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1993 J. Phys.: Condens. Matter 5 351

(http://iopscience.iop.org/0953-8984/5/3/010)

J. Phys.: Condens. Matter 5 (1993) 351–360. Printed in the UK

Interaction between ferromagnetic aerosols and a superconductor

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Received 23 December 1991, in final form 23 September 1992

Abstract. The behaviour of ferromagnetic aerosols near a superconductor surface has been investigated. Some regular features of the interaction between the microparticles and the superconductor were established. If the aerosols are illuminated, firstly decay of the previously induced current at the superconductor ring is observed when these aerosols are present in the field and secondly some particles are repelled from the superconducting surface with a force according to an inverse square law.

1. Introduction

This work is the logical continuation of earlier investigations [1–12] and is devoted to the observation of the magnetic charge effect on ferromagnetic aerosols.

The essence of the effect is as follows: when ferromagnetic aerosol particles are subjected to a high-intensity light beam, they move in the magnetic field along its lines of force; the reversal of the field vector H causes reversal of the particle motion; motion ceases when the field is switched off. An increase or decrease in the field strength or luminous flux intensity causes the particle velocity to increase or decrease, respectively. It has been found that this effect exists at a low temperature up to the boiling point of liquid nitrogen. These phenomena have been interpreted as due to the presence of magnetic charges on the microparticles. Such an interpretation does not seem to contradict the experimental results but these experiments do not negate categorically the possibility that other unknown mechanisms exist.

We think that the experiments described here, to a certain degree, exclude this possibility and provide essentially new additional information about the nature of the magnetic charge effect because, in fact, the aim is to detect the magnetic field of the particles directly. However, because of the type of experimental method used, only qualitative results are given and quantitative definition of the magnetic charge cannot be determined.

2. Interaction of the magnetically charged aerosols with the magnetic field of the superconducting ring

The idea of this experiment is based on the following assertion: the electric current induced in a superconducting ring must decay if a free magnetic charge (i.e. a charge which can move in the field) is present in the field of the ring.

0953-8984/93/030351+10$07.50

Thus, the experiment is reduced to observation of the magnetic field of the superconducting ring when illuminated ferromagnetic aerosols pass along the field axis.

Schematic diagrams of the experiment and of the installation are shown in figures 1(*a*) and 1(*b*), respectively.

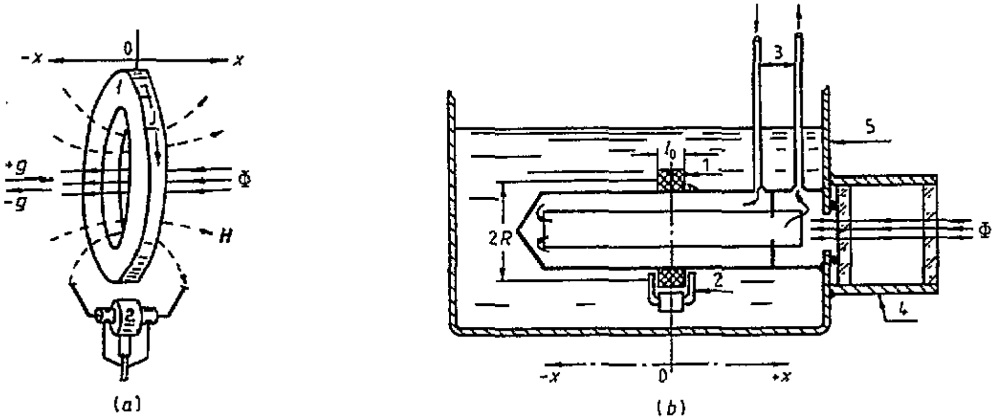

Figure 1. Schematic diagrams of (*a*) the experiment and (*b*) the arrangement for observing the decaying current in the coil: 1, superconductor coil (yttrium ceramic; $T_c = 92$ K); 2, detector of the magnetic field (difference microferrosonde); 3, aerosol flow system, where the curved arrows indicate the direction of motion of the gas (neon or nitrogen); 4, thermal optical window; 5, vessel with liquid nitrogen (cryostat), $\pm g$, the magnetic charge; $\boldsymbol{H}$, magnetic field strength; Φ, luminous flux of the light beam.

