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# Electric potentials associated with steady conduction currents in superconducting coils

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From attempts to observe electric fields arising from charge-neutral, current-carrying superconducting coils (NbTi, Nb and Pb) we conclude that effects previously reported are not fundamental departures from conventional electromagnetic theory. The null results predicted by Maxwell's theory are confirmed to within two parts in one thousand.

## 1. Introduction

### *1.1. Historical background*

Whether or not the magnitude of electric charge is independent of the motion of that charge is of fundamental importance in electromagnetic theory and remains a question of current interest [1–3]. In Maxwell's theory and special relativity, charge is a Lorentz scalar and, hence, is not dependent on motion.

Many experiments have been performed to test the question [4]. Most of them confirm conventional theory, however a series of experiments by Edwards, Kenyon and Lemon gave apparently contrary results [5–7]. The experiments were designed around a coil of superconductive wire connected to an electrometer. Current-correlated (hence, apparently velocity-dependent) electric fields appeared when the current in the coil was changed. This conclusion was inferred by changes in the potential of the coil relative to ground. It was as if the coil had acquired a charge.

The present experiments are an attempt to establish whether the previous results truly represent a fundamental departure from Maxwell's theory or were merely spurious signals from conventional sources [8]. Another recent experiment using a beam-power radio tube isolated in a Faraday cage gave negative results [9].

### *1.2. Theoretical background*

The theoretical framework from which experimental results can be predicted has previously been throughly discussed [5,7]. We here briefly describe that framework.

The Liénard–Wiechert potentials for a moving charged particle may be expressed to order $1/c^2$ ($c$ being the vacuum speed of light) in terms of the present quantities, velocity, $\boldsymbol{v}$, acceleration, $\boldsymbol{a}$, and the position vector, $\boldsymbol{r}$, from the particle to the field point. When such an expression is applied to a net-charge-neutral conductor with steady currents in a closed circuit by integrating over all possible charges, the resulting electric field is zero. On the other hand, to represent possible second-order deviations from classical theory, velocity terms are introduced with arbitrary coefficients and the electric field may be expressed as

$$\boldsymbol{E}=\frac{1}{4\pi\epsilon_0}\int\frac{\rho}{r^2c^2}\,[\gamma_1 v^2\boldsymbol{n}+\gamma_2(\boldsymbol{n}\cdot\boldsymbol{v})^2\boldsymbol{n}+\gamma_3(\boldsymbol{n}\cdot\boldsymbol{v})\boldsymbol{v}]\,\mathrm{d}^3x\,, \quad (1)$$

where $\rho$ is the conduction charge density and $\boldsymbol{n}=$

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$\boldsymbol{r}/r$. The parameters $\gamma_1$, $\gamma_2$, and $\gamma_3$, if nonzero, represent deviations from Maxwell's theory.

### 1.3. Experimental arrangement

Using the general formulation in eq. (1) we consider the experimental situation in question: a coil of superconductive wire of length $L$ into which a current $I$ can be introduced as represented in fig. 1. Fig. 2 is a reproduction of cutaway drawings of the assembly taken from a previous publication [7]. The coil is surrounded by a closed conducting shield. A velocity-dependent electric field would raise the coil to a potential $\Phi$ relative to ground just as though the coil had become charged. The potential would depend upon the gamma parameters, the geometry of the system and the distribution of current density $\boldsymbol{j}$

