. Geometry of a hollow cylindrical Josephson junction.

The cylindrical junction and the solenoid which produced an externally applied axial magnetic field were mounted coaxially and magnetically shielded by a superconducting Pb container and two coaxial μ metal shields mounted inside and outside of the Dewar. The measurements were performed in a shielded room.

The temperature dependence of the maximum zero-field dc Josephson current of this cylindrical junction was in excellent agreement with the theoretical results derived by Ambegaoker and Baratoff.[4] The dependence of the self-resonant steps on the applied circular magnetic field produced by passing a current through Nb wire on the center axis of the cylindrical junction was in good agreement with the theory of Kulik.[5] These results guaranteed the quality of our cylindrical junction.

A cylindrical junction was first placed in a uniform axial magnetic field $H_z = H_t$ at temperature 4 K and cooled below T_c(Sn), the transition temperature of the Sn film, and then the applied magnetic field was slowly turned off. The axial magnetic field was thus trapped in the junction by the flux-

TABLE I. The dimensions of a typical cylindrical Josephson junction.

Substrate	$D = 5.01$ mmϕ (o.d.)	$L = 25$ mm
Nb film	0.60 μm thick	$T_c = 8.40$ K
Sn film	0.40 μm thick	$T_c = 3.18$ K
junction	$W = 0.095$ mm	

trapping property of multiply connected superconductors.

Biasing the cylindrical junction at a constant junction current I_j, smaller than the maximum zero-field dc Josephson current I_c (which was typically about 60 mA at 3.19 K), we have measured the variation of the junction voltage V with the applied axial magnetic field H_z (i.e., V-H_z characteristics). Figure 2 shows the V-H_z characteristics for various I_j as a parameter at 3.19 K and $H_t=0$ (i.e., the case of no trapped axial flux quanta in the junction). The continuously varying junction voltage with the externally applied magnetic field can be explained as a manifestation of a flux-flow motion in the junction, and a dip in the voltage is caused by the resonant dc Josephson-current singularities.[6] The resonance occurs when the propagation velocity v of the moving vortex train produced by the applied magnetic field matches the phase velocity of the electromagnetic wave induced by the ac Josephson current in the junction.[7]

On the plane of V-H_z characteristics we can draw the resonance lines (broken lines in Fig. 2) which satisfy the relation[7,8]

$$V=(\bar{c}/c)H_z d \tag{1}$$

in a planar Josephson junction, where c is the speed of light in vacuum and $d=\lambda_1+\lambda_2+t$ with λ_i the London penetration depth of the superconducting films and t the thickness of the oxide layer. H_z is the actual field strength inside the junction, and it is not equal to the externally applied field as we shall see later.

The remarkable difference between the characteristics for the case $H_t=0$ and those for the case $H_t\neq 0$ is that one can draw two resonance lines for the former but four resonance lines for the latter, and that there is a triangular-shaped part near the origin for the case $H_t\neq 0$. It was found that the apex of the triangular-shaped part V_t (which corresponds to the voltage of the tip of the current step in the I-V characteristics at the same temperature and the same trapped flux) and the space between the resonance lines on a quadrant is proportional to the amount of the trapped flux. After measuring the characteristics of Fig. 3, the temperature was lowered to 2.67 K. The dips in the junction voltage then became more pronounced, but the spacing between the resonance lines and the value of V_t hardly changed. Similar data were obtained for the other junctions fabricated. The double resonance persisted even in the presence of a trapped field in a superconductor near the junction although the symmetry of the V-H curve was deformed accordingly.

Following the resonance condition of Eq. (1), the experimental equation which represent the resonance lines in the existence of the trapped flux in the junction is expressed as

$$V=(\bar{c}/c)\,|\,H_t\pm\alpha H_z\,|\,d, \tag{2}$$

where H_t is the trapped magnetic field which is one-half the spacing between the intersections of the resonance lines and the H_z axis, and α is a factor by which the external field penetrates in the junction. The value of α is determined from Figs. 3(a), 3(b), and 3(c) to be 0.13 ± 0.03. Considering this penetra-