The current I is induced in the ring outside the installation. Then, the ring 1 is transferred into the cryostat of the installation and is mounted on the work table. This procedure requires a small Dewar flask, a permanent magnet, some grips and some dexterity.

The magnetic field of the ring may be measured in any suitable way, but the magnetometer must be very stable because the experimental time required is long. In our installation we used a differential microferrosound instrument 2. It was placed near the ring 1 in the cryostat and had a drift of no more than $\pm 0.5\%$ during 24 h when the electric current in the ring was small.

The magnetometer conditions are not changed when the light beam or the aerosols are used. However, in the presence of either a light beam or aerosols, the current in the ring decays (figure 2).

In this experiment we used a laser beam ($\lambda = 4400$ Å; power, 25 mW) and for the aerosols an electric spark source with iron contacts [4, 7]. The aerosols were transported by an inert gas (neon or nitrogen).

Figure 2 illustrates the change in the magnetic field of the ring with exposure time for two different sets of measurements. Points a indicate the moments of injection and points b indicate the moments of removal of the aerosols from the ring region. Point c corresponds to the initial point where the ring starts to heat (the destruction and disappearance of the superconductivity are the result of total evaporation of liquid nitrogen from the cryostat).

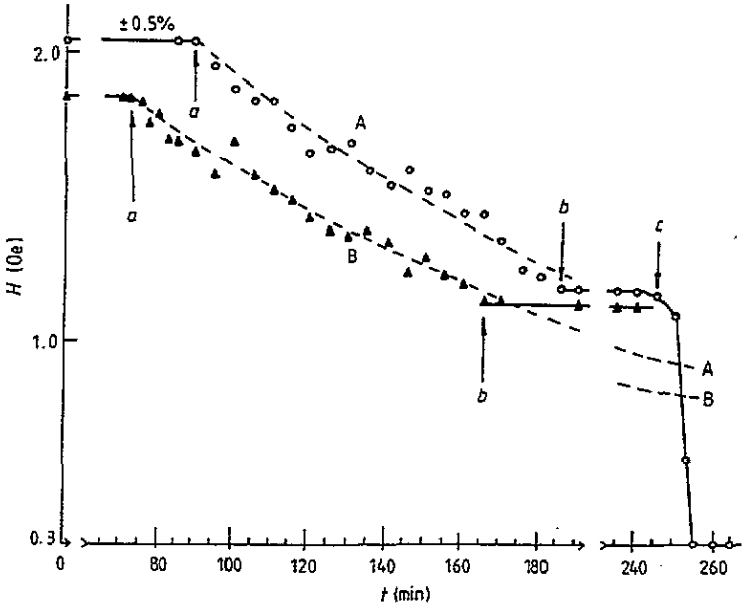

Figure 2. The time diagram for the magnetic field of the superconductor coil. The full triangles were obtained 2 d after the open circles. This figure may be regarded as illustrating the reproducibility of the experiment.

The difference between the magnetic fields for the initial points a of the two curves arises because of the way in which the ring current is induced and has no significance. The nature of the curves between points a and b is easy to explain in the framework of the magnetic charge concept.

Let us suppose that in the magnetic field of ring 1 (figure 1(a)) there are particles with a magnetic charge g and the average density of their distribution in the light beam is n. Such particles move in the field, as shown in figure 1(a). To transfer an infinitely small magnetic charge

$$\mathrm{d}G = n\sigma g\,\mathrm{d}x \tag{1}$$

the amount of power required is

$$\mathrm{d}W = n\sigma g H v\,\mathrm{d}x \tag{2}$$

where n is the density of the particles having magnetic charge g, σ is the cross section of the light beam, H is the magnetic field strength and v is the velocity at which the particles move. In this case, the particles move in a viscous medium. Thus, by the Stokes law,

$$v = gH/K \tag{3}$$

where $K = 6\pi\eta r$ (η is the viscosity and r is radius of the particle).

In our experiment, $\sigma \ll \pi R^2$ (R is the average radius of the ring) and, thus, the problem turns into a one-dimensional task. At the axis of the ring we have

$$H = (1/c)[4\pi R^2/(R^2 + x^2)^{3/2}]I \tag{4}$$

where c is the velocity of light and I is the electric current in the ring.