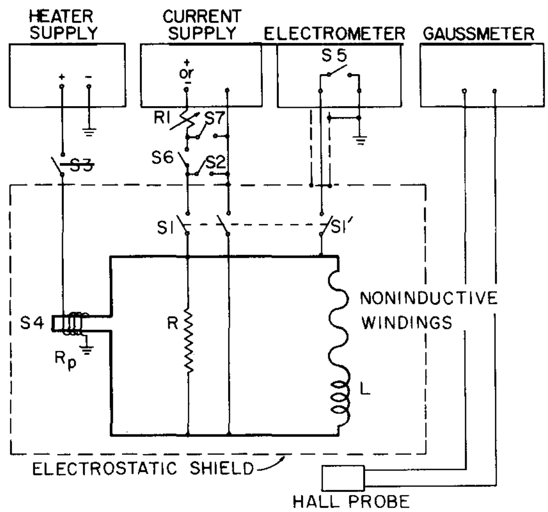


Fig. 1. Diagram of the basic circuit. S4 is a heat-activated switch that is covered by liquid helium. When S3 is closed current flows through resistive windings, the heat from which drives the hairpin section of superconductive wire normal. This raises the resistance $R_p$ to a value many times $R$. Thus closing S3 in effect "opens" S4. Current is introduced into the circuit as follows: (S2 and S7 remain open and S6 remains closed during this entire procedure). With S4 open (S3 closed) S1 is closed, causing current to flow from the external supply through the superconducting coil. When the current reaches the desired magnitude, S4 is closed (S3 is opened) and S1 is opened which puts the superconductive circuit into a persistent mode. While in this mode S1′ and S5 are closed and potential measurements are begun. The dependence of the potential upon the current is observed by causing the current to decay through $R$ by once again opening S4 (closing S3).

within the wire. The potential is calculated from

$$\Phi=\frac{\epsilon_0}{C}\int \boldsymbol{E}\cdot\mathrm{d}\boldsymbol{S}\,, \qquad (2)$$

where $C$ is the coil to ground capacitance. Using eq. (1) this can be expressed as

$$\Phi=\frac{\kappa\alpha L I^2}{\rho C A c^2}\,, \qquad (3)$$

where $A$ is the wire cross-sectional area, $\rho$ is the superconducting charge density and $\alpha$ is a parameter used to account for non-univorm current densities through the relation

$$\alpha=\frac{A}{I^2}\int j^2\,\mathrm{d}A\,. \qquad (4)$$

The parameter $\kappa$ in eq. (3) represents the deviation from conventional electromagnetic theory. It depends upon the gamma parameters and the geometry of the system. For values of the gamma's on the order of 1 (as, for example, in Weber's electrodynamic theory [10]) $\kappa$ would also be on the order of 1. Conventional theory yields $\kappa=0$.

A maximum value of $\alpha$ can be estimated using superconductor theory. The current density in a type I superconductor decreases exponentially with distance into the wire. If $a$ is the radius of the wire, $r$ the distance from the center of the wire, and $\lambda$ the penetration depth (typical values of which are near $4\times10^{-8}$ m) then, using

$$j=\frac{I}{2\pi a\lambda}\exp[-(a-r)]\,, \qquad (5)$$

eq. (4) gives to first order in $\lambda/a$

$$\alpha_{\max}=a/4\lambda\,. \qquad (6)$$

Uniform current density across the wire cross section is represented by $\alpha=1$. For a type I superconductor we would expect $\alpha=\alpha_{\max}$. On the other hand, type II materials should have lower $\alpha$ values because internal current filaments could form. We select the value $\alpha=\alpha_{\max}/40$ for type II superconductors although this is but a rough estimate.

The materials used were NbTi and Nb (both type II) and Pb (type I). The radii $a$ were $6.35\times10^{-5}$ m, $6.35\times10^{-5}$ m and $2.54\times10^{-4}$ m, respectively. For Nb and Pb, experimental values [10,11] for $\lambda$ were

