Spinning magnets and Jehle's model of the electron*

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We have improved a classical test of unipolar induction. In this experiment a cylindrical sample of magnetized steel is spun about its axis inside a hollow, insulated steel sphere. According to the moving-line theory of unipolar induction the rotating magnetic field generates an electric field $\vec{E}=-(\vec{\omega}\times\vec{r})\times\vec{B}$ in the region exterior to the magnet. This field will have the effect of elevating the potential of the enclosing sphere. We have searched in vain for such an effect and conclude that if the magnetic field lines are moved at all by the rotation of a magnet about its axis they are dragged with a coefficient less than 1.4×10^{-4}. This limit is approximately 100 times more stringent than the 1912 measurement of Kennard. We discuss the application of this work to Jehle's recent model of leptonic charge.

INTRODUCTION

For nearly a century after its discovery by Faraday in 1832, the unipolar generator was a conundrum for the theory of electromagnetism.[1] The experimental facts were not in dispute. A cylindrical bar magnet is spun about its axis. Pressed against the magnet is a stationary wire *ABC*, touching the pole of the magnet at *A* and the equator at *C*. A current is observed in the wire. This current is the quotient of the electromotive force and the total resistance of the circuit formed by the wire and the return path through the conducting magnet. In turn the emf is the product of the frequency of rotation and the magnetic flux through any conical surface having a vertex at *A* and a perimeter defined by a circle of revolution through the point *C*, (see Fig. 1).

Although the experiments were undisputed, their explanation was. The most vexatious question concerned the "seat" of the emf. Was this electromotive force produced by charged carriers in the magnet moving across stationary lines of force, or was it rather the lines of force which rotated with the magnet thereby inducing an emf in the wire *ABC*? Nineteenth century physicists were equally divided in their support for the moving-line (ML) and stationary-lines (SL) hypotheses. Weber was the chief proponent for moving lines.[2] Faraday eloquently expressed the stationary-line hypothesis: "The system of power about the magnet must not be considered as necessarily rotating with the magnet, any more than the rays of light which emanate from the sun are supposed to revolve with the sun."[3] Unfortunately, the unipolar induction experiment, being sensitive only to the emf around the complete loop, could not identify whether the origin of this force was in the stationary wire or spinning magnet.[4,5]

To determine the seat of the emf it is necessary to open the circuit. This is done by replacing the wire with a cylindrical capacitor mounted coaxially around the spinning magnet. According to the ML hypothesis the motion of the magnetic field lines in the region outside the magnet should produce an electric field

$$\vec{E}=-\frac{\vec{V}}{c}\times\vec{B}=-(1/c)(\vec{\omega}\times\vec{r})\times\vec{B}\,, \qquad (1)$$

where $\vec{\omega}$ is the angular speed of rotation of the bar magnet. (Here the minus sign arises because the laboratory is rotating with angular velocity $-\omega$

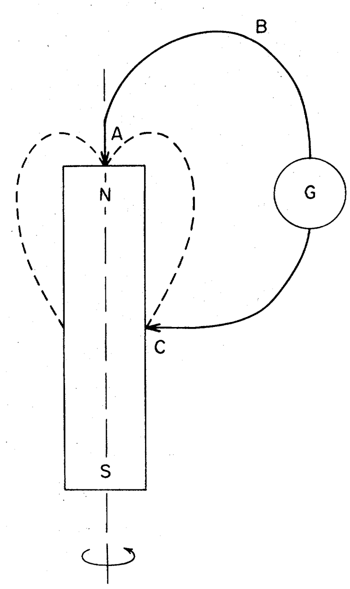

FIG. 1. Faraday's unipolar generator. A spinning magnet generates a current in the stationary wire *ABC*. The driving emf is proportional to the magnetic flux through the dashed surface.

relative to the magnet.) In the central region of the magnet this electric field is nearly radial. Hence, a cylindrical capacitor wrapped around this region should become charged.

Alternatively, if the SL hypothesis is correct, the charge carriers in the magnet will be moved radially by the Hall effect. The electric field arising from this distribution of charge, however, is electrostatic in origin and hence can be shielded by grounding the inner shell of the cylindrical capacitor. Thus, according to the stationary-line hypothesis the capacitor should not be charged by spinning the bar magnet.