From (4), (3) and (2) we obtain

$$dW = (n\sigma/Kc^2)g^2[16\pi^2 R^4/(R^2+x^2)^3]I^2\,dx. \tag{5}$$

As the particles migrate across the boundary of the light beam continuously, the density n of the particles is constant. Thus,

$$W = \frac{16\pi^2\sigma R^4}{Kc^2} ng^2 I^2 \int_{-\infty}^{+\infty} \frac{dx}{(R^2+x^2)^3}. \tag{6}$$

W is the total power for the transference of the total charge in the limits of the light beam.

Obviously, the source of this power is the electric current of the ring and the balance

$$W + W_L = 0 \tag{7}$$

exists, where

$$W_L = (LI/c^2)(dy/dt) \tag{8}$$

and L is the self-induction coefficient of the ring.

From equations (8) and (6) we obtain

$$\frac{dI}{I} = -\frac{16\pi^2\sigma R^4}{KL} ng^2 \left(\int_{-\infty}^{+\infty} \frac{dx}{(R^2+x^2)^3} \right) dt. \tag{9}$$

The integral is given by

$$\int_{-\infty}^{+\infty} \frac{dx}{(R^2+x^2)^3} = \frac{3\pi}{8R^5}. \tag{10}$$

The self-induction coefficient of the ring is

$$L \simeq 2\pi^2 R^2/l_0 \tag{11}$$

where l_0 is the thickness of the coil along its axis.

From equations (9)–(11) we obtain

$$dH/H = dI/I \simeq -(3\pi\sigma l_0/KR^3)ng^2\,dt \tag{12}$$

and its solution is

$$H = H_0 \exp[-(3\pi\sigma l_0/KR^3)ng^2 t]. \tag{13}$$

Thus, if our concept is correct, we must have an exponential decrease in the magnetic field strength of the ring, where the time constant is

$$\chi \simeq (3\pi\sigma l_0/KR^3)ng^2. \tag{14}$$

In figure 2 these exponential curves are shown as broken curves. For curve A $\chi = 1.0633 \times 10^{-4}$ and, for curve B, $\chi = 1.0186 \times 10^{-4}$. Thus, equation (13) and the experimental data are in qualitative agreement.

A spread of the experimental points in the decreasing section of the curve could be caused by the irregular fluctuation of the particle density n because of the instability of the aerosol source.

It is interesting to make some numerical estimations for the following parameters: $\sigma = 5.026 \times 10^{-3}$ cm^2; $R = 0.425$ cm; $l_0 = 0.5$ cm; $\eta = 6 \times 10^{-5}$ P.

Let us suppose that $r = 10^{-6}$ cm and $g = g_D = 3.29 \times 10^{-8}$ G cm^2 (Dirac's monopole). Then we have, for curve A, $n = 359$ cm^{-3} and, for curve B, $n = 345$ cm^{-3}. There are some elements of speculation in this example but these values look probable.

In this case, the total charge has been passed through the ring for an exposure time of about $10^6 g_D$ or about $2 \times 10^2 g_D$ s^{-1} (total stream intensity I). However, $I = j\sigma = n\bar{v}\sigma$, where $\bar{v}$ is the average velocity of the particles moving through the ring given by $\bar{v} = I/n\sigma$. Also $\bar{v} = gH/6\pi\eta r$, i.e. $H = 6\pi\eta r\bar{v}/g$. After putting numerical values in this equation we find that $H \simeq 3.4$ Oe, which is consistent with experimental data (figure 2) in the limits $\pm 50\%$.

We repeat that this estimation is very approxiate and may be used only as a rough reference point as the selection of the values of r and g is somewhat arbitrary.

Nevertheless, equation (13) and the experimental data are in good qualitative agreement; so the magnetic charge model is compatible with the experimental results.

3. Behaviour of the magnetically charged aerosols near a superconducting surface

The idea of this experiment is based on the following assertion: because of the presence of the Meissner effect, a repulsive force governed by the inverse square law must act on a microparticle having a magnetic charge near a superconducting surface. Thus, the experiment reduces to observation of the movement of the particle near the superconducting surface and to the detection of the particles moving along a normal to that surface.

Schematic diagrams of the experiment and of the installation are shown in figures 3(*a*) and 3(*b*), respectively.