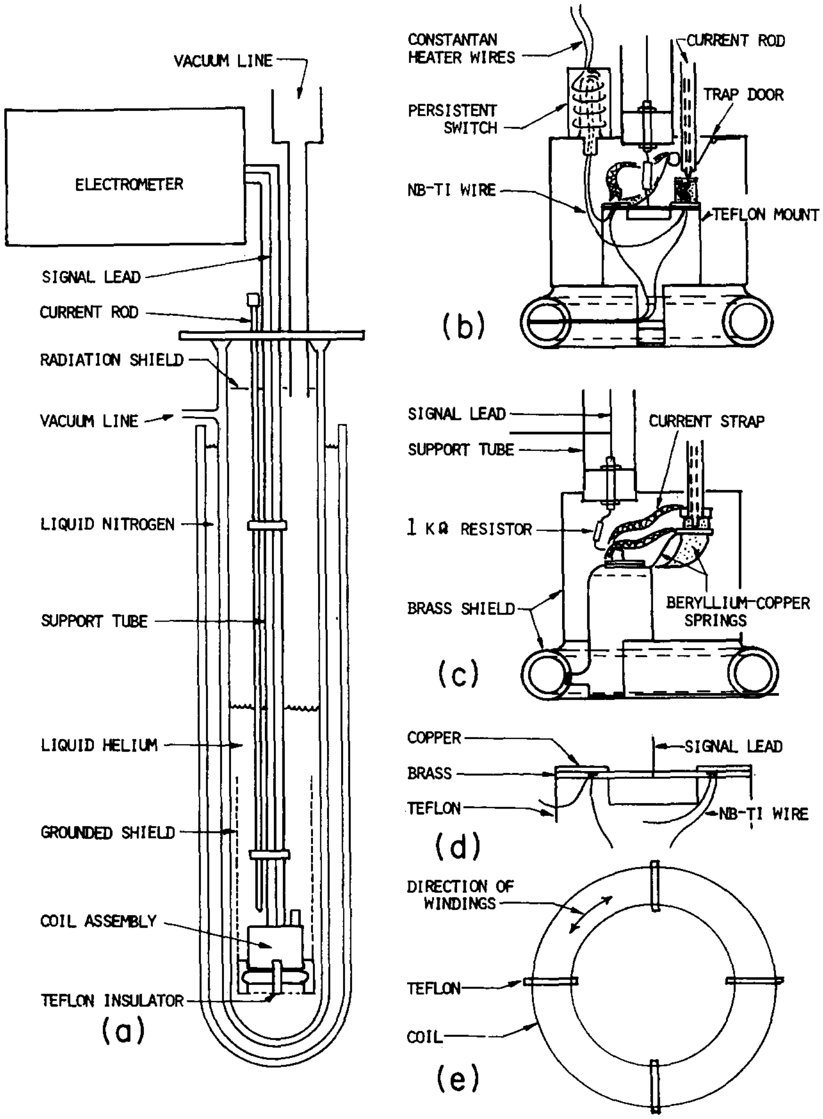


Fig. 2. Cutaway drawings of the apparatus for most variations. (a) Overall view. (b), (c) Two side views of the coil ssembly drawn in $\frac{1}{2}$ scale. (d) Enlarged view of the shunt resistor and mount. (e) Top view of the coil. The coil assembly is surrounded by the brass shield which has $\frac{1}{32}$ inch thickness. The support tube is $\frac{3}{4}$ inch outer diameter and has some sections that are copper and others that are stainless steel for thermal isolation. This tube also serves to shield the signal lead which is a 0.010 inch diameter constantan wire. The support tube was electrically grounded. The coil assembly shield was electrically insulated from the support tube by teflon insulators.

used: $3.9\times10^{-8}$ m and $3.7\times10^{-8}$ m, respectively. For NbTi we used the value of $\rho$ estimated by Edwards et al. [7], $9.0\times10^{9}$ C/m$^3$, and $\lambda^2=m/\mu_0\rho_s e$ to get $\lambda=2.25\times10^{-8}$ m. Using the above data we obtain the $\alpha$ estimates for NbTi, Nb and Pb: 18, 10 and 1700, respectively. Note the high sensitivity of Pb.

In a given experiment we use eq. (3) to determine $\kappa\alpha$. Then from the above considerations on $\alpha$ we can infer a value, a range or an upper limit for $\kappa$.

### 1.4. Measurements of $\kappa\alpha$ using superconductors

The earlier results obtained by Edwards et al. [5–7] are summarized as follows:

(1) The potentials are current dependent, behaving as $I^{2.02\pm0.05}$.

(2) To determine $\kappa\alpha$ values Edwards et al. used eq. (3) with $A=1.3\times10^{-8}$ m$^2$, $\rho=9.0\times10^9$ C/m$^3$ and $C=96$ pF. From this and measured values for $\Phi$ they determined $\kappa\alpha$ values ranging from 18 to 890.

((3) The signal was present in a Faraday cage setup. In that configuration the electrometer input was connected to a cage surrounding the superconducting coil rather than to the coil itself. Any effect that only redistributes the charge on the coil without affecting its total apparent net charge is unlikely to be the source of the potential.