The experiment was performed in 1912 by Kennard.[6] Although sensitive to potentials as small as 0.02 of that predicted by the ML hypothesis, the experiment failed to find any. In a different version of the experiment a stationary cylindrical capacitor was placed inside a rotating solenoid. Again the moving-line theory [Eq. (1)] predicts an induced potential across the capacitor upon spinning the solenoid. Barnett,[7] Pegram,[8] and Kennard[9] separately looked for such an induced potential without success.

Although the experiments were unambiguous, the authors differed in their interpretations. Kennard and Pegram argued that the ML theory had been decisively squelched. Barnett felt that the moving lines might produce a polarization of the ether such as to cancel exactly the induced electric field.[10] In 1922 Barnett's argument was analyzed and rejected in the thorough review by Tate.[11] Thus, 90 years after its invention, physicists found a generally acceptable explanation for the phenomenon of unipolar induction.

Interest in the moving-line theory has recently been revived. Djurić has given a detailed analysis of both the closed-loop (Faraday) and open-loop (Kennard *et al.*) versions of the unipolar generator. He finds that neither version can distinguish between the ML and SL hypotheses.[12] Indeed, his analysis when applied to our experiment leads to an expected null result regardless of whether the SL or ML theory is assumed. We are not in agreement, however, with Djurić's analysis. (See Appendix.)

Jehle has recently incorporated the ML hypothesis into an intriguing model for the charge of a lepton.[13] It is generally believed that the charge of an electron is fundamental and that its magnetic moment arises from a spinning charge. Jehle proposes the reverse. The magnetic moment is fundamental. Because the electron is spinning, it drags its magnetic flux lines around with it, thus producing an electric field. Since the magnetic field of a dipole varies as $1/r^3$ and the velocity of a field line varies as r, the induced electric field varies as $1/r^2$ and is thus suggestive of the Coulomb field of a point charge. For an isolated spinning dipole, the field is neither completely isotropic nor completely radial, but can be made so for a physical electron by averaging over various directions of the spin. The average rotation (*Zitterbewegung*) frequency needed to fit the known electric charge is readily seen to be

$$\Omega = \frac{ec}{\mu_B} = \frac{2mc^2}{\hbar} = 2\times 10^{21}\ \text{rad/sec}. \qquad (2)$$

Perhaps this frequency may be detected in a rotating-magnet experiment. Suppose that when the magnet spins with an angular velocity ω, the *Zitterbewegung* frequency of an electron is changed to $\Omega \pm \omega$ depending on whether its spin is opposed or aligned with the axis of rotation.[14] Since in a ferromagnet there is an excess ΔN of electrons polarized along the axis of magnetization, spinning a magnet might be expected to yield an apparent increase in the charge of the magnet

$$\Delta Q = e\Delta N\omega/\Omega. \qquad (3)$$

We shall see that the large value of the *Zitterbewegung* frequency Ω is canceled by the large number of unbalanced spins ΔN to give a detectable charge increase ΔQ. Indeed the Kennard experiment[6] itself is sufficient to rule out the naive interpretation of Jehle's model given here. Still it may be desirable to strengthen the limit of Kennard's experiment by a factor of 100. Such is the goal of our experiment.

EXPERIMENT

According to the moving-line hypothesis, a rotating magnet may be viewed as carrying its lines of force with it. Let us modify this hypothesis by introducing a dragging coefficient k' such that the lines of force move at a fraction k' of the frequency of the magnet. Then the ML hypothesis corresponds to $k'=1$, and the SL hypothesis corresponds to $k'=0$. Equation (1) becomes

$$E = -(k'/c)(\vec{\omega}\times\vec{r})\times\vec{B}. \qquad (4)$$

Using Gaussian units and spherical coordinates, a dipole magnet of moment m (emu) will have a distant field

$$B_r = (2m/r^3)\cos\theta, \quad B_\theta = (m/r^3)\sin\theta, \qquad (5)$$

and consequently

$$E_r = (k'm\omega/cr^2)\sin^2\theta, \qquad E_\theta = -(2k'm\omega/cr^2)\sin\theta\cos\theta. \qquad (6)$$

