Topological pinning and flux flow in Ceramic Superconductors

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Measurements of the I-V characteristics, in the fluxon mixed state region of the phase diagram of the superconducting ceramic $La_{1.85}Sr_{0.15}CuO_{4-\delta}$, show a behavior that cannot be explained within the renormalized Ginzburg-Landau theory, useful to describe the static behavior of the mixed state. The I-V curves are characteristic of geometrical pinning associated to the multiple connected nature of the granular system. Flux flow is seen to be induced when activating the critical state of the Josephson junctions. We have no theoretical explanation for the I-V characteristics found for different fields and temperatures.

74.70.Vy, 74.70.Mq, 74.50+r

From the begining of the research in the high T_c superconductors[1] it was pointed out that the superconducting properties of the oxide ceramics are typical of granular materials. Only very recently a fairly complete experimental phase diagram of well characterized samples of the ceramic $La_{1.8}Sr_{0.2}CuO_{4-\delta}$ has been determined[2]. The phase diagram shows qualitative and quantitative agreement with results predicted by granular mean field theories[3].

The agreement demonstrates that the broad temperature and magnetic transition widths in ceramics should not be taken as the result of an inhomogeneous material with a broad distribution of critical parameters. The broadening is a consequence of thermally induced phase fluctuations of the order parameter, nucleated in superconducting regions (islands), interconected by Josephson junctions. The medium field theory[3] describes the superconducting properties of the granular material within a Gingzburg-Landau picture where the coherence and penetration lengths are renormalized. In this limit the topological details of the superconducting network are disregarded.

Remanent magnetization measurements[2,4] show the existence of two well defined temperatures: the superconducting nucleation temperature T_{co} in the islands and the temperature where superconductivity is phase locked throughout the sample, T_c. The electrical resistivity becomes zero at T_c. Experimental results show[2,4] that in ceramics of $La_{1.8}Sr_{0.2}CuO_{4-\delta}$ the superconducting islands have an average diameter of approximately 2 μm. The Josephson coupling between them can be tuned controlling the oxygen concentration. In this way T_c has been changed[2,4] from few degrees below T_{co}, for the most oxygenated sample, down to 14 K below T_{co}, for samples where the oxygen concentration has been reduced in 0.3 % of the total oxygen content.

A generalized Bean model was introduced[5] to describe the critical state of the granular sample. The critical current obtained from the major magnetization loops[6], in the low field regime, coincide with that obtained from transport measurements[4]. This result has induced us to ask whether the flux dynamics of granular systems follows the general behavior of vortex flow in homogeneous type II superconductors in the presence of pinning centers.

In this work we study the dynamics of the quantized magnetic flux (fluxons) induced by currents flowing through the Josephson junctions. This flux should not be confused with that due to vortices nucleated within the superconducting islands. The fluxon mixed state is induced below T_c, in the low field region of the phase diagram. The upper field limit for this pure fluxon mixed state, is determined by whatever is smaller, the quenching field of the Josephson critical currents of the links or the lower critical field H_{c1} of the superconducting islands.

Before discussing the experimental behavior of granular systems it is convenient

to review the expected[7] voltage behavior associated to the movement of vortices in homogeneous type II superconductors with pinning centers.

The driving force on a vortex is the Lorentz force. Once it exceeds the pinning force the vortex lattice moves with a steady drift velocity. In moving through the superconductor the vortices experience a viscous force that give rise to dissipation. A voltage appears in the direction of the transport current, given by

$$V = L\frac{J_T B\Phi_o \sin^2\Theta - f_p B \sin\Theta}{c^2\eta} \qquad (1)$$

where $\vec{J_T}$ is the transport current density, L the distance between voltage contacts, f_p the elemental pinning force, $B = n\Phi_o$ the induction field associated to n vortices per square centimeter, each of them carrying a flux quantum Φ_o, Θ is the angle between $\vec{B}$ and $\vec{J_T}$ and η is the only parameter that depends on the properties of the material, representing the viscosity for flux motion. The first term in Eq.(1) is characteristic of vortex motion and is independent of pinning. The second term is proportional to the pinning force. It is then clear that flux flow is characterized by a differential resistivity proportional to $\sin^2\Theta$. However, the voltage is proportional to $\sin^2\Theta$ only if $f_p = 0$.

