EXPERIMENTAL COMPARISON OF THE GRAVITATIONAL FORCE ON FREELY FALLING ELECTRONS AND METALLIC ELECTRONS*

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A free-fall technique has been used to measure the net vertical component of force on electrons in a vacuum enclosed by a copper tube. This force was shown to be less than $0.09mg$, where m is the inertial mass of the electron and g is 980 cm/sec^2. This supports the contention that gravity induces an electric field outside a metal surface, of magnitude and direction such that the gravitational force on electrons is cancelled.

Measurements of the gravitational force have been made only on bulk matter,[1,2] neutral particles[3] of ordinary matter, and photons.[4] Morrison and Gold have suggested that antimatter may be repelled by ordinary matter.[5,6] While indirect evidence from virtual antimatter in nuclei[7] and short-lived antiparticles[8] suggests that antimatter has normal gravitational properties, no direct measurements have been made. A repulsive force would be particularly interesting, not only because it would violate the equivalence principle of general relativity, but also because it would provide a mechanism for the large-scale separation of matter and antimatter in the universe.[5,6] In order to test the gravitational properties of antimatter, it was decided to compare the gravitational acceleration of positrons and electrons in the earth's field.[9] This article describes the completion of the first half of this comparison, namely a determination of the acceleration of electrons in a vacuum surrounded by a metal tube in the earth's gravitational field.

Techniques for measuring the force of gravity on electrons are discussed briefly by Witteborn, Knight, and Fairbank,[10] and in detail by Witteborn.[11] The most successful method has been to analyze the time-of-flight distribution of electrons falling freely within a metal enclosure in which all vertical electric and magnetic potential-energy gradients have been reduced below 10^{-11} eV/m except for known or deliberately applied uniform electric fields. Such uniform electric fields should be on the order of $mg/e = 5.6\times10^{-11}$ V/m, where m is the inertial mass of an electron, g is the acceleration of gravity for bulk neutral matter, and e is the absolute value of the charge on one electron.

Vertical electric fields that might result from induced image charges are greatly reduced by surrounding the free-fall region with a long (91-cm) vertical copper drift tube (Fig. 1) having a very uniform inside diameter (5 cm with variations less than 0.0003 cm). Electrons are constrained to move along the axis of the drift tube by the magnetic field of a coaxial superconducting solenoid. The drift tube attenuates both the image potential and the potentials of the cathode and detector regions approximately as $\exp(-2.4z/a)$, where z is the distance from the nearest end of the tube and a is the tube radius.

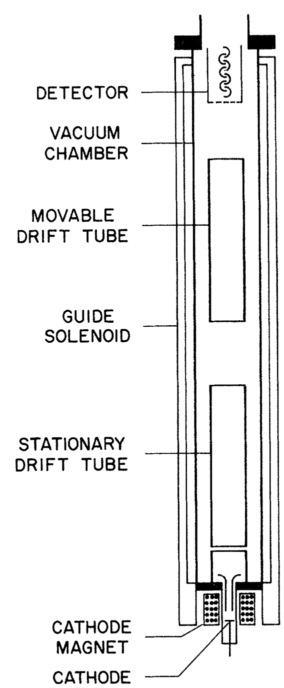

FIG. 1. Schematic diagram of the helium-immersed portion of the apparatus. Electrical wiring and Dewars and vacuum system are not shown. The results discussed in this paper were obtained with the stationary drift tube biased negative with respect to the vacuum chamber and movable drift tube, so that electrons moved slowly only in the stationary drift tube.

Electric fields resulting from the Thomson effect (voltage due to temperature gradients) are minimized by thermally insulating the drift tube everywhere except at one end which is connected to a liquid-helium bath outside the vacuum system by copper and sapphire rods. The Thomson coefficient for copper near 4.2°K is on the order of 10^{-6} V/deg, so temperature gradients had to be less than 10^{-5} deg/m.

The original decision to run the apparatus at liquid-helium temperatures was based on the desirability of using persistent currents to maintain a time-unvarying magnetic field in the free-fall region and also to gain the advantage of cryogenic pumping. The latter was almost essential to reducing the pressure below 10^{-11} Torr, so that interactions with induced dipoles of background gases would be sufficiently small and infrequent. The most important benefit of low temperature is the apparent masking of the patch effect. Spatial variations in the work function at the surface of the drift tube, due to random crystal orientations (the patch effect), are expected to cause variations in the potential 1 cm away of approximately 10^{-3} eV at room temperature.[11] Potential variations on the axis of a 2-cm-diam drift tube were shown to be less than 10^{-10} V/m[10,11] at 4.2°K. A possible mechanism for this is the adsorption of hydrogen and helium from the background gas during cooling. These gases are mobile enough on a gas-covered surface at 4.2°K to move to a site of minimum energy. This could result in a surface potential whose spatial variations are atomic in extent and thus much more likely to produce a uniform potential a few centimeters away.

