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Modified Arrhenius formula for the time decay of magnetic states in type II superconductors

T. Di Matteo, S. Pace, R. De Luca and M. Polichetti

Dipartimento di Fisica - Università di Salerno - 84081 - Baronissi (SA) - ITALY

We study the problem of the time decay of magnetic states in type-II superconductors by starting from the general expression of the Arrhenius formula as derived from classical stochastic mechanics. By appropriately writing the potential energy for a fluxon in the presence of a pinning center, we find that the attempt frequency in the Arrhenius formula depends on the current density J in such a way that the dissipation phenomena due to creep mechanisms approach zero for vanishing values of J.

1. INTRODUCTION

In the study of the vortex dynamics in high-Tc superconductors a non-linear increase of the creep barrier with decreasing current density has been observed by many groups [1-2]. In particular, from magnetic relaxation measurements, Maley *et al.* [1] have reported a sharp increase of the effective activation energy U as the current density J decreases. Analogous results have been found by Zeldov *et al.* [2], from transport measurements. The experimental results can be analysed within the collective pinning theory [3], which predicts the following inverse power law dependence of the potential energy from J: $U(J) = U_i(J/J_c)^{-\mu}$, where J_c is the critical current density, U_i is the effective activation energy for $J = J_c$, and the value of the exponent depends on the dimensionality of the system and the particular flux creep regime. In this model, though, the effective barrier height grows indefinitely as J goes to zero. Other models [4] predict the same diverging behavior for vanishingly small current densities.

In the present work we tackle the problem *ab initio* starting from the general expression of the Arrhenius formula for the escape probability of a single flux quantum by classical stochastic mechanics, in order to analyse in details the creep problem for independent fluxons. Therefore, by re-analysing the problem and starting from a particular shape of the potential well, which determines the current dependence of the flux decay problem, we find that the Arrhenius formula may be generalized in the following simple way:

$$\frac{1}{\tau} = \nu(J)\exp\left(-\frac{\Delta U_J}{k_B T}\right) \tag{1}$$

where k_B is the Boltzmann constant, ΔU_J is the potential barrier height, and $\nu = \nu(J)$ is the attempt frequency. In particular, we find that, for pinning centers larger than the coherence lenght ξ, the characteristic frequency ν goes to zero for vanishingly small current density values. In this way, dissipation due to creep mechanisms becomes negligible for decreasing values of J.

2. MODIFIED ARRHENIUS FORMULA

We start our analysis from a potential energy $U_J(x)$ which takes account of the presence of the current density J and of a finite size $2l$ of the pinning center, so that we assume:

$$\frac{U_J(x)}{U_o} = \left(\tanh\left(\frac{x-l}{\xi}\right) - \tanh\left(\frac{x+l}{\xi}\right) - \varepsilon_o \frac{J}{J_c}\frac{x}{\xi}\right) \tag{2}$$

where ξ is the coherence length and ε_o can be supposed to be equal to 1. By adopting the same assumptions as in the usual derivation of the Arrhenius formula, following Gardiner [5], the attempt frequency can be determined by the geometric mean of the curvatures of the potential well at the local minimum x_{min} and at the local maximum x_{max} of the potential. We therefore need to first numerically find the local extrema of the

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potential by setting $U'_J(x)=0$ where the prime stands for the first derivative with respect to x. We then set:

$$\nu(J)=\frac{1}{2\pi\beta}\sqrt{U_J''(x_{\min})U_J''(x_{\max})} \qquad (3)$$

where β is the damping constant which is supposed to be $\beta=1$ [5]. The second derivative $U_J''(x)$ can be analytically found, so that the characteristic frequency ν can be expressed completely in terms of J. In Fig.1 we report the ν vs. J dependence for the value of the ratio l/ξ=10. In the inset we show the current dependence of the resulting potential barrier height ΔU_J, where $\Delta U_J = U_J(x_{max}) - U_J(x_{min})$, for the same value of the ratio l/ξ. In this figure the horizontal line $\Delta U_J = k_B T$ is traced. This line marks the lower limit of the range of validity of Eq.(3), since the Arrhenius formula is derived under the following assumption: $k_B T \ll \Delta U_J$. Therefore, care must be taken in applying these results for J close to J_c.

3. RESULTS

Having consistently derived the attempt frequency $\nu(J)$ in the Arrhenius formula, we can find the electric field E_{creep} due to flux creep in the sample, and compare it with the corresponding quantity calculated without taking into account the current density dependence of the frequency ν. This can be accomplished by simply setting:

$$E_{creep} = E_o \frac{\nu(J)}{\nu_o} \exp\left(-\frac{\Delta U_J}{k_B T}\right) \qquad (4)$$

and by sustituting $\nu(J)$ with a constant value in order to compare the two ways of expressing the E vs. J dependence, as specified before. In Fig.2 we, therefore, show the E vs. J dependence in the two cases, for the values of the ratio $l/\xi = 4$ and 10.

Finally, we obtain, for $l/\xi \gg 1$ and $J \rightarrow 0$, much smaller values of E_{creep} than those reported in the literature neglecting the frequency dependence on the current density.

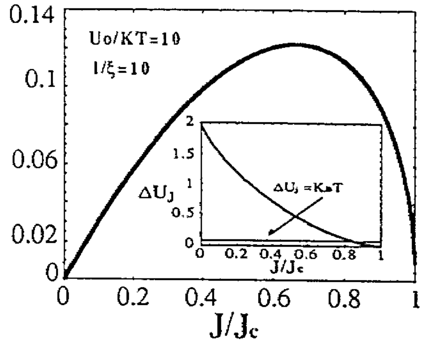

Figure 1. ν(J) curve for l/ξ=10. In the inset ΔU_J vs. J is showed for the same value of the ratio l/ξ.

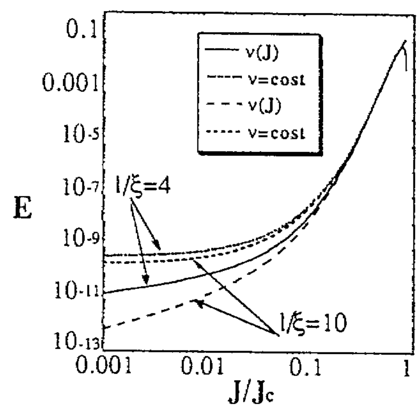

Figure 2. E_{creep} *vs.* J for l/ξ =4,10 with $\nu=\nu(J)$ and ν =cost.

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