The light beam of luminous flux Φ is along the horizontal plane of the superconducting ceramic 1 and intersects the optical axis of the microscope lens at right angles. The construction of 1 acts as a magnetic screen for the light beam canal x–x against external magnetic fields. In addition, neutralization of the external fields may be accomplished by use of a Helmholtz coil 8.

Observation of the aerosols is realized through the optical window 6 and the vision slit 7. To obtain photographs we used a camera with a rotary-disc shutter, and therefore time marks are obtained along the track of the particle, i.e. the particle track appears as a broken curve.

After the temperature of the superconductor ceramic was reduced below the characteristic transition temperature T_c (monitored with a thermocouple), injection of the aerosols together with an inert gas (Ne) was carried out through the tubes 3. Then a pause of some hours is necessary so that thermal equilibrium of the gas in the observation zone was attained (convection must cease).

The light beam must be switched on when the rotary shutter is turning and the optical shutter of the camera is opened. Let us consider a situation when just at this

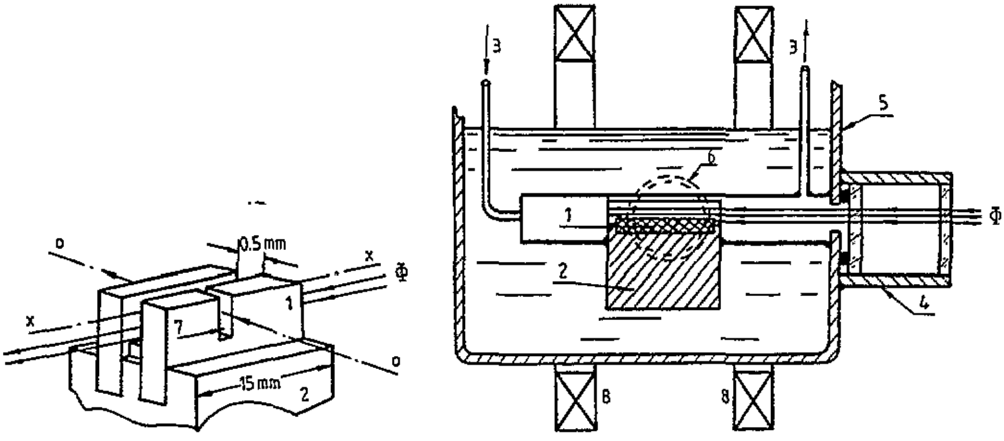

Figure 3. Schematic diagrams of (*a*) the experiment and (*b*) the arrangement for observing the aerosol motion near the superconducting surface: 1, superconductor (yttrium ceramic; $T_c = 92$ K); 2, copper body (thermostat); 3, aerosol flow system; 4, thermal optical window; 5, vessel with liquid nitrogen (cryostat); 6, thermal optical window for the microscope lens; 7, vision slit; 8, Helmholtz coil; Φ, luminous flux of the light beam; o–o, axis of the microscope lens.

moment a particle is near the superconductor and acquires a magnetic charge. Such a particle has its own magnetic field and its field must be repelled by the superconductor because of the Meissner effect. Therefore, such a particle starts to move away from the superconductor along the normal of the superconductor.

In fact, we observed these phenomena repeatedly. In figure 4 the trajectory of such a particle is shown. Because a rotary-disc shutter is used, the track of the particle is seen as a broken curve.

After the light beam has been switched on, the exposure lasts about 10 s; that is a sufficient time for the particle to cross the light beam from edge to edge a–a. In figure 4 the particle apparently starts at a lower point of the track. The track ends on the upper boundary of the light beam. Obviously, the particle does not have a constant velocity.

