## Thermal Conductivity

Preliminary determinations on matched blocks of well oriented graphite composites show that parallel to the basal planes of the crystallites the thermal conductivity is very high, and at least twenty times greater than the value parallel to their $c$ axes. For pure near-ideal graphites this anisotropy ratio may reach about 200, depending on the defect content[12]. With regard to thermal vibrations in these solids, it is interesting to find that thermal conductances rivalling the best natural metals are attained even in the well oriented composites, despite their conglomerate structure. Heat transport in pure graphite and in these composites is almost wholly by phonons. As is well known, phonon scattering effects lead to striking variations of thermal conductivity with temperature, but apparently at ordinary temperatures the conglomerate structure does not produce much more marked scattering than in near-ideal graphite itself. Presumably the good parallelism of neighbouring graphite crystallites permits transmission of phonons across any intervening polymer molecules without much attenuation. Technological consequences of this finding are potentially very important.

## Electrical Conductivity

Well oriented composites of graphite show unusual electronic behaviour. In the direction of the composite $a$ taxis, resistivity values for a particular material with 50 per cent of polymer showed a mean value of $\rho_a = 1 \cdot 72\ \Omega$ cm at 295° K, rising to $2 \cdot 05\ \Omega$ cm at 77° K. In the direction of the composite $c$ axis for the same material, corresponding resistivity values were $\rho_c = 264 \cdot 8\ \Omega$ cm at 295° K and $307 \cdot 8\ \Omega$ cm at 77° K. The large anisotropy ratio of about 150 is in the sense to be expected if electrical conduction is controlled by the well oriented crystallites of graphite. It may be compared with anisotropy ratios of only about 2 found in extruded polycrystalline graphites[11]. What is surprising is that the temperature coefficient of $\rho$ has about the same small negative value in both directions. This suggests that some kind of activation of the charge carriers enabling them to cross a small energy gap ($2$–$4 \times 10^{-3}$ eV) intervenes in electrical conduction. Possibly the charge carriers must tunnel through polymer macromolecule barriers; if so the magnitude of the barrier is surprisingly low. A somewhat similar situation with negative temperature coefficient of resistance applies for electrical conduction in very thin deposits of gold or platinum on insulating substrates of quartz glass or of barium titanate[14]. Electron transfer is thought to take place between separated islands of the metallic deposit. Well oriented graphite composites with a variety of polymers show similar small negative temperature coefficients, and a general conduction phenomenon seems to be involved.

## Thermoelectric Power

In pure near-ideal graphite, the remarkable anisotropy of thermoelectric power raises problems in solid state physics, as well as offering interesting potentialities in high temperature technology[15]. Well oriented graphite composites show a corresponding anisotropy of thermoelectric power. As might be expected with this very sensitive property, the absolute magnitude of the thermoelectric power is somewhat dependent on the polymer used. In a typical instance (20 per cent acrylonitrile copolymer) mean values were approximately $3 \cdot 3\ \mu$V/°C in the direction of the composite $a$ axis, and approximately $6 \cdot 2\ \mu$V/°C in the direction of the composite $c$ axis. Somewhat below room temperature the thermoelectric power changes sign; the equivalent band structure of these well oriented composites is probably modified by charge transfer effects to the polymer molecules. As is also the case for the electronic properties of carbons with conglomerate structure, and for molten conductors generally, there is a real need for new theoretical descriptions for collective energy levels in these condensed states of matter.


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# Experiments to determine the Force of Gravity on Single Electrons and Positrons


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Two experimental methods are described for measuring the gravitational force on electrons falling through vertical metal tubes. A third method is being devised to study the fall of positrons.


EXPERIMENTS to determine the gravitational properties of electrons and positrons by the time of flight technique have been under way at Stanford University for several years. In this article we will examine the motivation for the experiments, the methods used, the principal difficulties involved and the results obtained so far.