(4) Based on calculated parameters of the experiment, the following were deemed unlikely as being the source of the potential observed: thermoelectric effects, chemical potential, helium desorption, flux motion potentials and charge transfer on helium bubbles.

(5) One important question went unanswered: How can one account for the fact that different $\kappa\alpha$ values were observed in different runs? Because type II superconductors were used it is not unreasonable to expect some variation of $\alpha$ resulting from variations of the current pattern, but this could hardly be expected to explain the observed range of over a factor of 40. Furthermore, $\kappa$ is obtained from the $\gamma$'s, which are basic parameters of the theory, and from system geometry which does not change from run to run. Hence, $\kappa$ would be a constant. The fact that the $\kappa\alpha$ constant of proportionality changed dramatically from run to run is puzzling.

### 1.5. Need for experiments

In view of the prediction of Maxwell's theory the experimental results by Edwards et al. were indeed anomalous. There are several possibilities:

(1) The potentials observed by Edwards et al. were spurious; i.e., due to unidentified conventional sources.

(2) The potentials represent a new mechanism for producing electric fields albeit one that can be explained within the context of conventional electromagnetic theory.

(3) The potentials require a modification of conventional electromagnetic theory in this area of application.

The need for further study is evident.

## 2. Experimental procedure

The apparatus (see figs. 1 and 2) and the procedure for measuring the potential has been previously described in detail [7]. We summarize the procedure as follows: First, current is introduced into the coil from an external battery; the current in the coil is monitored by measuring the magnetic field produced by a few inductively-wound turns. The coil is then put into a persistent mode (zero resistance) and external contacts are removed. The electrometer, used to measure the electric potential with respect to ground, is then switched into the circuit. The electrometer connection was to (a) one end of the coil, (b) a center tap on decay resistor $R$ or (c) a Faraday cage surrounding the apparatus depending upon the particular apparatus configuration. Resistance $R$ is introduced into the circuit using an externally activated heat switch S4 causing the current to decay away while the potential is monitored. The result is a determination of $\Phi$. This constitutes one run.

In order to use eq. (3), values of $L$, $C$ and $A$ were determined for each experiment. Typical values are, respectively, 100–1000 m, 100 pF and $10^{-8}$ m$^2$. Then, using the $\alpha$ values mentioned earlier, values or limits for $\kappa$ were inferred.

## 3. Individual experiments and results

### 3.1. Dependence on circuit parameters

In the present experiments we investigated the dependence of the potential on the following circuit parameters: wire length $L$, coil inductance $L_c$ and circuit resistance $R$. Examination of the coil length was motivated by eq. (3). If velocity-dependent fields were responsible than we would expect

$$\Phi \propto LI^2 . \quad (7a)$$

On the other hand, if the magnetic energy was somehow responsible for the potentials then we would expect

$$\Phi \propto L_c I^2 . \tag{7b}$$

Another conventional explanation might involve thermoelectric or temperature-related effects in which case we would expect

$$\Phi \propto R I^2 . \tag{7c}$$

In this experiment we used a simple $L_c$R circuit which could be put into a persistent-current mode or into a decaying mode by switching in a brass resistor having resistance $R$. One coil, designated coil 0, was always in the circuit. It consisted of 15 m of 5-mil diameter NbTi wire wound inductively. Two other coils, 1 and 2, could be independently switched into the circuit in series with coil 0 (and with each other if both were being used). Coils 1 and 2 were wound noninductively; coil 1 had 186 m of wire and coil 2 had twice that much. The coils were designed so that coil 0 dominated the total inductance, magnetic field and vector potential and coils 1 and 2 dominated the wire length $L$.

To quantitatively examine the alternative relationships of eqs. (7) we introduce the parameter $\eta$ defined as

$$\eta = \frac{\Phi_m(\text{coil } 0)}{\Phi_m(\text{coils } 0+1+2)} , \tag{8}$$

where $\Phi_m$ is the mean potential for a series of runs.

For coil 0 there was no signal observed above the noise level so for $\Phi_m(\text{coil } 0)$ we use the upper limit which was determined to be $3\times10^{-6}$ V/A$^2$. The value of $\Phi_m(\text{coils } 0+1+2)$ was $(2.09\pm0.07)\times10^{-4}$ resulting in the experimental value $\eta<0.015$.

