ELSEVIER

Physica B 284–288 (2000) 585–586

PHYSICA B

www.elsevier.com/locate/physb

Escape of a Josephson vortex trapped in an annular Josephson junction

M.V. Fistul[a], M.G. Castellano[b], M. Cirillo[c], G. Torrioli[b], A. Wallraff[a], A.V. Ustinov[a,*]

[a]*Physikalisches Institut III, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany*
[b]*IESS-CNR, via Cineto Romano 42, I-00156 Roma, Italy*
[c]*Dipartamento di Fisica and Unitá INFM, Universitá di Roma "Tor Vergata", I-00133 Roma, Italy*

Abstract

Experiments on the thermal escape of a Josephson vortex trapped in a magnetic field–induced potential are reported. The measured critical current statistics in a wide range of applied magnetic field H shows that the vortex escape temperature $T_e \simeq T$ at large magnetic fields and $T_e \gg T$ for small values of H. We have developed a theory of vortex escape which explains the increase of T_e by the presence of a small residual pinning in the junction. A peculiar regime when vortex changes its shape in the process of escape is also analyzed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Annular Josephson junctions; Current statistics; Flux lines; Josephson vortices

---

It is well known that in a *small* Josephson junction the presence of fluctuations leads to transition from the superconducting state to the resistive state at a random value of the bias current I [1], resulting in a statistical distribution of the critical current $P(I_c)$ in the limit of small damping.

In a long Josephson junction of length $L \gg \lambda_J$, where λ_J is the Josephson penetration length, this transition may occur in the form of escape of a Josephson vortex (fluxon) from a pinning potential. The experimentally controlled cos-shaped potential can be formed in an annular junction placed in the external magnetic field H [2,3]. Here we report on the observation of critical current distributions in such a junction with a trapped vortex. We also derive the lifetime $\tau(I)$ of the superconducting state which allows to consistently explain the measurements.

Using the well-known Kramers theory [4], the dependence $\tau^{-1}(I)$ can be cast in the form of a functional integral over the Josephson phase distribution

$$\tau^{-1}(I) = \omega_p \int D\varphi \exp\left\{-\frac{U_J([\varphi])}{T}\right\} \times \exp\left[\left(-\frac{\sqrt{2}hA}{3\pi e T L}\right)\left(1-\frac{2\pi I}{hA}\right)^{3/2}\right],$$

where $A = |\int dx(d\varphi(x)/dx)\exp(i2\pi x/L)|$, ω_p is the plasma frequency, $h \propto H$ is the amplitude of the pinning potential and the Josephson junction energy $U_J([\varphi])$ is

$$\frac{I_0}{2e}\int_0^L \frac{dx}{L}\left[\frac{\lambda_J^2}{2}\left(\frac{d\varphi(x)}{dx}\right)^2 + (1-\cos\varphi(x)) - \frac{8\lambda_J}{L}\right].$$

Here, I_0 is the critical current of the junction without trapped fluxon. We obtain two regimes of fluxon escape. In the limit of a small potential, the lifetime $\tau(I)$ is given by the formula that is directly mapped to the case of small junction

$$\tau^{-1}(I) \simeq \omega_p\left(\frac{\bar{I}_c(H)}{I_0}\right)^{1/2}(2\varepsilon)^{1/4}\exp^{-(2\sqrt{2}\bar{I}_c(H)/3eT)\varepsilon^{3/2}}, \qquad (1)$$

where $\varepsilon = 1 - I/\bar{I}_c(H)$ and $\bar{I}_c(H)$ is the fluctuation-free critical current [2]. In the opposite limit $\bar{I}_c(H) \gg$

---

[*] Corresponding author. Tel.: + 49-9131-857-268; fax: + 49-9-131-15249.