## Gravitational Properties of Elementary Particles

The obvious lack of symmetry in the abundance of matter over antimatter in the solar system, and perhaps much more of the visible universe, led Morrison and Gold[1,2] to speculate that a gravitational repulsion exists between matter and antimatter. Because both particles and antiparticles have positive inertial mass, they would fall in opposite directions in a gravitational field if the speculation is correct. Thus one could distinguish between a gravitational field and an accelerating reference frame, in violation of the equivalence principle of general relativity. The equivalence principle would hold in systems composed predominantly of matter or antimatter but not in a mixed system. So far, of course, the effects of general relativity have been examined only in systems composed predominantly of matter.

Although the gravitational force on stable antiparticles has not been directly measured, some indirect evidence has been obtained from virtual and short lived antimatter. Schiff[3] showed that the mass of virtual antimatter present in nuclei of ordinary matter was sufficient to have been detected in the Eötvös experiments[4,5] if virtual antimatter had been repelled by gravity. Good[6] showed that the $K_0$ and $\overline{K}_0$ mesons (lifetime $<10^{-7}$ s) must have the same gravitational properties. Thus virtual antimatter and unstable antimatter have normal gravitational properties. The arguments of Morrison and Gold involved stable, real antimatter. Indeed, they proposed that electromagnetic mass would be attracted by both matter and antimatter. In this respect it should be added that positrons are not considered ideal test particles for determining the sign of the gravitational force because a large part of their mass is electromagnetic. It may be shown[7,8], however, that not all of the electron mass is electromagnetic. In the absence of a copious source of low energy antinucleons, we felt that the positron was the best test antiparticle.

The necessity of a repulsive force to provide for the separation of matter from antimatter has been largely removed by Alfvén[9,10], who proposed a number of electromagnetic mechanisms for matter–antimatter separation. There is no conclusive experimental evidence to show whether such mechanisms have in fact led to separation in the observable universe.

It seems that if positrons have the same gravitational properties as electrons, there would be very little change in physics except that future cosmological arguments will be unable to associate antigravity with antimatter. But if positrons have even slightly different gravitational properties (neglecting radiation reaction effects) very serious and far reaching consequences would result. First, general relativity would have to be modified. Second, we would know that the Milky Way galaxy is composed chiefly of matter, for the stars in it appear to revolve around its centre. Third, we would have strong reason to believe that somewhere outside our galaxy, perhaps beyond our limits of observation, there is an accumulation of antimatter.

If positrons or electrons or both were to display unexpected gravitational properties, some clues about the nature of gravity itself might be uncovered. For example, Swann speculated[11] on a mechanism for gravity which would produce an attractive inverse square force between two neutral ordinary particles or two neutral antiparticles but a repulsive force between a neutral particle and a neutral antiparticle. Binding energy and electromagnetic energy were implicitly excluded from consideration. He used electrons and positrons and their antiparticles as his "elementary" particles and treated neutrons as gravitationally equivalent to hydrogen atoms. The long range force between elementary particles of equal inertial mass was assumed to have the magnitude of the Coulomb force $q^2/4\pi\varepsilon_0 r^2$ (MKS units). The corresponding force between elementary particles of very different mass (that is, between electrons and protons or positrons and protons) was assumed to have the magnitude $q^2+\delta/4\pi\varepsilon_0 r^2$. This model leads to a net force between two hydrogen atoms of $-2\delta/4\pi\varepsilon_0 r^2$, where the negative sign indicates attraction. Swann showed that the net force between a hydrogen atom and an antihydrogen atom was $+2\delta/4\pi\varepsilon_0 r^2$. But with this model a neutral mass would attract a proton with exactly the same force as it would an electron. Each would be attracted with one half the force that a hydrogen atom would feel. Because of the difference in inertial masses, the electron acceleration would be 1,836 times that of the proton. The latter would fall with an acceleration of $0{\cdot}5g$. Of course, it should be emphasized that Swann's proposal was speculative and largely intended to show the importance of measuring the gravitational properties of elementary particles.