In the experiments we want to induce the fluxon mixed state avoiding the presence of vortices into the superconducting islands. To obtain this state the sample is cooled in zero field (ZFC) below T_c and then the field is applied at constant temperature. However, from a practical point of view, at the small fields and currents used in the experiments if vortices were to be present into the superconducting islands they should remain pinned, with no contribution to the total flux dynamics of the sample. From this point of view the results of ZFC should coincide with those of field cooling, as found experimentally.

In our measurements the flux movement is due to Lorentz forces induced by a constant transport current I_T, and an applied magnetic field $\vec{H}_a$. The flux motion is detected by the voltage generated in two electrical contacts soldered colinear with the electrical current contacts. In the experiments the voltage was measured as a function of I_T at constant $\vec{H}_a$. The current was changed either by rotating it with respect to the direction of the applied field or changing its magnitude at constant angle.

The earth magnetic field was supressed down to 0.05 Oe using a Helmholtz pair of coils. The power dissipated in the sample was always less than 10^{-8} Watts and no heating effects were detectable.

Since we wanted to study the flux flow in granular systems, we emphasize the granularity measuring in a deoxigenated sample of $La_{1.85}Sr_{0.15}CuO_{4-\delta}$ with $\delta = 0.01$, prepared as described elsewhere[8] and found X-ray single phase. The temperature

dependence of the electrical resistivity of a sample of $10 \times 20 \times 0.3$ mm^3 behaved equal to that reported previously[9] in similar materials. In the measurements the temperature was stabilized within 0.1 K.

The measurements of the electrical resistivity as a function of temperature, in zero applied magnetic field are shown in Fig. 1. These results were used to determine $T_{co} = 37.1$ K and $T_c = 17.5$ K.In this measurements the current density was 0.1 A/cm^2.

The voltage as a function of current for perpendicular and parallel orientations is plotted in Fig. 2. In the figure we have included results for two differents fields at $T = 8$ K. Results for other temperatures, below T_c, are similar to those of Fig. 2. In the inset we show in an expanded scale the behavior of the experimental data when the voltage tends to zero. Notice that the zero voltage is achieved at the same current I_m independent of its relative orientation.

Figure 3 shows the voltage as a function of the angle between $\vec{H}_a$ and $\vec{J}_T$ for different absolute values of $\vec{H}_a$, at $T = 8$ K. The solid line shows a $\sin^2\Theta$ fit to the experimental data. The small deviations between the data and the fit are due to the uncompensated ambient field. Similar curves were obtained at different currents and temperatures, below T_c.

The experimental data can be well fitted by an empirical expression of the form:

$$V = A_1(T, \vec{H}_a)[I_T - I_m(T, H_a)]^\alpha + A_2(T, \vec{H}_a)[I_T - I_m(T, H_a)]^\alpha \sin^2\Theta \qquad (2)$$

where the exponent α, found temperature and field independent within the experimental error, should be taken as a fitting parameter in the context of this paper.

The experimental results show two regimes. One for $I_T < I_m$ where the voltage is zero and a non-Ohmic one for $I_T > I_m$. The value of I_m is found to be field and temperature dependent although independent of the relative orientation between $\vec{H}_a$ and $\vec{J}_T$.

The only angular dependence of the voltage is given by the $\sin^2\Theta$ term, see Eq. (2). This result strongly suggest that the flux motion in this granular system takes place without pinning [see Eq. (1)]. On the other hand the zero voltage regime points out that the flux remains locked into the superconducting network until the current exceeds a minimum value, $I_m\ (T, H_a)$.

It is important to remark that once $I_T > I_m$ dissipation is induced in the sample, even when no force is acting on the fluxons, $\Theta = 0$. The results show that the Lorentz force induces flux motion only after the previously mentioned dissipative process is switched on.