Let us obtain the equation of particle motion in the framework of magnetic charge formalism. Firstly, we require the expression for the interaction force. A substance (in this case a superconductor) is magnetized in a magnetic charge field, and the energy of that magnetization is

$$W_m = \int_V w(\boldsymbol{r})\, dV \tag{15}$$

where the integral is taken over the full volume of the substance. The magnetization work per unit volume having a magnetic moment M is

$$w(\boldsymbol{r}) = \int H\, dM \tag{16}$$

where

$$M = \kappa H \tag{17}$$

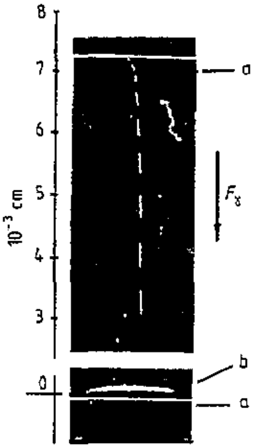

Figure 4. Photograph of the trajectory of a particle moving along the normal to the superconducting surface: a–a, limits of the light beam; b, patch of light at the superconductor surface; F_γ, gravitational force. The distance from the superconductor surface is plotted as the ordinate. A track of an uncharged particle is shown on the right-hand side of the upper photograph.

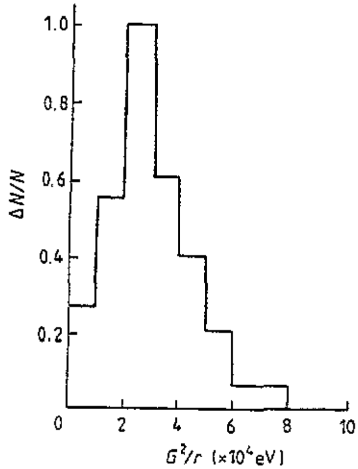

Figure 5. Histogram of the energy G^2/r distribution of the particles (experiment).

and κ is the magnetic susceptibility.

The magnetic intensity of a point charge G is

$$H = G/r^2. \tag{18}$$

In accordance with equations (15)–(18) we have for a half-space (it is sufficiently correct for this experiment) that

$$W_{\mathrm{m}} = \tfrac{1}{2}\kappa G^2 \int_y^\infty \frac{2\pi r^2}{r^4}\,\mathrm{d}r = \frac{\pi\kappa G^2}{y} \tag{19}$$

where y is the distance between the superconducting surface and the charged microparticle.

Obviously, the force of the interaction between the particle having a magnetic charge and the superconductor surface is

$$F = \mathrm{d}W_{\mathrm{m}}/\mathrm{d}y = -\pi\kappa G^2/y^2. \tag{20}$$

For the superconductor, $\kappa = -1/4\pi$. Thus,

$$F = G^2/4y^2. \tag{21}$$

In fact, the force F is the force of interaction between a magnetic charge and its image. The direction of the force F is due to the sign of the magnetic charge. The force F is always repulsive (the Meissner effect).

Let us obtain the equation of particle motion. The element of the particle trajectory is

$$\mathrm{d}y = v\,\mathrm{d}t. \tag{22}$$

The velocity of the particle is

$$v = F/6\pi\kappa r \tag{23}$$

because the particle moves in a viscous substance where the Stokes law is valid. So

$$\mathrm{d}y = (G^2/4y^2 6\pi\eta r)\,\mathrm{d}t \tag{24}$$

or

$$y^2\,\mathrm{d}y = (G^2/24\pi\eta r)\,\mathrm{d}t \tag{25}$$

where η is the viscosity and r is the radius of the particle. The solution of equation (25) is

$$\int_{y_i}^{y_j} y^2\,\mathrm{d}y = \frac{G^2}{24\pi\eta r}\int_{t_i}^{t_j}\mathrm{d}t \tag{26}$$

or

$$y_j^3 - y_i^3 = (G^2/8\pi\eta r)(t_j - t_i). \tag{27}$$

This is the equation of motion of the magnetically charged particle near the superconducting surface.

From this equation it follows that, if any two time intervals are equal, i.e.

$$t_j - t_i = t_k - t_n = \tau \tag{28}$$

then

$$\theta = y_j^3 - y_i^3/y_k^3 - y_n^3 = 1. \tag{29}$$

This formula may be used as a criterion of the reality of the magnetic charge concept. If equation (29) is satisfied by the experimental results, the law (21) holds for this experiment. In this experiment the time marks are made by means of the rotary-disc shutter. In figure 4 the length of the time mark is $\tau = 2.5\times10^{-2}$ s, and the arithmetic average value of θ is very close to unity. Thus, in this experiment we obtained some features which agree with the primary concept.

However, we have also observed other features which do not keep within magnetic charge limits; at the same time the attraction of the particles to the superconductor surface *was* recorded. Investigation of the motion of such particles is shown to be absolutely consistent with an inverse square law (21) too. Of course, this also demands an explanation.