## Experimental Method

The gravitational potential gradient for an electron at the Earth's surface is expected to be $mg=5{\cdot}6\times10^{-11}$ eV m$^{-1}$. All electric and magnetic potential gradients must be reduced below about $10^{-11}$ eV m$^{-1}$ or measured to this accuracy in an experiment intended to detect the gravitational force. It would not be desirable to attempt the experiment inside an insulating box, because a single electric charge trapped in the insulator even 5 m distant from the test region would exert a force on an electron greater than $mg$. To surround the experiment with a metal container raises the problem of surface charge induced by the freely falling electron. But if the metal is a long vertical cylinder, the induced surface charge produces only a horizontal force on the electron.

The electrons are constrained to move along the axis of the cylinder by a coaxial magnetic field. Inhomogeneities in the magnetic field $\Delta B$ will cause spatial variations in the magnetic potential

$$\Delta\Phi_{\text{mag}} = 2\mu_\beta \Delta B\ (n + \frac{1}{2} + \frac{s}{2}\gamma_s)$$

where $\mu_\beta=6\times10^{-9}$ eV gauss$^{-1}$ is the Bohr magneton, $n$ is a positive integer, $s=\pm\frac{1}{2}$ is the spin, and $\gamma_s=2{\cdot}0023$ is the spin gyromagnetic ratio. In a region shielded by conventional materials, $\Delta B$ can be reduced to about 0·01 gauss. This would lead to potential variations of $10^{-10}$ eV and more for most electrons. Thus the magnetic potential variations would be larger than the expected gravitational potential change in a 1 m fall except for those electrons in the "ground state"—those, that is, having $n=0$ and $s=-\frac{1}{2}$. The ground state electrons experience magnetic potential variations of only about $10^{-13}$ eV. To ensure that all of the "low energy" ($E<10^{-6}$ eV) electrons are in the ground state, the cathode may be placed in a region of high magnetic field (3,000 gauss), so that all electrons not in the ground state are accelerated as they leave the cathode region (Fig. 1). As the electrons are emitted in pulses, those with low energy become spatially separated from the others and reach the detector later. Late arrivals consist entirely of ground state electrons because all others are accelerated as they leave the cathode.

A variety of techniques had to be used to reduce other undesired forces. The cylinder diameter (5 cm) was accurate to $\pm0{\cdot}3\times10^{-3}$ cm to avoid serious variations in electric image potentials. The cylinder, made of oxygen free copper, was thermally isolated from its vacuum conta ner except at the bottom end. This was necessary so as to reduce spatial temperature variations to below $10^{-5}$ degrees m$^{-1}$ and sufficiently minimize the Thompson e.m.f. the coefficient of which is of the order $10^{-6}$ V degree$^{-1}$. To reduce sufficiently the interactions with background gases the pressure in the free fall region had to be less than $10^{-11}$ torr. This was done with an ion pump by excluding