The I-V characteristics demonstrate that despite the success of the renormalized Ginzburg-Landau theories to describe the static characteristics of the fluxon mixed state they cannot explain the behavior of the dissipative state of the granular system.

The picture of a granular system as an ensemble of superconducting islands interconected by Josephson junctions provides a natural explanation for the dissipative process associated to the case $\Theta = 0$. Within this picture the voltage appears after the transport current exceeds the field dependent Josephson critical current.

A naive interpretation of the voltage induced by flux motion, within the same picture, could be that once the transport current equals the Josephson critical current, the pinning is canceled and flux motion is induced by the Lorentz force. However, the suppression of pinning by a finite current should induce a voltage jump at I_m, contrary to the experimental observation.

Although at the present time we have no formal explanation justifying the empirical expresion (2) we suggest that this behavior is intimately related to flux flow in multiple connected superconducting networks[10]. To see this let us remind that in a type II supercoductor with space translational symetry the magnetic flux is determined by the number of vortices. The local currents circulating in the material are those associated to the magnetic configuration given by the superposition of the field of the vortices. The flux flow is induced as a consequence of the superposition of those currents with the transport one. In a multiple connected network the magnetic configuration might have a pictorical resemblance to that of vortices in a type II superconductor but its origin and current distribution is quite different. The magnetic flux in a multiple connected system is made up of a flux associated to the external field, locked into the supercoducting network, plus an extra flux proportional to the product of the current circulating in the circuit, times some inductance associated to the topological distribution of the network. The transport current can interact only with this last part of the flux.

The multiple connected picture also provides an explanation for the existence of magnetic metastable states and the induction of equilibrium through dissipative processes in the Josephson links. In this sense the fluxon pinning is geometrical and is related to the topological characteristics of the superconducting network.

In conclusion the knowledge of the experimental equilibrium phase diagram of the superconducting granular ceramic has allowed us to study the pinning of fluxons and the dissipative state caused by their motion. It is shown that pinning has a geometrical origin and that the flux motion is induced activating the critical state of the junctions. We have no theoretical explanation for the I-V characteristics, empirically represented by expression (2). The posibility of tunning the critical current with small changes of the oxygen content opens the posibility of further studies of the magnetic and transport properties of multiple connected systems in different regions of temperature and field, using the same sample.

It is interesting to point out that the $\sin^2\Theta$ dependence and the minimun voltage in

the parallel orientation have been recently reported[11] as characteristics of dissipative flux motion in $Y_1Ba_2Cu_3O_{7-\delta}$ single crystals. Although in a different context the lack of Lorentz force dissipation has been suggested[12] to be related to the existence of Josephson junctions in single crystals.

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FIG. 1. Resitive transition in zero applied field. The up arrow ($\uparrow$) shows the temperature where the transition begins T_{co}. The down arrow ($\downarrow$), where it ends, T_c.

FIG. 2. V-I characteristic curve for different applied magnetic fields. The voltage is plotted for the field parallel and perpendicular to the current. ($\Box$), $\vec{H}_a$ = 2 Oe; ($\odot$), $\vec{H}_a$ = 4Oe. The inset shows in an expanded scale the V-I curve when the voltage tends to zero for $\vec{H}_a$ = 2 Oe.

FIG. 3. Angular dependence of the dissipation at $\vec{J}_T$ = 0.1 A/cm^2 for three applied magnetic fields: ($\Box$), $\vec{H}_a$ = 2 Oe; ($\diamond$), $\vec{H}_a$ = 2.5 Oe; ($\odot$), $\vec{H}_a$ = 4 Oe. The solid line represents a $\sin^2\Theta$ fit to the experimental data.