We compare this observed value of $\eta$ with those predicted by the relationships of eqs. (7a)–(7c) which we calculated as follows: Using (7a) we calculate $\eta(L)$. The values of the potential are dependent upon $\kappa\alpha$ which varied from run to run. To establish an upper limit on $\eta$ we let $\kappa\alpha$ assume its extreme value of 890 while using the observed value, 415, for coils 0+1+2. This yields $\eta<0.082$. The observed value, 0.015, lies within this interval.

The relative inductances in the circuit with coil 0 alone and with coils 0+1+2 were determined by comparing the decay time constants. Differences in the time constants for the four coil combinations were not larger than the uncertainty to which the values could be determined which was 3%. Using (7b) this yields $\eta(L_c)>0.97$ which is too high. The value of $\eta(R)$, as predicted by eq. (7c), was obtained by comparing the rate of decay of the current with the resistor in the circuit to that with it out of the circuit. In this way we conclude that the entire circuit resistance appears in the resistor $R$ to within 1% uncertainty. This gives $\eta(R)>0.99$ which is well above the observed value, 0.019, so resistive effects must not be a factor.

The parameter $\eta$ falls within the expected range of values predicted by eq. (7a). However, the expected values from eqs. (7b) and (7c) are 51 and 53 times larger, respectively, than the maximum limit of the observed value. We conclude that the potential is dependent upon the length of the coil but not upon resistance or inductance.

### 3.2. Superposition

Another expected characteristic of the potentials that we examined using the configuration of the last section was linear superposition of potentials from different coils in the circuit. To test this we formed a superposition parameter, $\zeta$:

$$\zeta = \frac{\Phi_m(\text{coils } 0+1+2)}{\Phi_m(\text{coils } 0+1)+\Phi_m(\text{coils } 0+2)-\Phi_m(\text{coil } 0)} . \tag{9}$$

This test assumes that, for each coil, the pattern of the current density, indicated by $\alpha$, as well as the value of $\kappa$, do not change during a particular series when switching from one coil configuration to another, however the test does permit $\kappa\alpha$ changes between series. If superposition of the signals produced by a combination of coils holds, then $\zeta=1.00$.

Particular strengths of this test are its independence from the $\kappa\alpha$ values of each coil and from their lengths.

Three series of runs were performed, in one of which coil 2 had 186 m of wire rather than 372 as reported in section 3.1. Superposition held in every case. The value of the mean superposition parameter $\zeta$ is $0.98\pm0.03$. This result, as well as the previous result with the $\eta$ parameter is consistent with the idea that the source of the potential is related to the current within the coils.

### 3.3. Niobium coil experiments

A number of important properties of superconductors are dependent upon the Ginzburg–Landau (GL) parameter which is the ratio of the penetration depth to the coherence length. The GL parameter is a measure of the pinning of fluxoids in the material: Because moving fluxoids can produce voltages it seemed plausible that the potentials might depend upon the GL parameter. To examine this question we ran the experiment using Nb wire which has a GL parameter of 0.78, whereas for NbTi it is greater than 20.

We repeated the basic experiment using a coil of 5-mil diameter niobium wire with formvar insulation. The niobium was zone refined with manufacturer's purity specification of 0.99999. The coil was 610 m long and was bifilar wound with four additional inductive turns. Data were taken in two series three days apart. The first series of experiments was done at the usual temperature of 4.2 K. The second series was performed between the temperatures of 1.79 and 1.95 K which is below the lambda point.

There are three important similarities between the Nb and the NbTi data. First, the potential during a run was an even function of $I$ and approximately followed the $I^2$ exponential behavior. Second, the run-to-run magnitude changes seen with NbTi applied also to Nb. Third, the mean $\kappa\alpha$ factors for each series, 173 and 104, were in the range of mean values obtained from NbTi coils.

We conclude that there is no significant behavioral difference in the effect that is related to the Ginzburg–Landau parameter.