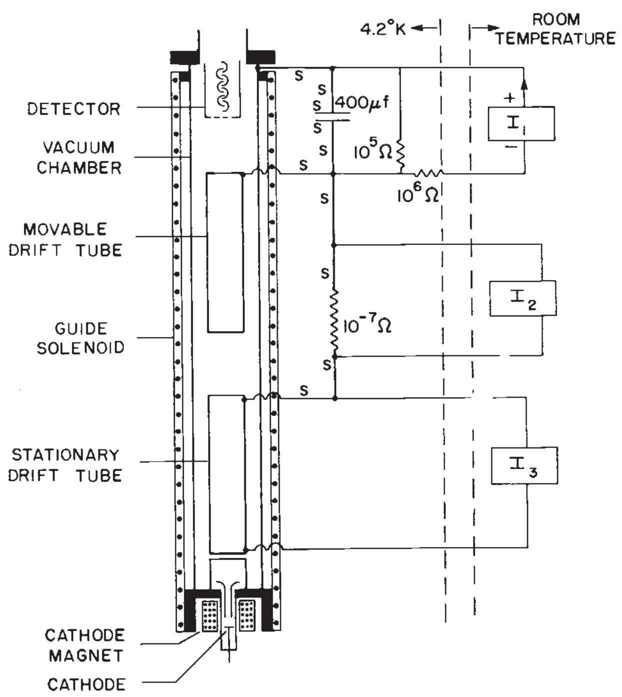


Fig. 1. Schematic diagram of the free fall apparatus: the wires labelled "s" are superconducting. The regulated current supply $I_1$ maintains both drift tubes at a negative (positive in positron experiments) voltage relative to the vacuum chamber. $I_2$ controls the relative potential of the two drift tubes. In the first experiment the movable drift tube was positively biased so that electrons moved slowly only in the stationary tube. The current $I_3$ produces a uniform electric field in the stationary drift tube.

all organic and volatile materials from the system and cooling the entire free fall region to 4·2° K.

Another source of potential variations in the cylinder is the patch effect[12]. This arises from the variations in work function along a metal surface as a result of the crystalline nature of the surface. Different crystal faces have work functions which differ typically by 0·1 V. If one assumes that the faces are encountered in a random fashion on a metal surface, then spatial variations in potential $\Delta\Phi$ may be estimated by $\Delta\Phi = 0{\cdot}06\ (a/r)$ eV (ref. 13), where $a$ is a characteristic patch dimension and $r$ is the distance above the surface. This would lead to potential variations of about $10^{-4}$ eV if $a = 0{\cdot}0045$ cm (a typical crystal size for oxygen free copper) and $r = 2{\cdot}5$ cm. Our drift tube was electroformed onto a polished aluminium mandrel which was later dissolved away. This process is expected to leave an amorphous surface so that the dimension $a$ was much smaller than 0·0045 cm, but other surface irregularities of macroscopic size surely were present during our experiments. Preliminary experiments performed with a pilot model free fall apparatus 2 cm in diameter indicated that at 4·2° K the potentials along the tube axis were uniform to about $10^{-9}$ or $10^{-10}$ eV (ref. 13). We do not know what causes this apparent reduction in potential irregularities. We speculate that adsorbed gases may be smoothing out the variations.

Forces on the electrons are studied by a time of flight technique. Initially a burst of about $10^8$ electrons is emitted from the cathode. The arrival of each electron at the top of the tube causes the electron multiplier to produce a pulse which is amplified and carried to a multichannel scaler. The multichannel scaler stores the number of pulses arriving in each of 400 successive time intervals (typically 2·5 ms intervals) following the initial burst from the cathode. Because of the mutual repulsion of electrons in the drift tube, no more than one electron with energy less than $10^{-10}$ eV can be expected from the original burst of electrons. Thus the experiment must be repeated over and over to produce a statistically reliable distribution of electron flight times.

If the moving electrons encountered only a constant force $F$ the distribution of electron flight times would be cut off at time $t_{\max} = \sqrt{2mh/|F|}$. Thus in the ideal cases the force on the electron could be determined directly from the time of flight distribution. The gravitational force is expected to be $-mg$. An additional vertical force $qE_{\mathrm{W}}$ (to be discussed later in this article) is expected from the walls of the metal cylinder; $q$ is the charge of the free falling particle. An adjustable force $qE_{\mathrm{a}}$ may be applied by running a current vertically through the drift tube walls. Thus

$$t_{\max} = \sqrt{2mh/|(mg + qE_{\mathrm{W}} + qE_{\mathrm{a}})|}$$

By finding $t_{\max}$ for several values of $E_{\mathrm{a}}$ one would expect to be able to determine $(mg + qE_{\mathrm{W}})$ and $m$ for the electron or other particles tested. The actual data reduction is complicated by electric fringing fields, delayed detector pulses caused by electron trapping and background noise in the detector.