Note that $-E$ is the gradient of a potential $\phi = (k'm\omega/cr)\sin^2\theta$. The electric field is thus conservative. It has, however, a finite divergence everywhere:

$$\nabla\cdot\vec{E}=(k'm\omega/c)[8\pi\delta(r)/3-(4/r^3)P_2(\cos\theta)]. \quad (7)$$

Here P_2 is the second-order Legendre polynomial, and $\delta(r)$ is the Dirac δ function. Thus, the distant electric field of a spinning magnet in free space is that of a charge density

$$\rho_{\rm eff}=(k'm\omega/c)[2\delta(r)/3-(1/\pi r^3)P_2(\cos\theta)]. \quad (8)$$

The first term is equivalent to an isolated charge

$$Q_{\rm eff}=2k'm\omega/3c$$

at the origin. The second term represents a quadrupole charge density whose value falls rapidly to zero at large distances. Our experiment is an attempt to measure the isolated charge represented by the first term.

In principle, the experiment consists in spinning a bar magnet about its axis at the center of a hollow, insulated steel sphere. The steel sphere, in turn, is inside a grounded conducting cage. The spinning magnet induces a charge $Q_{\rm eff}$ on the sphere which is thereby elevated to a potential

$$U=Q_{\rm eff}/C=2k'm\omega/3cC. \quad (9)$$

Here C is the capacitance between the sphere and the cage.

In practice, to decrease the vulnerability of the experiment to thermal noise and to $1/f$ noise the magnet was replaced by silicon-iron sheets which were magnetized at an audio frequency. This frequency was low enough that the experiment could still be considered quasistatic. Then to shield the voltage detector from emf's induced by the alternating magnetic fields, a stationary iron pipe was placed around the rotating solenoid.[15]

The assembled apparatus (see Fig. 2) was very similar to that used in the experiment described in the preceding article.[16] The local ground was provided by a cubical copper mesh cage 1.5 m on a side. The mesh was formed from wires 0.3 mm in diameter and spaced 1.6 mm apart. A lock-in amplifier detected the potential difference between the copper cage and a steel sphere 1.1 m in diameter and 5 cm thick. Inside the steel sphere were two shields: a copper sphere 1.0 m in diameter and 0.19 cm thick and an iron pipe 60 cm long, 30 cm in diameter, and 1 cm thick. The magnetizing field was produced by a rotating solenoid 20 cm long consisting of 430 turns of 2-mm-diam copper wire (AWG #12) wrapped around a core 4.5 cm in diamter. Jammed inside the core were 770 g of silicon-iron sheets similar to those customarily used in transformers (see Fig. 3).

To maximize power transfer a 1-Ω resistor and

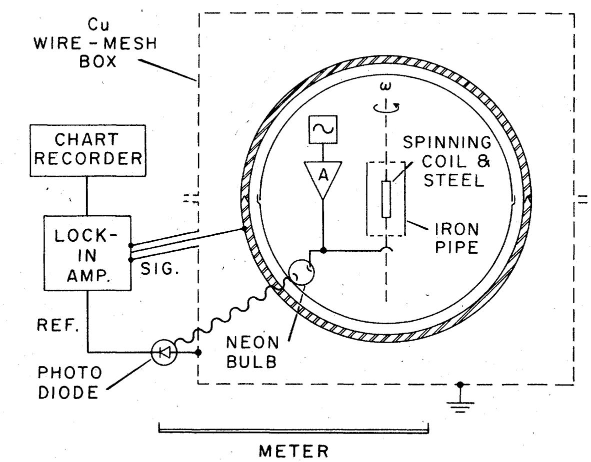

FIG. 2. Schematic of the apparatus. The signal from the oscillator is amplified (A) and applied by brushes to a spinning solenoid having a steel core.

a 4-μF capacitor were added in series with the solenoidal coil (21 mH), thus forming a RLC circuit which resonanted at the oscillator frequency (550 Hz). Using this circuit it was possible to pass 1.2 A (rms) through the coils, thereby producing a field of approximately 1250 G in the iron. The RLC