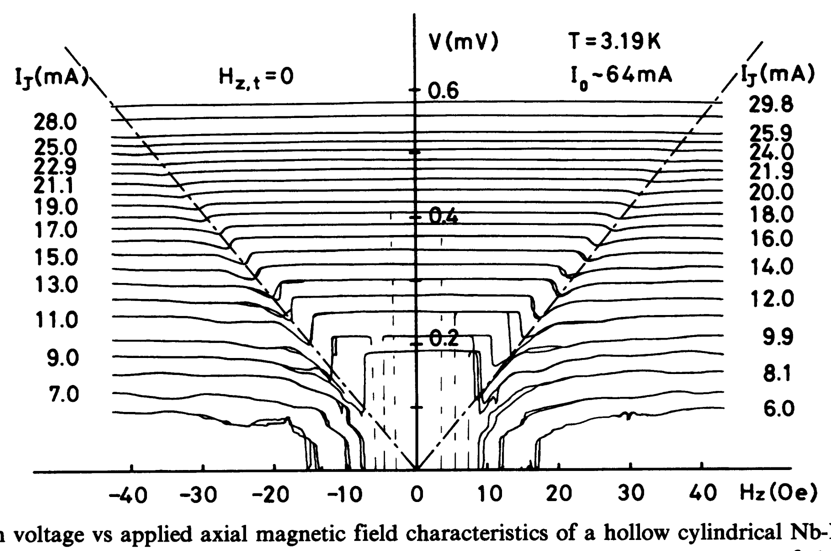


FIG. 2. Junction voltage vs applied axial magnetic field characteristics of a hollow cylindrical Nb-NbO$_x$-Sn Josephson tunnel junction at $T=3.19$ K for various junction currents I_j as the parameter in the absence of the axial trapped flux quanta in the junction. Josephson penetration depth $\lambda_J(T)$ is 0.157 mm.