While the guide solenoid was supposed to produce a magnetic field uniform to one part in 10^4, and was operated at fields of only 7-20 G, inadequate external shielding could have allowed spatial variations in the vertical field as large as 0.05 G. Interactions between field gradients as small as 0.05 G/m and the magnetic moment arising from the spin and orbital motion of the electron produce forces at least $10mg$, except for ground-state electrons. The magnetic energy due to zero-point orbital motion is almost precisely cancelled by the spin magnetic energy for electrons in the ground state. By locating the electron source in a strong magnetic field (3000 G), the electrons not in the ground state are formed with a magnetic potential energy of over 10^{-6} eV. The ground-state electrons are affected only by the interaction of the field gradient with the anomalous magnetic moment which is nearly 2000 times smaller and oppositely directed. Thus, a group of electrons emitted from the cathode becomes spatially segregated according to both initial velocity and magnetic state. Those reaching the drift tube with kinetic energy below 10^{-6} eV must be in the ground state.

Electrons that traverse the drift tube are detected by an electron-multiplier tube (Fig. 1), whose output after amplification and pulse-height analysis is a single count for each detected electron. The number of electrons arriving in each 2.5-msec time interval after the release of a pulse of electrons from the cathode is stored in the memory of a 400-channel scaler. Each pulse contains about 10^9 electrons, but at most one with energy below 10^{-9} eV. After the flight times of electrons in about 10 000 pulses are accumulated, the distribution of flight times is analyzed to determine the net potential in the drift tube as described below.

If there were no fields in the tube other than that of gravity, and all electrons left the cathode at the same time, none could reach the detector after time $t_{\max}=(2h/g_f)^{1/2}$, where h is the length of the drift tube, and g_f is the acceleration of freely falling electrons. However, the action of gravity on the particles in the metal walls of the drift tube gives rise to a uniform electric field which Schiff and Barnhill[12] calculated to be of magnitude $E_w=mg/e$ and directed so as to exactly cancel the force of gravity on electrons, provided, of course, that $g_f=g$, where g is the acceleration of gravity for electrons in bulk matter. In addition, we found it desirable to apply a weak uniform electric field E_a by running a dc current through the walls of the drift tube parallel to the axis. Including these fields, one gets for the maximum observable flight time

$$t_{\max}=[2hm/(mg_f-eE_w+eE_a)]^{1/2}. \quad (1)$$

By measuring $t_{\max}$ for several values of E_a, one may check both the mass m of the particles being studied and the quantity mg_f-eE_w.

In experimentally observed time-of-flight distributions, the numbers of counts per channel decrease with increasing flight time until a constant background level is reached. The flight time at which the distribution becomes constant is assumed to be t_{max}. Visual examination of distributions obtained with different values of E_a shows that t_{max} varies inversely with $\sqrt{E_a}$. Furthermore, the magnitude of the dependence is in agreement with particles having the electronic mass. For example, from a distribution taken when the applied field was 5×10^{-11} V/m, t_{max} can be visually identified as about 0.370 sec, while a distribution obtained with 1.3×10^{-10} V/m has a visual cutoff near 0.200 sec. Insertion of these visual estimates into Eq. (1) gives about 10^{-11} V/m for $E_w - mg/e$, which is less than $0.3mg/e$, and 5×10^{-31} kg for m which shows that the particle is an electron.

In most of the data, the effect of the applied fields is partially obscured by statistical fluctuations in the number of counts per channel and by the constant background count, making a computer analysis of the data desirable. In addition, the distributions were affected by the trapping and gradual release of electrons near the cathode, and by fringing electric fields near the ends of the drift tubes. To account for all these effects, one must relate the entire time-of-flight distribution to the fields present in the drift tube, the energy distribution of source electrons, and the background count. Let ϵ be the minimum kinetic energy of an electron as it goes through the drift tube. Let $N(\epsilon)$ be the number of electrons emitted from the cathode with energies between zero and ϵ. $N(\epsilon)$ is proportional to ϵ in the narrow range of energies whose flight times were measured. If these electrons thermalized before entering the drift tube it may be shown[11] that the distribution seen at the detector would be proportional to $\epsilon^{1/2}$. In analyzing our results we assumed $N(\epsilon)=C\epsilon^\gamma$, where γ was determined from the experimental distributions. Let t be the time of arrival at the detector and t_e the time of entry into the drift tube. From the energy integral we have

$$t-t_e=(\tfrac{1}{2}m)^{1/2}\int_0^h \frac{dz}{[\epsilon-\Phi(z)]^{1/2}}, \qquad (2)$$

where $\Phi(z)$ includes all the linear potential-energy terms as well as the fringing potentials. It was approximated through most of the drift tube by the linear terms $(mg_f-eE_w+eE_a)z\equiv Fz$, and in the region of maximum potential (minimum electron velocity) by a quadratic term in z whose coefficients were calculated to match the curvature of $\Phi(z)$ to that calculated from the known fringing potentials. Calculation of $t-t_e$ for many values of ϵ permits an inversion of the energy integral to obtain ϵ as a function of $t-t_e$, $(mg_f-eE_w+eE_a)$, and m.