## Experimental Results

Data obtained in experiments with different applied forces are shown in Fig. 2. By defining the "cut off" as the lowest value of $t$ for which $\mathrm{d}N/\mathrm{d}t$ goes below the flat portion of the curve (determined by averaging the last 0·5 s), one may get crude values of $m$ and of $F = mg + q(E_{\mathrm{W}} + E_{\mathrm{a}})$ from two distributions. The distributions in Fig. 2 give $m = 1{\cdot}1 \times 10^{-30}$ kg and $mg + qE_{\mathrm{W}} = 1{\cdot}3 \times 10^{-11}$ V m$^{-1}$. The sensitivity of the distributions to small changes in $E_{\mathrm{a}}$ was sufficient to confirm that the particles forming the distributions were electrons. Further information was deduced from the distributions by making least squares fits of a theoretical distribution function in which the force was one of several adjustable parameters. The other parameters accounted for background noise and assumed power law forms for electron energy distribution and emission from potential traps. The parameters were adjusted by a computer optimization program. The results, which were reported elsewhere[14], are summarized in Fig. 3 and show that the only vertical force present in the free fall region was the applied electric field. Thus the gravitational force appears to be cancelled by the electric field produced by the walls of the tube.

This result is in agreement with a calculation by Schiff and Barnhill[15] which showed that the electrons in the walls of a vertical metal cylinder would adjust their positions just enough to produce an electric field $mg/e$ directed so as to oppose the gravitational force. The field would also be present in the centre of the cylinder.

The electric field caused by ion displacement induced by gravity in the cylinder walls was shown to be negligible using the Schiff–Barnhill approach, but other theorists disagree. Dessler *et al.*[16] and Herring[17] claim that a much larger potential gradient of the order of $10^{-7}$ eV m$^{-1}$ should arise as a result of the ion lattice displacement. The overlying weight of the drift tube causes the bottom of the tube to be compressed more than the top. This could lead to a work function gradient and, according to ref. 16, an electric field in the tube. The question is still unresolved in spite of the apparent agreement between Schiff and Barnhill's theory and the free fall experiment, because the unknown mechanism that shields the patch effect may also shield the lattice compression effect.

Further evidence that the time of flight distribution curves did in fact arise from very low energy electrons was obtained by Knight[18]. He used a modified version of our pilot model electron free fall apparatus to measure magnetic forces on the electrons by noting the change in their time of flight distribution as the magnetic field gradient was varied by about 1,000 gauss/cm$^{-1}$ over a distance of a few cm. His ability to measure the anomalous magnetic moment of the electron to an accuracy of $\pm 30$ per cent demonstrated that many of the particles in his drift tube were ground state electrons with energies less than $10^{-9}$ eV.