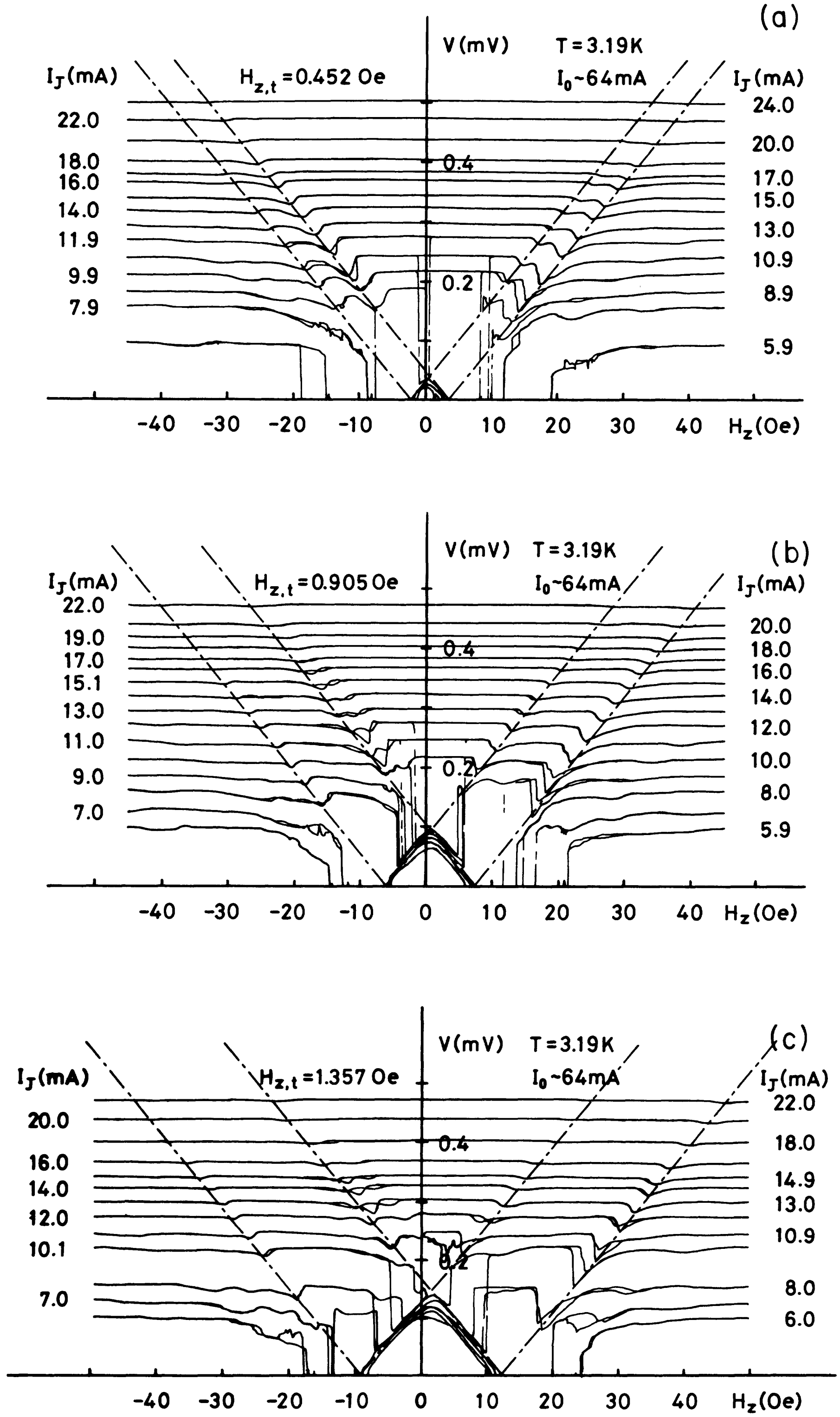


FIG. 3. (a) V-H_z characteristics of the cylindrical junction at 3.19 K for the case H_t=0.452 Oe. (b) V-H_z characteristics of the cylindrical junction at 3.19 K for the case H_t=0.905 Oe. (c) V-H_z characteristics of the cylindrical junction at 3.19 K for the case H_t=1.357 Oe.

tion factor α in the case $H_t = 0$, Eq. (1) should be replaced by $V = (\bar{c}/c)\alpha H_z d$, where H_z is now the external field.

Without the trapped field the two resonance lines are degenerate and only one resonance is observed experimentally as in Fig. 2. When the flux is trapped in the junction, the degeneracy splits into two modes as the result of broken symmetry as seen in Fig. 3. It is also observed in Figs. 2 and 3 that the limiting speed remains unchanged in the presence of the trapped field. Using $d = 1660$ Å estimated from the self-resonant step in the applied circular magnetic field[9] and the value of $\alpha = 0.13$, we obtain $c = 6.65 \times 10^8$ cm/sec as the propagating velocity of the moving vortex.

The properties of cylindrical junctions have been studied theoretically[10] and experimentally,[3] but all of them were based on assuming a homogeneous field distribution in the junction. The present experimental results can only be explained by an inhomogeneous structure in the field distribution as discussed below.

Since the speed of the vortex-antivortex moving azimuthally was found to be close to the speed of circular fluxoids propagating axially,[9] we suspect that these resonances have the same origin with those in a plane junction and that in some part of the cylindrical junction the flux density is $H_t + \alpha H_z$ and in some other part it is $H_t - \alpha H_z$. The resonance data implies, therefore, that pairs of the vortex and antivortex were introduced into the endless junction by the applied external field. To explain these results the following mechanism might be considered.

(1) Applied field lines are deformed near the edge of the junction.

(2) The deformed field lines are pulled through the edge into the junction to create pairs of vortex and antivortex.

(3) The pairs are separated by the Lorentz force caused by the junction current.

The consequence of this process is that a finite number of pairs is introduced into the junction. This process might be equivalent to the creation of a negative diamagnetic field by the screening circular current in the outer superconductor, inhomogeneously superposed on the applied field. This viewpoint on the present experiments would suggest that the perfect diamagnetic state can be dynamically inhomogeneous in the presence of the junction current which constantly supplies energy to drive the vortex trains. Then the factor α would better be called the inhomogeneity factor.

The key points which are necessary to explain the experimental results consistently are the following.

(A) The vortex and antivortex do not annihilate each other when they meet while going around the junction, but they pass through each other.

(B) The vortices and antivortices are not distributed homogeneously. The field distribution is composed of several vortex trains and antivortex trains of finite length.

The reason by which the point (A) is essential is as follows: If they were to annihilate each other the antivortices would have to be annihilated by the already existing trapped vortices before they propagate in the junction. If so, some simple consideration elucidates that one cannot introduce the applied field into the junction when αH_z is smaller than H_t, which is not consistent with the experimental results. When αH_z is greater then H_t the expected field strength of the vortex trains would be αH_z and $H_t - \alpha H_z$, which is again inconsistent with the experimental observation on the resonance lines. On the other hand if the vortices and antivortices pass through each other, one would expect the field strengths $\alpha H_z + H_t$, $-\alpha H_z + H_t$, and H_t for any value of H_z. The above observation is true only if the point (B) is guaranteed. Otherwise the first two field regions would be added up and we would have only H_t throughout the junction. An H_t resonance is difficult to observe in I-V curves or in V-H_z curves, although evidence for it can be seen in the latter.