We found experimentally that we obtained the maximum number of slow electrons when there was a "trap" (a positive voltage with respect to the drift tubes) near the cathode. Thus we had to assume that some, if not all, of our very low-energy electrons had spent some extra time in this trap before traversing the drift tubes, which would effect t_e. Escape from the trap may occur by multibody collisions with other electrons, or by collisions with background gas, or as a result of voltage fluctuations in the electrodes near the trap. Since the time-of-arrival data obeyed a power law, we assumed that the number of electrons entering the drift tube at time t_e varied as $t_e^{-\eta}$. Since only t is measured, we must integrate the distribution over the various entry times starting at τ, a nonzero minimum value of t_e. The number of electrons arriving after time t is thus

$$N(\alpha,\gamma,\eta,t,F)=\alpha\int_\tau^t[\epsilon(t-t_e,m,F)]^\gamma t_e^{-\eta}dt_e \qquad (3)$$

where α is an empirical constant proportional to the total number of electrons observed. The number of counts in a given time interval Δt is $\Delta N/\Delta t+\beta$, where β is the background noise per time interval. A least-squares fit was made of $\Delta N/\Delta t+\beta$ to each data set obtained for each value of E_a, using F, α, β, γ, and η as adjustable parameters. This was done on an IBM 7090 computer with the aid of a nonlinear least-squares fitting program.[13] The computer-optimized values of F are shown in Fig. 2 plotted as a function of the applied field. It is clear from the figure that mg_f-eE_w must be extremely small. An average of $F-eE_a$ of 11 of the data sets taken with $E_a<2.5\times10^{-10}$ V/m yields 0.13×10^{-11} eV/m for mg_f-eE_w, with a statistical standard deviation of 0.47 $\times10^{-11}$ eV/m. Taking into account inaccuracies in h, in flight time measurements, and in the applied-field measurement, we find an overall standard deviation of 0.51×10^{-11} eV/m or about $0.09mg$.

The experiment showed that the vertical component of force acting on an electron falling along the axis of a vertical copper tube 5 cm in diameter is less than $0.09mg$. This result

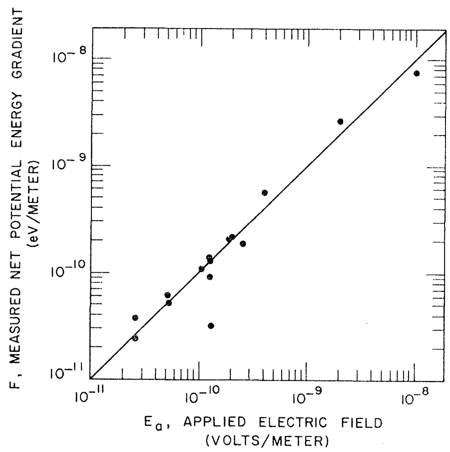

FIG. 2. Experimentally measured potential-energy gradients F versus applied electric fields E_a. The solid line represents $F=eE_a$ for a particle having the inertial mass of the electron.

agrees with the theoretical calculation of Schiff and Barnhill.[12] We conclude that the force of gravity on electrons inside a metal is the same as that on electrons in a vacuum.

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METHOD FOR $\pi\pi$ OR $K\pi$ PHASE-SHIFT ANALYSIS*

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Based on the assumed dominance of one-pion exchange in the reaction

$$\pi^- + p \to \pi^- + \pi^+ + n, \qquad (1)$$

several analyses have been reported[1] in which the $T=0$ s-wave $\pi\pi$ elastic-scattering phase shift (δ_S^0) was obtained over a range of $\pi\pi$ mass in the ρ region. These analyses generally fall into two classes: (i) those in which the effects of absorption are taken account of incompletely (or not at all), and (ii) those in which the analyses depend on the detailed validity of a theoretical treatment of the absorption. It is the purpose here to point out that the $\pi\pi$ phase shifts may be extracted from the data (at least in the region of the ρ resonance) without complete prior knowledge of the helicity amplitudes in Reaction (1), using therefore only a subset of the assumptions used in the absorption model,[2] all of which have observable consequences and which may be subjected to test. Furthermore, it is shown below that for data in a sufficiently narrow band of total center-of-mass energy E^* and production angle β (or momentum transfer t to the nucleon) in Reaction (1), empirical values of the helicity amplitudes may be extracted from the data. The arguments contained herein should apply equally to the reaction $\pi^+p \to \pi^+\pi^-N^{*++}$ and to the determination of the $K\pi$ phase shifts [at least in the $K^*(890)$ region] if the π-exchange dominated reaction $K^+p \to K^+\pi^-N^{*++}$ is used.

The fundamental assumption common to the one-pion-exchange models with and without absorption is that the amplitude, to reach the final state in (1) with given $\pi\pi$ relative orbital