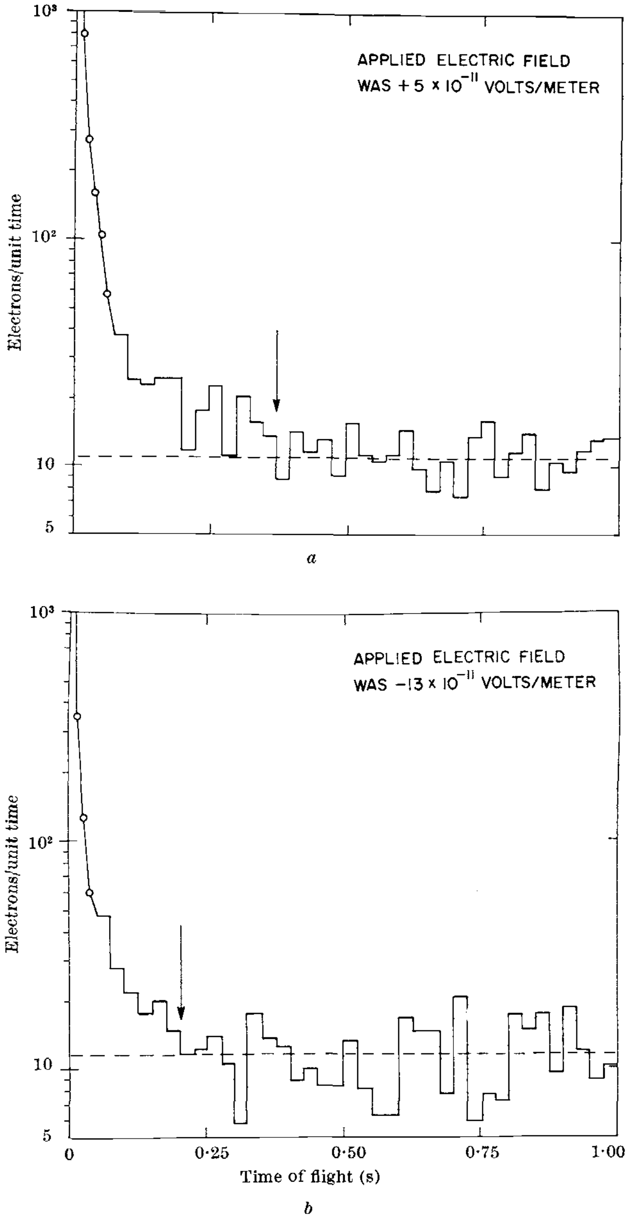


Fig. 2. Time of flight distribution curves. The horizontal scale in each graph is the time of flight of electrons. On the vertical scale the number of electrons the flight of which ended in each 2·5 ms time interval is plotted. In the histogram the values are averages of ten such intervals. These numbers represent the accumulated counts from about 30,000 pulses of electrons. The arrows point to the apparent cut off which is the flight time at which the distribution appears to flatten out into the background noise. The background noise is simply the average of the last 0·50 s of data and is indicated by the dashed line.

## Experiment with Movable Drift Tube

It is important to note that the gravitational potential gradients of electrons and positrons could be compared by a different method even if the patch effect were not shielded. This method uses the movable drift tube shown in Fig. 1. Voltages are applied to the upper drift tube and to the chamber wall relative to the lower drift tube to achieve the potential profile shown in Fig. 4. The time of flight distribution should have the maximum number of

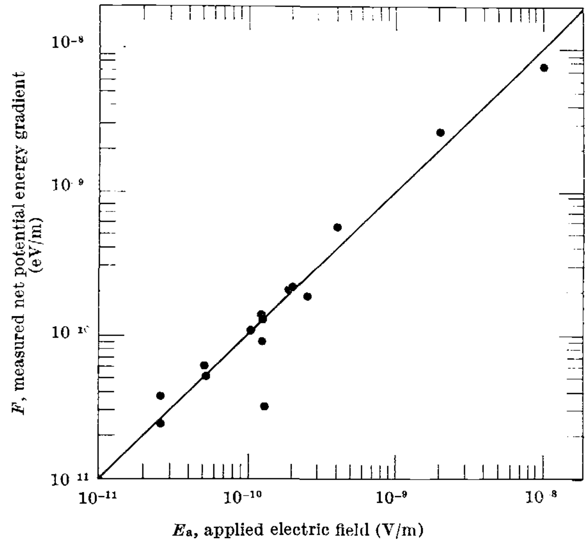


Fig. 3. Measured force versus applied force. The vertical value is the force determined from analysis of the time of flight distribution curves. The horizontal value is the absolute magnitude of the deliberately applied electric field. The solid diagonal line represents $F = |eE_a|$ for a particle having the electron's inertial mass.

slow electrons when the total potentials in the two drift tubes are equal. The potential of the upper tube relative to the lower is varied by sending a highly regulated current (1 part in $10^5$) through a $10^{-7}\ \Omega$ resistor connecting the two tubes. Connexions to the tubes are made with superconducting wires to minimize Johnson noise. By increasing the distance between the two drift tubes the gravitational potential is altered. Any such potential change not compensated by the field from the wall (only that part predicted by Schiff and Barnhill in this case) must be compensated by the applied voltage difference between