### 3.4. Magnitude variation analysis

The large changes in the magnitude of the potential from run to run has been puzzling. As in earlier publications we characterize the magnitude by applying eq. (3) to the observations and assigning $\kappa\alpha$ values. One can hardly imagine variations in $\kappa$ inasmuch as $\kappa$ results from constants of the theory and simple geometrical considerations. On the other hand, because $\alpha$ depends upon the precise nature of the current distribution within the superconductor, the $\alpha$ values could be subject to some variation. Fluxoid-type current paths might be imagined, at least in type II materials, which depend upon fluxoid pinning and possibly are more dense during one run than another. Thus $\alpha$ might depend upon the history during a particular cool down although, frankly, we have no clear details to offer on this conjecture and because the observed variability is so extreme (factors of up to 100) it seems quite unlikely that it can be accounted for in this manner.

Perhaps there are other possible explanations for the $\kappa\alpha$ variations although we must admit that accounting for them while at the same time maintaining the interpretation that a nonzero value of $\kappa$ represents a fundamental change in electromagnetic theory is rather like "swallowing a camel".

In all of our earlier experiments as well as most of the present ones only positive potentials (with positive $\kappa\alpha$ values) were observed, however several of our recent experiments using NbTi had negative signal magnitudes with $\kappa\alpha$ values ranging from $-13$ to $-681$. Three coils had consistently negative magnitudes. Another coil gave negative potentials during one series and positive potentials on the next. We cannot explain this switch from positive to negative potentials but one thing is clear: It seems to doom our earlier interpretation of the potentials as straightforward, fundamental deviations from conventional electromagnetic theory. From eq. (3) we see that the potential involves three types of quantities: First are those which by definition are positive. These include $\alpha$, $L_c$, $L$, $I^2$, $C$, $A$ and $c$. Second is the charge carrier density, an unlikely candidate for a change of sign. Finally we have $\kappa$, which is a fundamental constant of the theory and therefore not a candidate for a change. Consequently it would seem impossible for the potential values to reverse in sign. The fact that they do is telling evidence that they are not due to the fundamental mechanism described by eq. (3).

An additional feature of the potentials that appeared through our analysis of the magnitude data from all experiments is that the clustering of $\kappa\alpha$ values for individual series appears to form a Gaussian distribution. For example, for one series consisting of 40 measurements the mean $\kappa\alpha$ value was $104\pm6$. A least squares fit of a Gaussian function gave a standard deviation with a reduced chi-squared value for the fit of 0.97, corresponding to a 46% probability that such a chi-squared value or higher would result from random deviation alone.

Further analysis of the $\kappa\alpha$ distributions for all series of runs strongly suggests that for each undisturbed series the standard deviations from the mean are proportional to the mean values themselves. By "undisturbed" we mean that the coils do not experience any mechanical or undue electrical disturbances while a series of runs is being performed. Under such a condition the value of chi-squared for the fit was 0.243, corresponding to a probability of 94%. This indicates a strong linear correlation between the mean $\kappa\alpha$ values and the standard deviations about those means.

### *3.5. Pb coil experiments*

Because all previous experiments were made with type II superconductors, we repeated the basic experiments using a coil wound with wire made of a type I material. The coil consisted of Pb wire with a manufacturer's purity specification of 0.99999. The 151 m long wire was 20-mil diameter and had a 3-mil insulating nylon jacket. It was bifilar wound on a nylon spool in the form of toroid. In addition to 448 bifilar turns there were four inductive turns to provide a field for current monitoring. The apparatus was not in the Faraday cage configuration; the voltage pickoff point was at the end of the superconducting coil.

We performed 173 separate runs using the Pb coil. There were no signals observed above the noise level. The fact that no signals ever appeared is strong evidence that the potentials in other variations were not fundamental. According to the hypothesis being tested potentials must be observed in the present case as well as in others. The nonappearance of a signal in this case leads us to conclude that the other potentials were anomalous. This conclusion is supported by a conventional explanation for the appearance of potentials which will be given later. The determined value of $\kappa\alpha$ is $0\pm2.0$; using $\alpha_{Pb}=1700$ (section 1.3) this translates into $|\kappa|<0.0019$.