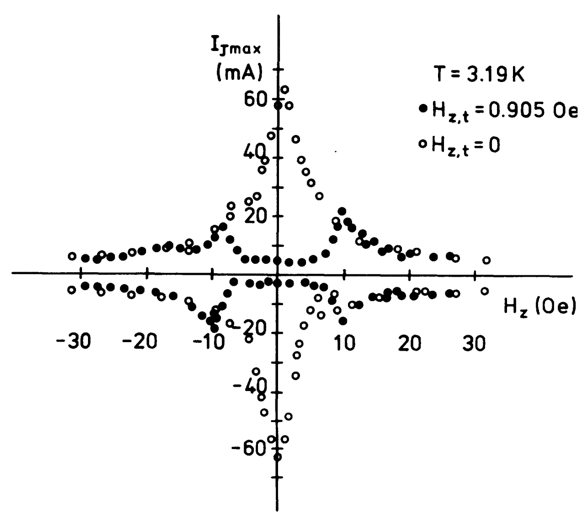


FIG. 4. The maximum current of the junction as a function of applied magnetic field. Open circles correspond to the case $H_t = 0$ and solid circles correspond to the case $H_t = 0.905$ Oe.

In order to examine the validity of our picture we have measured the maximum current for the junction $I_{j,\max}$ above which the junction is in voltage state, as a function of the applied external field with and without the trapped field in the junction. (See Fig. 4.) Open circles represent the $I_{j,\max}$ without the trapped field. The closed circles represent the $I_{j,\max}$ in the presence of the trapped field of 0.905 Oe. The detailed analysis of the curves will be reported elsewhere, and here we mention only the features relevant to the field distribution in the junction. Without the trapped field, the $I_{j,\max}$ is a monotonically decreasing function of the applied field in the measured region, while it shows an interesting peak at the external field strength of about 10 Oe, when $H_t = 0.905$ Oe. If the field distribution is homogeneous in the junction, the maximum current in the presence of the trapped field should also be monotonically decreasing. It is, therefore, most natural to consider that the field is inhomogeneously distributed to form positive-field and negative-field regions. Because the maximum current of the junction in case of inhomogeneous field distribution is determined by the smallest absolute value of the field in the distribution, it increases with increasing negative field which reduces the positive trapped field until it completely cancels the trapped field. The peak of the maximum current appears at the point where the internal negative field becomes equal to the trapped field. And then the negative field exceeds the trapped field and the resultant field tends to decrease the maximum junction current. From this viewpoint it is then natural to consider the maximum current as being symmetric with respect to the direction of the applied field. If the field penetrates homogeneously through the junction in the direction parallel to the applied field, one cannot expect a symmetry in the maximum current in the presence of the trapped field nor the peak which was observed at about 10 Oe. From the peak position the penetration factor is estimated to be $\alpha = 0.10 \pm 0.01$, which agrees within the experimental error with the value estimated from the resonance curves.

To conclude, in cylindrical Josephson junctions one can create by an external axial field, vortex and antivortex pairs which propagate azimuthally in opposite sense to each other without annihilation. They are observed only by trapping a certain amount of flux before the junction is cooled below T_c. The penetration factor of these vortex-antivortex pairs to the applied field strength was 0.13 ± 0.03.

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[1]See, for example, B. I. Halperin, in *Physics of Low Dimensional Systems, Proceedings of the Kyoto Summer Institute,* edited by Y. Nagaoka and S. Hikami (Kyoto Publishing Office of Progress of Theoretical Physics, Kyoto, 1979).

[2]K. Nakajima, Y. Onodera, T. Nakamura, and R. Sato, J. Appl. Phys. 45, 4095 (1974).

[3]M. D. Sherrill, Phys. Lett. 82A, 191 (1981); M. Bhushan and M. D. Sherrill, in Proceedings of the 16th International Conference on Low-Temperature Physics, UCLA [Physica 107B + C, 735 (1981)].

[4]V. Ambegaokar and A. Baratoff, Phys. Rev. Lett. 10, 486 (1963); 11, 104 (1963).

[5]I. O. Kulik, Zh. Tekh. Fiz. 37, 157 (1967) [Sov. Phys.—Tech. Phys. 12, 111 (1967)].

[6]K. Nakajima, H. Ichimura, and Y. Onodera, J. Appl. Phys. 49, 4881 (1978).

[7]R. E. Eck, D. J. Scalapino, and B. N. Taylor, Phys. Rev. Lett. 13, 15 (1964).

[8]B. D. Josephson, Adv. Phys. 14, 419 (1965).

[9]M. Kuwada and Y. Onodera (unpublished).

[10]D. R. Tilley, Phys. Lett. 20, 117 (1966); O. D. Cheichvili, Fiz. Tverd. Tela 11, 185 (1969) [Sov. Phys.—Solid State 11, 138 (1969)]; M. D. Sherrill and M. Bhushan, Phys. Rev. B 19, 1463 (1979).