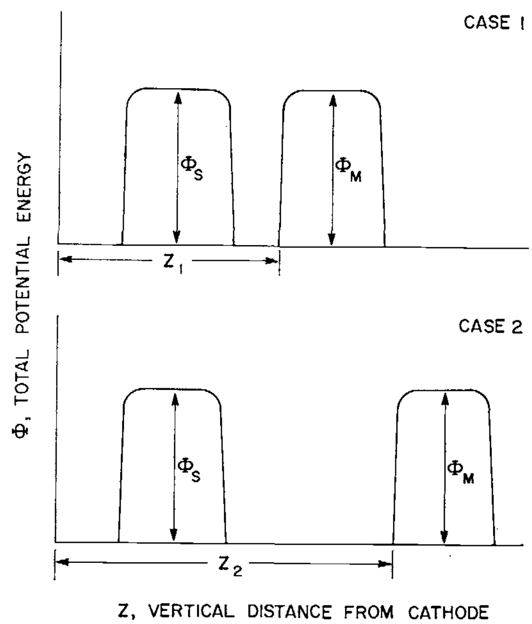


Fig. 4. Potential versus height in movable drift tube apparatus. In case 1 the total potential $\Phi_M$ of the movable drift tube has been made equal to $\Phi_S$, the total potential of the stationary drift tube, by adjustment of the applied voltage between the tubes to the value $V_1$. In case 2 the movable tube has been moved higher by the amount $z_2 - z_1$. The applied voltage is readjusted to the value $V_2$ which again makes $\Phi_M = \Phi_S$. The change in total potential energy for a particle of charge $q$ caused by the change in height $z_2 - z_1$ is just $q(V_2 - V_1)$.

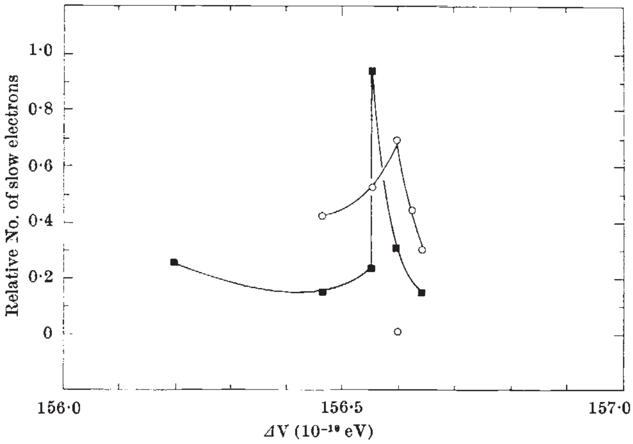


Fig. 5. Data from movable drift tube experiments. The horizontal axis is the applied potential difference between the movable and stationary drift tubes. The vertical axis is the ratio of the number of electrons with flight time between 25 and 50 ms to the number with flight times between 12·5 and 25 ms. Each ratio requires 10 to 15 h of data accumulation. ○, Separation = 1 cm; ■, separation = 31 cm.

the tubes. Thus the gravitational potential change is determined from the change in applied voltage required to equalize the two total potentials.

Using this method with electrons afforded data that were apparently affected much more than expected by potential fluctuations of the vacuum chamber relative to the drift tubes. This caused a spread in energies of electrons entering the upper drift tube. As a result it took 10–15 h to get a usable distribution for a single potential setting. Many settings were required to determine the intrinsic relative potentials (primarily the contact potential difference) of the two tubes. Fig. 5 shows a summary of data taken in similar conditions at drift tube separations of 0 and 30 cm at several potential settings. Each point represents the ratio of "slow" electrons (those taking between 25 and 50 ms to traverse the tubes) to "fast" electrons (those taking from 12·5 to 25 ms). The total potentials of the drift tubes are assumed equal at the maxima of these ratios. The maxima are $5 \times 10^{-12}$ V apart for 30 cm change in separation which indicates that the total potential change experienced by electrons falling through distance $z$ was a little less than 30 per cent of $mgz$. The accuracy of these data does not seem to be as good as that taken in the single drift tube experiment ($\pm 9$ per cent[14]) but may be improved if the electronic noise can be reduced. The total potential change expected is zero for electrons and 2 $mgz$ for positrons, provided that both have gravitational properties consistent with general relativity.