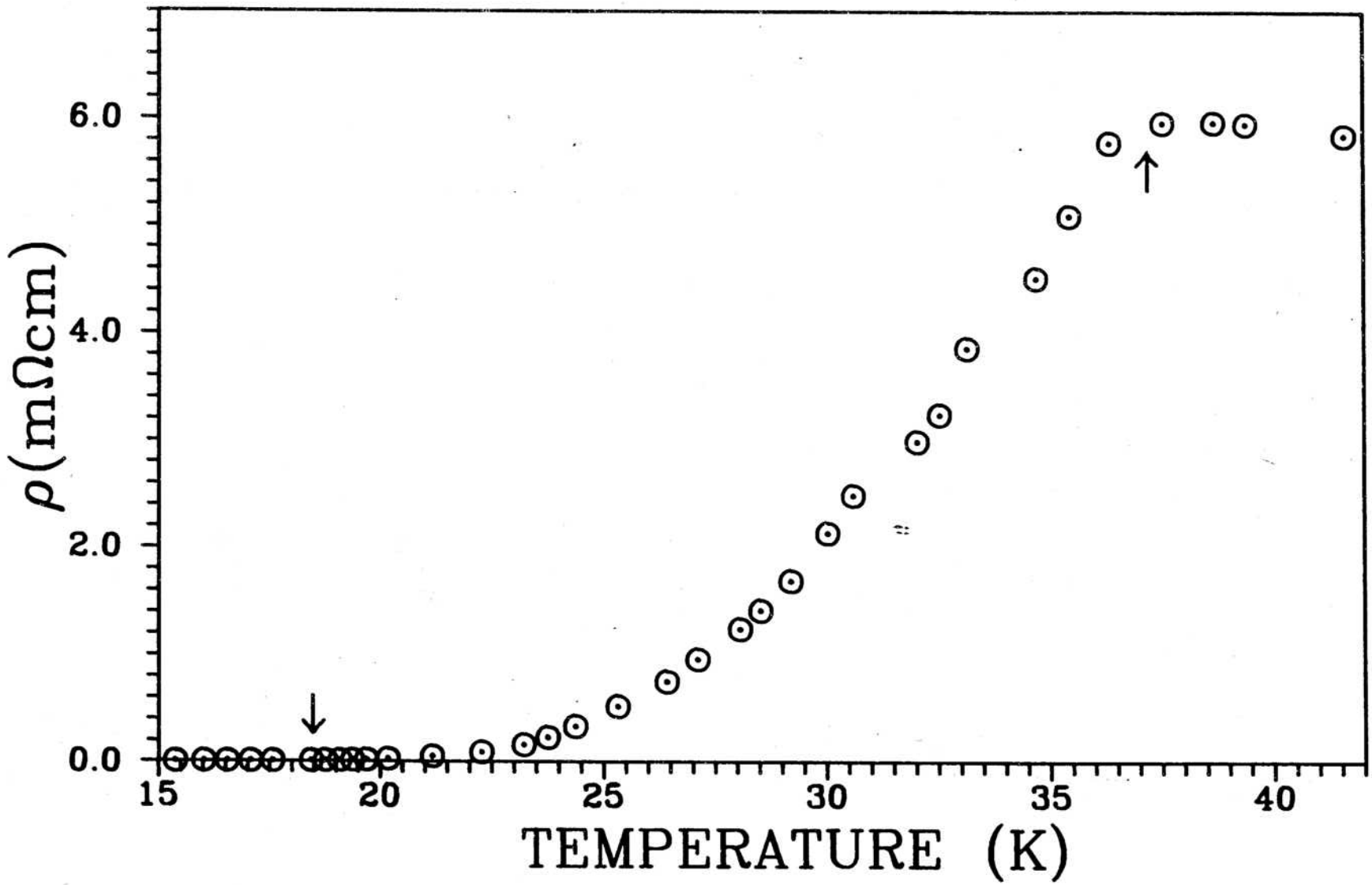

Fig 1

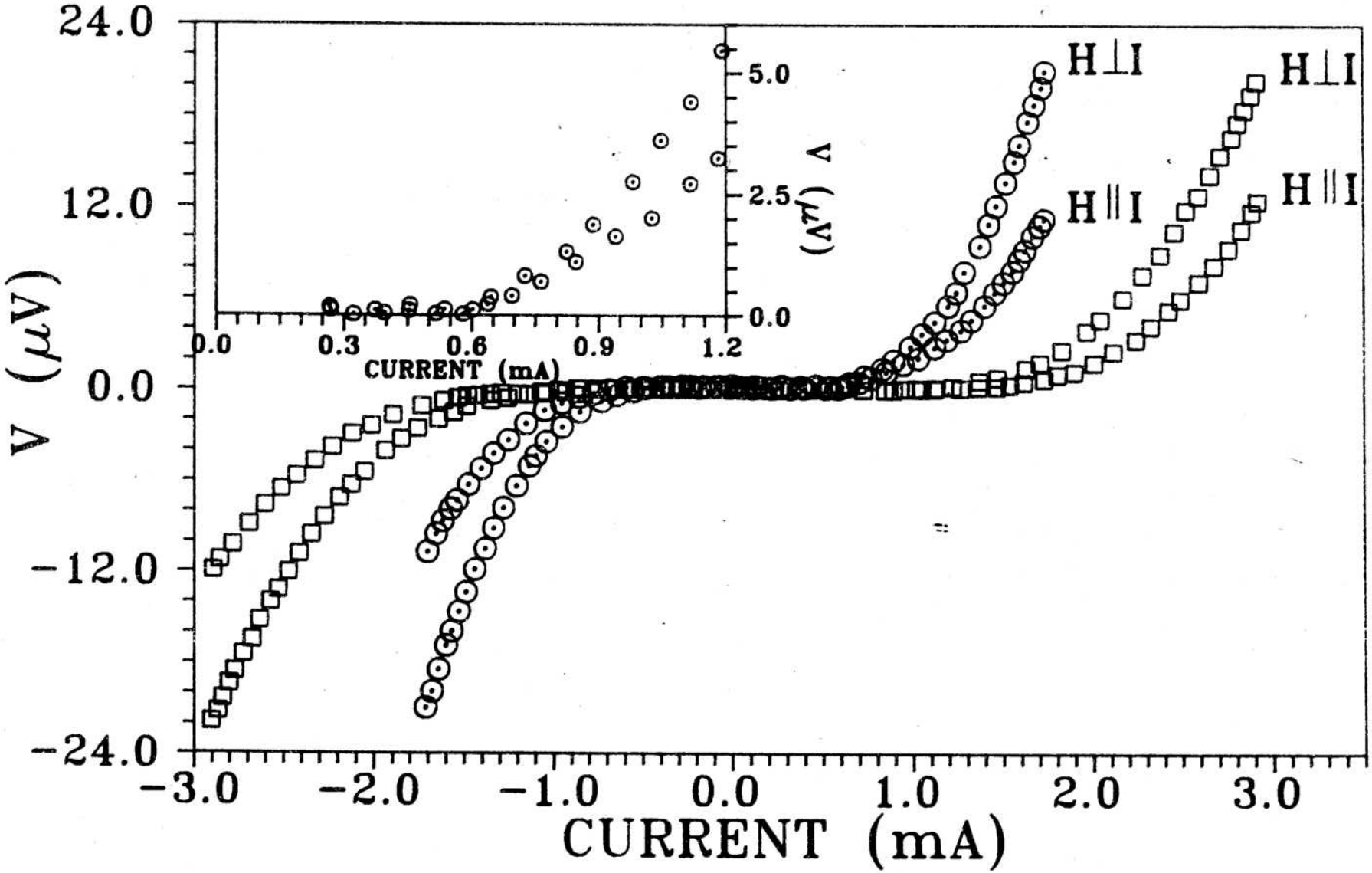
24.0
12.0
0.0
−12.0
−24.0
V (μV)
−3.0
−2.0
−1.0
0.0
1.0
2.0
3.0
CURRENT (mA)
H⊥I
H∥I
H⊥I
H∥I
5.0
2.5
0.0
V (μV)
0.0
0.3
0.6
0.9
1.2
CURRENT (mA)