First of all we consider the electrostatic interactions. In this case the particle must be equivalent to a point electric charge.

There are at least two variants for realization of this condition:

(1) interaction between the electric charge of the particle and its image at the superconductor;

(2) interaction between the electric charge of the particle and an independent electric point charge placed on the superconductor surface.

One may state at once that, as we know nothing about the surface state of the superconducting ceramic, we have no arguments against the second variant. However, this phenomenon was observed only at temperatures below the critical point T_c. Thus, there is little probability that this phenomenon is caused by contamination (e.g. dust) which can form a spotty structure of the electric charge of the ceramic surface.

We can consider the first variant in more detail.

From equation (27) we can obtain only the ratio G^2/r because neither G nor r is known separately. It is

$$G^2/r = 8\pi\eta(y_j^3 - y_i^3)/(t_j - t_i). \tag{30}$$

The ratio G^2/r is the potential energy of a charge at the surface of a particle.

In figure 5 the histogram of the energy G^2/r distribution of the particles is shown. It is, in fact, a characteristic line of the detection device and covers both attraction and repulsion.

If G is the electric charge, then $G = ne$, where e is the electron charge and n is an integer. Therefore the potential energy per electron is ne^2/r.

The probable value of the particle radius in this case is of the order of 10^{-6} cm [7]. Thus, in accordance with figure 5, ne^2/r is of the order of 10^2 eV ($n = 500$). Naturally, such a situation is unreal because the latter value is larger than the electric work function of a metal oxide. The particle cannot have such a number of electrons (if the charge is negative) and, at the same time, to create a large positive charge, high-energy ionization sources, which are not used in our experiment, (and triboelectrification too) are necessary.

Thus, this scenario may be rejected as very doubtful. However, in spite of this, we do not have an irrefutable argument for the absence of electrostatic interactions.

It is possible that this problem will be solved by experiment with aerosols separated from charged particles by means of a special electrostatic field. (It was noticed earlier [4] that electric charges and magnetic charges are both present at the particles, as a rule.) However, then it will be necessary to use an elementary superconductor and liquid-helium temperature. This certainly complicates the experiment from an engineering viewpoint.

It is possible there is a third method. In any case, further investigations and additional experiments are necessary.

4. Discussion

So we have the results of two experiments. At this stage the results may not be interpreted from a general viewpoint. The experiment with the ring allows us to draw the conclusion that our data are consistent with the magnetic charge model uniquely.

The observation of the Meissner effect in the second experiment is questionable. It is quite possible that we have an ordinary combination of two independent mechanisms caused by Coulomb interactions—magnetic and electric interactions—and the problem can be reduced to consideration of these mechanisms separately. It is also possible that the magnetic interaction in this experiment is generally absent, and then there is the problem of the large electrical charges. However, perhaps we have a situation caused by over-simplification of the initial model of the process.

Indeed, imagining that a particle is a point object moving along a magnetic force line, which was justified in our earlier experiments [1–12], in this case may give us only a very rough idea of the situation. As we stated before, we have observed that, under a very high magnification of the photographic track, some particles have a wavy line with an amplitude between $10r$ and $100r$ (r is the particle radius). One can imagine that this is a plane projection of the helical path of the particle, the axis of the spiral being along the magnetic force line [11]. The attempt to explain this phenomenon by the Lorentz force was unsuccessful. This problem has been investigated by Ehrenhaft [14]. Numerous photographs of such tracks are contained in Ružička's [15] work, which was compiled from Ehrenhaft's studies.

The absence of a satisfactory theory for the question discussed makes it difficult to understand our results. However, the theoretical studies of Lochak [16, 17], Daviau [18] and, especially, Barrett [19] give us hope. In accordance with these studies, magnetic charges (monopoles) may be created in the conditions existing in our experiments (interaction between ferromagnetic microparticles and light).

All the above is a good illustration of the complexity of the phenomenon. Therefore the results that we obtained must be regarded as preliminary. As the problem is very important, it is necessary to make a careful analysis of the scientific data and a new theory is required.

We hope that our experiments will attract the attention of researchers and that these experiments be repeated as soon as possible so that greater understanding of the problem is facilitated.

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