## The Positron Experiment

At present, Mr John Madey of Stanford University is developing a source of slow positrons with which to perform free fall experiments. The main problem is to reduce the energy spread of positrons to the extent where there is a reasonable probability of having a $10^{-10}$ eV positron leave the bottom of the drift tube in a known 10 ms time interval.

We plan to use a four stage process to reduce the energy spread of positrons emitted from a radioactive source. In the first stage the positrons impinge on a thin mica slab the opposite face of which has a thin metal coating on it. Cherry[19] has shown that when positrons pass through such a slab, a few of them (about 30 per mCi of source $s^{-1}$) emerge in the energy range 0–10 eV. Madey has obtained similar results at Stanford (private communication from J. M. Madey). The second stage, not yet tried, is to trap and store these positrons in a magnetic and electrostatic bottle, and then to release them at desired intervals into the third stage. The third stage will consist of a small diameter cylinder made of a resistive material. It will be coaxial with and placed just below the same drift tube that was used in the free fall experiments. The positrons are expected to lose energy to the walls of the resistive medium by eddy currents (private communication from J. M. Madey). Thus the positrons will lose energy without the danger of annihilation. Part of the resistive region will be maintained at $10^{-3}$ V below the drift tube potential, so that after a time estimated as 10 s all of the positrons originally released from the electromagnetic bottle will be in a $10^{-3}$ V trap. We expect from one to ten positrons to be trapped in this way. Further reduction of the energy spread by this method is limited by the patch effect and by thermal noise, so the fourth stage of reduction uses the drift tube where these effects are very small. If the drift tube potential were lowered instantaneously all the positrons would escape from the trap together, with a $10^{-3}$ eV energy spread. But if the drift tube potential is lowered slowly enough, this energy spread can be enormously reduced at the cost of some loss of knowledge of the time at which the positrons leave the trap. Let $\Phi(t)$ be the drift tube potential relative to the bottom of the trap, and let $E$ be the kinetic energy and $v$ the velocity of a trapped positron. When the positron enters the drift tube at time $t_e$, its kinetic energy $\varepsilon$ becomes fixed at $E - \Phi(t_e)$. The trap has length $l = 1$ cm. The maximum value of $\varepsilon$ is just $\varepsilon_m = -\frac{2l}{v}\frac{d\Phi}{dt}$, as $\frac{2l}{v}$ is the maximum time a particle can stay in the trap when $E \approx \Phi(t)$. When the positron escapes $E \approx \Phi(t)$, so that $v \approx \sqrt{2/m}\ \Phi^{1/2}$ inside the trap. Therefore $\varepsilon_m dt = -2l\sqrt{m/2}\ \frac{d\Phi}{\Phi^{1/2}}$. Integration yields

$$\varepsilon_m t = 2l\sqrt{2m}\ [\Phi^{1/2}(0) - \Phi^{1/2}(t)] = 2{\cdot}5 \times 10^{-9} \text{ eV s}$$

If we are willing to let the escape time be uncertain by 0·01 s then the energy spread is reduced to only $2{\cdot}5 \times 10^{-7}$ eV. Every 2,500 pulses from the source should yield at least one $10^{-10}$ eV positron. The positron time of flight distributions would be studied by one of the methods already used on electrons.

In conclusion, we have used two methods to examine extremely small forces on electrons falling through vertical metal tubes at low temperatures. Both methods indicate that the gravitational potential change is cancelled by an electrical potential to less than $10^{-11}$ eV $m^{-1}$. A method has been devised that is expected to produce enough low energy positrons to permit measurement of their gravitational properties in free fall experiments.

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