Fig 2

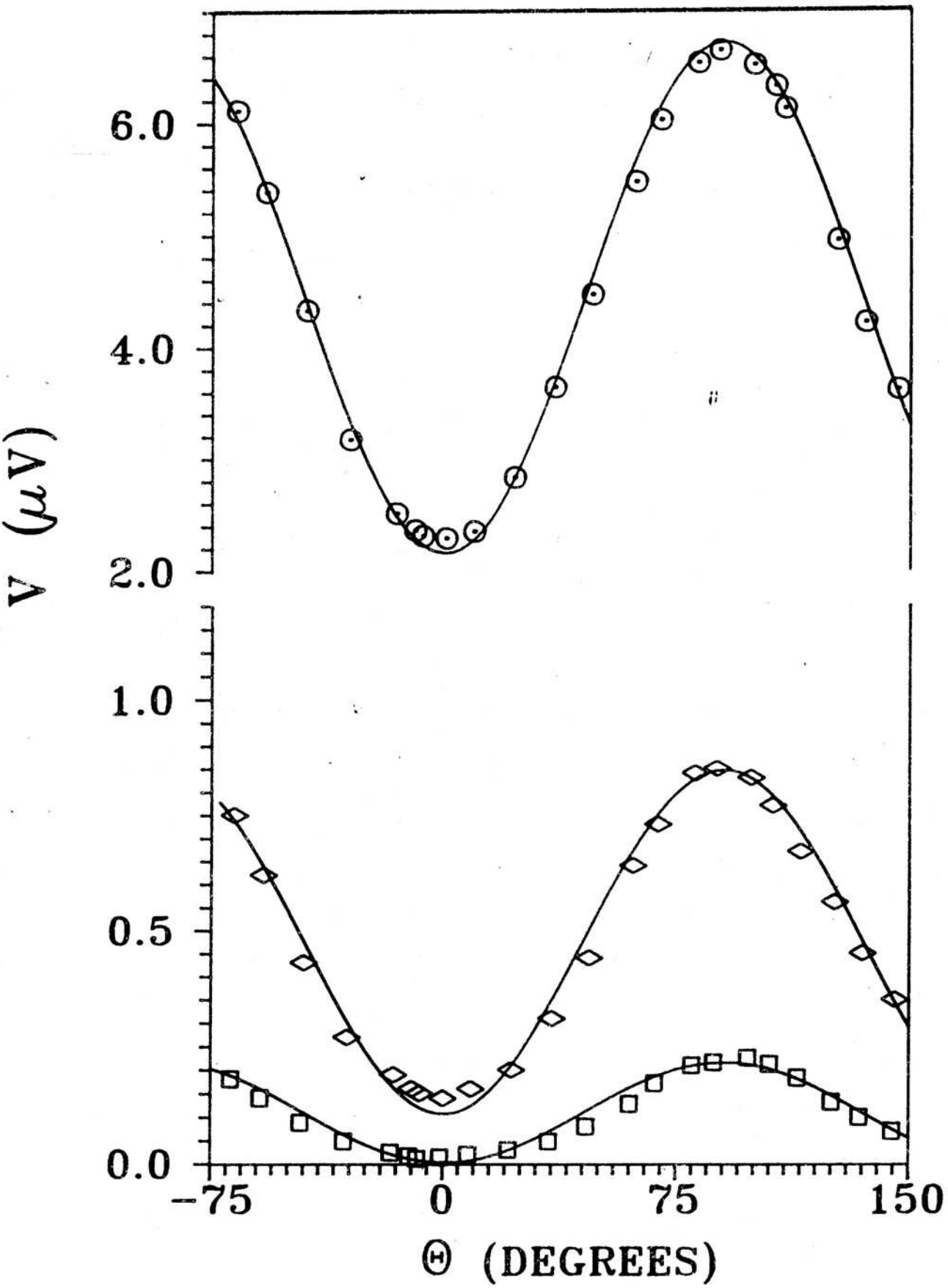

Fig 3