### *3.6. New Faraday cage configuration*

In variation II of the experiments of Edwards et al., a Faraday-cage configuration was used [7]. The present configuration was different in three ways:

(1) An altered assembly at the end of the brass support tube permitted the electrometer input line to be connected either directly to the superconductive coil circuit (non-Faraday cage configuration) or to the outside of the surrounding brass box (Faraday configuration).

(2) A doubly shielded heat switch in which the heater coil wires were completely enclosed by a grounded metal shield and the superconductive hairpin segment was enclosed by, but electrically isolated from, another metal shield which itself was connected to the brass box enclosing the superconductive circuit. In the Faraday cage experiments of Edwards et al., the resistance used to decay the currents was permanently in the superconductor circuit. The present arrangement allowed the resistance to be introduced when desired.

(3) A grounded graphite coating inside the liquid helium dewar replaced the bronze screening which had served as the outer cage in the previous Faraday configuration. This also allowed the use of somewhat different teflon insulators to separate the inner shield from this new outer shield.

These tests were performed in seven separate series of runs. In four series the runs were in the non-Faraday configuration and in three they were in the Faraday configuration.

In all runs of each series in the non-Faraday configuration, $I^2$ voltages were observed which had $\kappa\alpha$ values ranging from 26 to 275, well within the range of positive values observed earlier (12–890). Furthermore, the fits of $n$ to $I^n$ are, on the whole, in agreement with the previous fits which determined that $n$ was very near 2.0 so we conclude that these voltage signals are of the same type and general origin as those of previous superconductive coil experiments.

Whereas the earlier Faraday configuration experiments gave current-correlated voltages, the present ones did not. The results were null whether or not a heat switch was in the circuit. The differences might have been due to changes in the teflon insulators used in this variation.

Because of the agreement of the new values of the primary parameters $\kappa\alpha$ and $n$ with the previous ones, we conclude that the voltage signals appearing in the new non-Faraday cage configuration are of the same type and general origin as those of the previous superconductive coil experiments. However, that no signal appeared in any of the new Faraday tests implies that the observation of an $I^2$ signal is somehow dependent upon the test configuration. Furthermore, if the $I^2$ signal observed is really the fundamental $v^2$ signal originally sought, it should not require a contact for its mediation and should be independent of the measurement configuration.

The probability of obtaining the observed test results in the two configurations is expressed by $P=pN(1-p)F$ where $p$ is the probability of observing the signal on series of runs, and $1-p$ is the probability of observing no signal. The number $N$ of series of non-Faraday configuration tests (in which signals were observed) is 3 and the number $F$ of series of Faraday configuration tests (no observed signals) is 4. The maximum probability of coincidentally making observations so dependent upon the configuration sequence is thus $P=0.00084$.

This low probability to coincidentally observe such a sequence is strong evidence that the $I^2$ voltage signal is dependent upon the voltage measurement configuration and argues against an interpretation of the $I^2$ signal as representing the fundamental $v^2$-dependent electric field originally sought.

We use eq. (3) to obtain a limit on $\kappa$ from this experiment. With an experimental resolution on the ratio $\Phi/I^2$ of $2.5\times10^{-6}$ V/A$^2$ and using $\alpha_{\mathrm{NbTi}}=18$ we obtain $|\kappa|<0.05$.

## 4. Summary and conclusions

We now summarize the results of the present experiments:

(1) *Nb and NbTi coils (type I superconductors).*

(a) Potentials were observed. In individual runs they were functionally dependent upon $I^2$.

(b) Run to run potential magnitudes differed markedly. The $\kappa\alpha$ values, which are a measure of the magnitudes as defined in eq. (3), range from $-681$ to $+890$. One NbTi coil had positive values during some series and negative values during others.

(c) $\kappa\alpha$ values for individual series form Gaussian distributions with the widths of the distributions being linearly proportional to the means.

(d) The potential magnitudes were linearly dependent upon the length of the coils.

(e) The potential magnitudes were not dependent upon circuit inductance.

(f) The potential magnitudes were not dependent upon circuit resistance.

(g) The potential magnitudes measured separately in different coils added linearly to give the magnitudes when the coils were connected in series.

(h) There was no discernable change in the behavior of the potentials observed using a Nb coil cooled below the lambda point.

(i) Potential characteristics were basically the same in two materials having very different Ginzburg–Landau parameters (Nb with 0.78 and NbTi with $>20$).