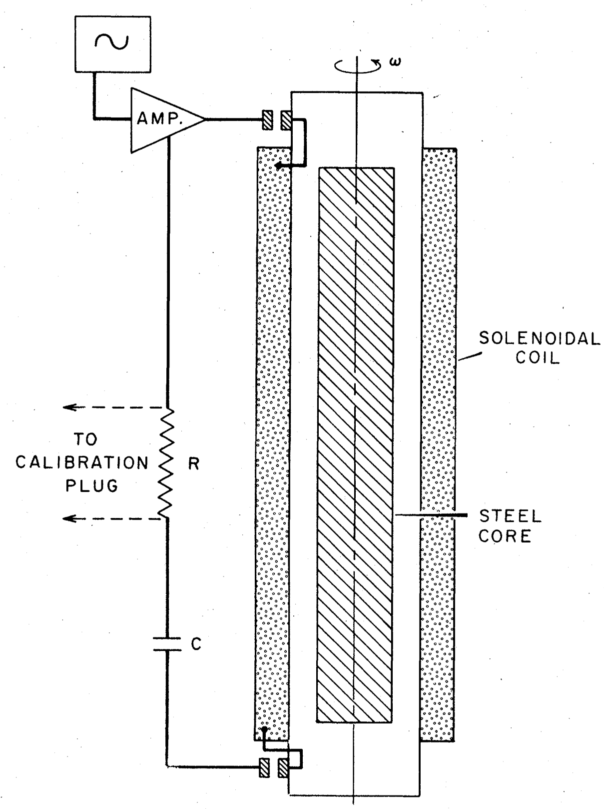

FIG. 3. Detail of spinning solenoid and steel core.

circuit also permitted the experiment to be calibrated using the technique described in the preceding article.

To determine the sensitivity we rewrite Eq. (9):

$$k' = 3cCU/2m\omega. \tag{10}$$

Here C, the capacitance between the steel sphere and the wire cage, was measured to be 200 cm (225 pF). The angular velocity of the solenoid was 250 rad per second. The magnetic moment m of the iron core was determined by measuring the solenoid's inductance both with and without the core. We found $m = 8000$ G cm^3 (8 Am^2).

The potential U of the steel sphere was measured in several 3-hour runs similar to those described in the preceding paper. Once again the sensitivity of the experiment was doubled by reversing the phase of the reference channel of the lock-in amplifier with respect to the current through the coil. One half the difference between the potential observed with the reference signal in phase with the coil current and out of phase is the desired signal (I signal). Data were also taken with the phase of the lock-in amplifier at quadrature with the current in the coil ($\dot{I}$ signal).

All data were taken both with the direction of rotation up and with it down as well as with the coil stopped completely. Finally, to distinguish between the effect of stray magnetic fields leaking outside the sphere and genuine potentials the lock-in amplifer was moved so as to measure the potential at two different pick-off points. The data are summarized in Table I. From this data we conclude that the induced potential dependent on rotation is consistent with zero and is most likely less than 3×10^{-11} statV or 10 nV (90% confidence).

Using Eq. (10) we can set an upper limit

TABLE I. Measurements.

		Signal (rms) U	
Signal pick-off point	ω	I[a] (nV)	$\dot{I}$[b] (nV)
South side of copper cage	up	−7	3
	0	−8	3
	down	0	0
West side of copper cage	up	2	−2
	0	−5	0
	down	2	−2

[a] I signal is positive when U is in phase with the current through the solenoid. A positive value for k' should give a positive signal U when $\vec{\omega}$ is up and a negative one when $\vec{\omega}$ is down.

[b] $\dot{I}$ signal is positive when U leads the current by 90°.

$$|k'| < \frac{(3)(3\times 10^{10}\ \text{cm/sec})(200\ \text{cm})(3\times 10^{-11}\ \text{statV})}{(2)(8000\ \text{G cm}^3)(250\ \text{rad/sec})},$$

$$|k'| < 1.4 \times 10^{-4}.$$

Previous experimenters were mostly concerned with distinguishing between the SL hypothesis ($k' = 0$) and the ML hypothesis ($k' = 1$). Accordingly, they did not state explicitly what departure from $k' = 0$ would be allowed by their data. We give below our estimate 90% confidence limits on $|k'|$ from the data presented in these experiments:

Kennard (1912) 0.02,

Barnett (1912) 0.02,

Pegram (1917) 0.05,

Kennard (1917) 0.20.