E-mail address: ustinov@physik.uni-erlangen.de (A.V. Ustinov)

0921-4526/00/$ - see front matter
PII: S0921-4526(99)02208-5

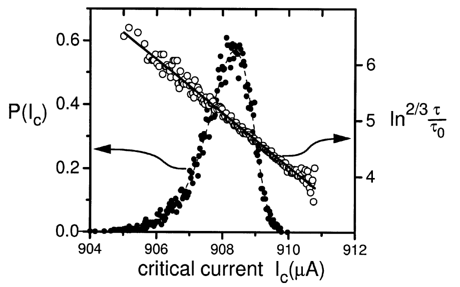

Fig. 1. Typical measured $P(I)$ (solid circles) and $\tau^{-1}(I)$ (open circles) curves together with the analytical dependence (solid line) given by the Eq. (1).

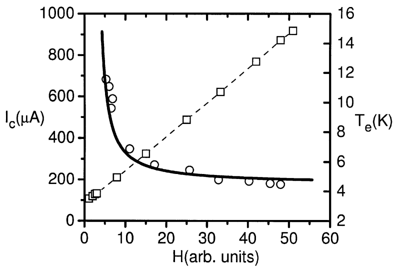

Fig. 2. The critical current $\bar{I}_c(H)$ (open squares) and escape temperature $T_e(H)$ (open circles) versus the applied magnetic field. The solid line is given by the Eq. (3).

$I_0(eT/I_0)^{1/4}$ the potential well squeezes the fluxon and the latter changes its shape in the process of escape. Here $\tau^{-1}(I)$ is given by

$$\tau^{-1}(I) \simeq \omega_p \left(\frac{\bar{I}_c(H)}{I_0}\right)^{1/2} e^{-I_0\varepsilon^2/2eT}. \qquad (2)$$

Experiments have been performed on Nb/Al–AlO$_x$/Nb long annular Josephson with mean radius 46 μm and width 5 μm. The measured value of I_0 was 2.0 mA. At the temperature $T = 4.2$ K we measured the statistical distribution of critical currents $P(I_c)$ in a wide range of magnetic field H (see Fig. 1). Using a well-established procedure [1,5] we found that the lifetime $\tau(I)$ shows a good agreement with the expected $\varepsilon^{3/2}$ scaling (Eq. (1) and Fig. 1). In our range of parameters we did not observe the regime described by Eq. (2).

We obtained a linear dependence of $\bar{I}_c(H)$ (dash line in Fig. 2) which reflects the proportionality of the potential depth to H [2,3]. Using Eq. (1) we calculated the escape temperature T_e for different values of $\bar{I}_c(H)$ (see Fig. 2). We found that the $T_e \approx T = 4.2$ K at high H, but $T_e \gg T$ in the limit of small H. We argue that the non-zero $\bar{I}_c(0)$ and the increase of T_e at small values of H are both due to the presence of a small residual pinning potential in the junction. Our analysis shows that in the presence of both pinning potentials (small local potential and a large one controlled by H) Eq. (1) conserves its form but T_e depends on $\bar{I}_c(H)$

$$T_e \simeq \frac{T}{(1-(2/3)\bar{I}_c(0)/\bar{I}_c(H))}. \qquad (3)$$

Using this expression for T_e and the value of $\bar{I}_c(0)$ we find good agreement with experimental data (solid line in Fig. 2).

Acknowledgements

M.V.F. thanks the Alexander von Humboldt Stiftung for supporting this work.

References

[1] K.K. Likharev, Dynamics of Josephson Junctions and Circuits, Gordon and Breach, Philadelphia, PA, 1986.
[2] N. Gronbech-Jensen, P.S. Lomdahl, M.R. Samuelsen, Phys. Rev. B 43 (1991) 12 799.
[3] A.V. Ustinov, B.A. Malomed, N. Thyssen, Phys. Lett. A 233 (1997) 239.
[4] H.A. Kramers, Physica 7 (1940) 284.
[5] M.G. Castellano et al., Phys. Rev. B 54 (1996) 15 417.