(2) *Faraday cage configuration*

A NbTi coil was examined in both Faraday cage and non-Faraday cage configurations. All non-Faraday-cage runs resulted in signals ($26\leqslant\kappa\alpha\leqslant275$) whereas all Faraday cage runs gave no signals ($|\kappa|<0.05$). The probability of such a sequence of signal and nonsignal series of runs occurring randomly is 0.00084.

(3) *Pb coil experiment.*

In 173 runs using a coil made of Pb wire (a type I superconductor) there was never a positive signal. The bound obtained is $|\kappa|<0.0019$.

We conclude that the $I^2$-correlated potentials observed in these experiments as well as those in our previous experiments [7] do not represent a fundamental deviation from standard electromagnetic theory and that conventional electromagnetic theory is confirmed. Our overall upper limit on $|\kappa|$ is 0.002.

Potentials observed in experiments using Nb and NbTi superconductors do have several properties expected of fundamental electric fields (see 1a, 1d–1g above). On the other hand, several crucial experiments failed the test (see 1b, 2 and 3). To truly represent a fundamental deviation of the type postulated (eq. (3)), every one of the tests must be passed. If the tests are well-constructed and unambiguous, a single failure would force us to discard the hypothesis being tested and direct our attention to some other explanation of the potentials in the cases where they are being observed.

## 5. Explanation of potentials

Our conclusion, that currents in closed superconducting circuits do not give rise to electric fields as a primary result of the motion of the charge carriers, leaves one question remaining: why were secondary potentials seen with some materials in some configurations? These potentials initially led us to the conclusion that the hypothesis might be true. After an extensive examination of this question we have concluded that stray charges on teflon insulators induced a potential difference when conductors moved slightly as the result of magnetic forces on the conductors which changed when the coil current was changed.

When using one particular apparatus configuration we observed huge potential shifts (up to $\sim 1$ V). After a careful search the following picture emerged: When the current decayed, energy was dissipated as heat in the liquid helium. This caused a lowering of the helium level in the apparatus. In turn this changed the temperature gradient across a portion of the apparatus which, through thermal expansion, altered the position of conductors relative to stray charges on some teflon insulators which were used (1) to isolate the coil of superconductor wire from its mounting box, (2) to isolate the rest of the superconductor circuit and (3) to isolate the signal lead to the electrometer. As a consequence the voltage induced by the stray charge changed.

Although the circumstance involving the configuration of components of the apparatus and giving rise to the huge potentials was rather peculiar, we thought that the more usual, smaller potentials ($\sim 10$ mV) might have a similar origin. Arguing that heat was the source of the motion which resulted in electrostatic induction could not be maintained, however because the potentials we usually observed were proportional to wire length (1d) and not to usual sources of heat such as Joule heating or disipation of energy stored in the field resulting from inductive windings. Other sources of heat, such as the kinetic energy of the electrons were too small to be considered.

We have concluded that the change in position of different parts of the apparatus, leading to electrostatic induction, resulted from internal stresses produced by magnetic forces within the coil. Although the coils were wound in a manner so as to minimize the magnetic fields (just a few inductive windings) there were, nevertheless, rather large fields very near the wire. These fields would produce a force on adjacent wires. Approximating the field as equal to that produced by a long straight wire, we have $B=\mu_0 I/2\pi r$ where $I$ is the current in the wire and $r$ is the distance to nearby wire sections. The resulting force per unit length is approximately $4\mu_0 I^2/2\pi r$. This force is proportional to the square of the current as required and although the detailed manner in which the forces would add and cancel is very complicated it is reasonable that the total effect would be proportional to the wire length. The induced electrostatic potential change would also depend upon the magnitude (and sign) of the charge isolated on nearby insulators which, of course, could vary from run to run.

For a current of 100 A and a distance to nearby wire sections equal to one wire diameter the force per unit length is 60 N/m. Such a force seems capable of distorting the coil sufficiently to induce the millivolt signals. Because the capacitance in the circuit was so small, a change in the positioning of the conductors as little as $10^{-8}$ m could produce the observed effects.

This mechanism accounts for all of the observed features of the potential including large magnitude differences and sign changes.

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