SUMMARY

The preceding discussion has been used to set a limit of the dragging coefficient k' with which a rotating bar magnet carries its lines of force. It is tempting to view the same dragging coefficient microscopically, and thus to infer that the spinning electron itself drags its lines of force with a coefficient less than 1.4×10^{-4}. As Jehle, has noted, however, this inference may be incorrect.[14] If so, we must ask what experiment can be done to confirm or deny the existence of a *Zitterbewegung* frequency of the electron.

ACKNOWLEDGMENTS

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APPENDIX

Djurić's recent analysis, when applied to our experiment leads one to expect a null result even if the ML hypothesis is assumed.

To see why this is so, it is convenient first to give an equivalent circuit which represents our own interpretation of our measurement. Assuming the ML hypothesis, we believe the potential U [Eq. (9)] is the emf; the load is the parallel combination of the capacitance between the steel sphere and the copper cage (225 pF) and the input resistance of the lock-in amplifer (100 MΩ). At the charging frequency of the experiment (550 Hz), the impedance associated with the capacitance (Z_1) is much smaller than that of the lock-in amplifier (Z_2). Thus, the latter acts as it should, i.e., as a voltage detector. [See Fig. 4(a).]

Djurić, however, believes that the electric field of a rotating dipole [Eqs. (6)], being non-Coulombic, cannot be screened by ordinary metallic conduc-

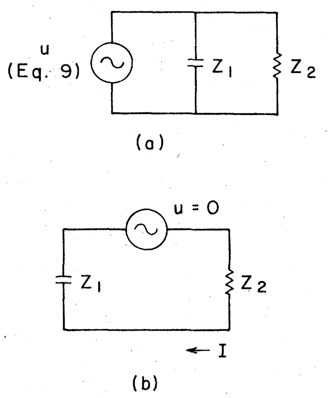

FIG. 4. Equivalent circuit of present experiment (a) using our hypotheses; (b) using Djurić's (Ref. 12).

tors.[17] Accordingly, the only driving emf which could appear must be in series with Z_1 and Z_2.[18] Furthermore, since neither the capacitor nor the lock-in amplifier is rotating, this emf must be zero.[19] The resulting circuit is illustrated in Fig. 4(b). Since $Z_1 \neq Z_2$, this circuit yields no current I and, hence, zero potential difference across Z_2.

We differ with Djurić in his assertion that because an electric field is not completely Coulombic, it cannot be screened by metallic conductors. As we have shown in Eqs. (7) and (8), the divergence of the electric field of a rotating magnetic dipole contains two terms. The second, corresponding to a quadrupole charge density of strength varying as r^{-3} indeed cannot be completely shielded by a metallic conductor. The first term, however, represents an isolated charge at the origin. This charge can be completely shielded by a spherical conducting shell. Our detector measures the resulting charge induced on this spherical shell.

It should be noted that the shielding is electric rather than magnetic. The fact that part of our detector was made of steel is of no essential significance.[15]

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[14]This assumption that the angular velocity of the lattice may be directly added to that of the electron is plausible classically since interactions between neighboring atoms are responsible for the phenomena of ferromagnetism. However, Jehle himself is not certain whether this classical picture holds for the physical electron: "What electric effect the rotation of the bar magnet implies depends on whether the rotation of the bar magnet causes a change in the spinning frequency of the flux loop forms or not. The spinning frequency $\Omega = 2mc^2/\hbar$ implies spinning with velocities far above the velocity c, and it is a rotational motion which the entire magnetic field performs. So it is not obvious what change there arises due to rotation of the bar magnet. The spinning of the flux loop forms might be considered to be effectively a spinning with respect to (absolute) nonrotating space; alternatively the spinning might be considered as an addition of the rotation angular velocity to $2mc^2/\hbar$." (H. Jehle, private communication.)

[15]The iron pipe shielded the inside of the sphere in a fashion which was not spherically symmetric. Thus, the effective charge induced on the steel sphere will be modified by a small nonzero value coming from the second term of Eq. (8). The effects of this modification, however, is to *increase* the sensitivity of the experiment. We ignored this effect.

[16]D. F. Bartlett and B. F. L. Ward, preceding paper, Phys. Rev. D 16, 3453 (1977).

[17]Ref. 12, especially pages 681 and 684.

[18]Ref. 12, Eq. (13).

[19]Ref. 12, Eq. (25).