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THE LYTTLETON-BONDI UNIVERSE AND CHARGE EQUALITY

Lecture XIII

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Preface

These notes were taken from a series of seminars on Gravitation and Relativity presented at the Institute for Space Studies, NASA Goddard Space Flight Center during the academic year 1961-1962. Professor R. H. Dicke of Princeton University organized the series as an introduction to the subject for non-experts, emphasizing the observable implications of the theory and the potential contribution the space sciences may make towards a better understanding of general relativity.

The approach has been conceptual rather than formal. For this reason, this record does not include a complete mathematical development of the subject, but, we hope, does contain sufficient mathematics to elaborate on the conceptual discussions.

The notes were prepared with a minimum amount of editing from a transcript made from recordings of the lectures. The speakers have not had the opportunity to read and correct the final manuscript. Hence, we accept responsibility for errors and omissions.

H. Y. Chiu

W. F. Hoffmann

1. Introduction.

Whether or not the electron charge magnitude exactly equals the proton charge magnitude is an interesting and fundamental question in physics. In this lecture I should like to discuss the theoretical arguments on this question, some implications to physics, astronomy and cosmology of a slight departure from charge equality, and the most recent experimental determinations of the electron-proton charge ratio.

As you know, experimental findings of the late 19th and early 20th centuries culminating in Millikan's oil drop experiment led to the conclusions that electric charges occur always as integral multiples of a smallest unit, and that the smallest unit for positive charge (the proton) is equal to the smallest unit for negative charge (the electron). Thus an atom or molecule which consists of equal numbers of electrons and protons should be electrically neutral. In 1932 the neutron was discovered and it was found to have zero charge. By now there are some 30 so-called elementary particles known, and each of these appears to have a charge of +1, 0, or -1 electron charge unit.

2. Implications of a Charge Difference.

Ideally elementary particle theory should predict the observed spectrum of the elementary particles including their charge and mass ratios. Modern quantized field theory can describe discrete particles but cannot predict the values of a particle's mass and charge. These must be obtained from experiment. The invariance of the theory under charge conjugation (the interchange of particle and antiparticle) does provide a theoretical prediction that a particle and its antiparticle should have charges which are equal in magnitude but opposite in sign. For example, the electron and positron charges should have the same magnitude. Also the proton and antiproton charges should have the same magnitude. However, theory does not predict the ratio of the magntidues of the charges on two different particles, for example, the ratio of the electron to proton charge.

Indeed in view of modern charge renormalization theory the question of the electron-proton charge ratio becomes rather deep and somewhat ambiguous. If the bare charges of the electron and proton were equal, then conventional renormalization theory with gauge invariance would require that the renormalized electron and proton charges should also be equal. However, Gell-Mann and Nambu [(1)] have remarked that if in

(1) M. Gell-Mann, Proceedings of the Tenth Annual International Conference on High Energy Physics (Interscience Publishers, Inc. New York (1960), p.792.

addition to the photon there were another neutral vector particle which is coupled to the proton but not to the electron, then even though the bare charges of the electron and the proton were equal, the renormalized charges would be expressed in terms of ambiguous, quadratically divergent integrals and might not be equal.

Feinberg and Goldhaber [2] have discussed the connection between the conservation laws and charge equalities of particles. At present the absolute conservation laws of charge, baryon number, and lepton number are all independent and are believed valid for any particle reaction. Because of the independent conservation laws for baryons and leptons, use of charge conservation in the known reactions involving elementary particles does not of itself determine the ratios of the charges of all the elementary particles. For example the apparent absence of the reaction $p \rightarrow e^+ + \pi^o$ leaves the ratio of the electron to proton charges undetermined. Conversely, if the electron (lepton) and proton (baryon) charge magnitudes were different, then the absence of such a reaction, or, more generally, the conservation of baryons would follow from the conservation

(2) G. Feinberg and M. Goldhaber, Proc. Natl. Acad. Sci. U. S. 45, 1301 (1959).

of charge instead of being an independent principle.

In the 20th century there has been considerable speculation about the effect on large-scale matter of a slight difference, δq, in the magnitudes of the electron and proton charges. Questions have been raised concerning the effect of such an inequality on gravitation, on the magnetic fields of astronomical bodies, and, recently, on cosmology.

As to the relevance of charge inequality to gravitation it is suggestive to compare the electrical force between two protons to their gravitational force. This ratio is:

$$\frac{F_{el.}}{F_{grav.}} = \frac{e^2/r^2}{Gm_p^2/r^2} = 1.2 \times 10^{36} \tag{1}$$

which is, of course, a very large number. If the electron charge is $q_e = -e$ and the proton charge were a slightly different magnitude,

$$q_p = (1 + y)e \tag{2}$$

then the charge on the hydrogen atom would be $+ye$, and the ratio of the electrostatic force between two hydrogen atoms to their gravitational force would be

$$\frac{F_{el.}}{F_{grav.}} = \frac{(ye)^2}{Gm_H^{\ 2}} = 1.2 \times 10^{36}\ y^2 \tag{3}$$

This ratio is 1 when $y = 0.9 \times 10^{-18}$. Hence if there were 1 part in 10^{18} difference between the proton and electron charge magnitudes, then the electrostatic force between two hydrogen atoms would be equal in magnitude to the gravitational force.

The very large ratio of electrical to gravitational forces and their similar dependence on the inverse square of the distance between the particles suggest the possibility that gravitational forces might arise due to some small breakdown of the normal theory of electrical forces. Lorentz proposed that the gravitational force might arise because of a slight difference between the force of repulsion between two particles with charges of the same sign and the force of attraction between two particles with charges of the same magnitudes but of unlike sign. Swann [(3)] has also discussed this possibility and has considered it in connection with matter and antimatter.

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(3) W. F. G. Swann, Phil. Mag. 3, 1088 (1927); Astrophysical J. 133, 733 (1961).

The origin of the magnetic fields of astronomical bodies is another problem for which the possibility of a slight charge difference may be relevant. Einstein [4] remarked that a slight difference between the proton and electron charge magnitudes would, of course, lead to a net volume charge for matter composed of equal numbers of protons and electrons. Hence a rotating object such as the earth would have an associated magnetic field similar to that of a magnetic dipole. At the pole the field would be given by:

$$H_{pole} = 2P/R^3 \tag{4}$$

where R is the radius of the earth and P is its magnetic dipole moment:

$$P = \frac{0.2\omega MR^2}{c} \frac{\sigma}{\rho} \tag{5}$$

where ω is the angular velocity of the earth, M is the mass, σ is the charge density and ρ the mass density. For a proton charge given by equation (2)

$$\frac{\sigma}{\rho} = \frac{ye}{m_H} \tag{6}$$

where m_H is the mass of the hydrogen atom. If we assume that the earth's magnetic field of 0.6 gauss at the pole is entirely due to this charge inequality, then $y = 3 \times 10^{-19}$.

Blackett [5] observed in 1947 that the ratios of the magnetic dipole moment as computed from equation (5) to the angular momentum for three astronomical bodies--the earth, the sun and the star 78 Virginis--have nearly the same value of

$$\frac{P}{I}_{\text{earth, sun, star}} \simeq 1.1 \times 10^{-15} \tag{7}$$

Furthermore, the ratio of the orbital magnetic moment to the orbital angular momentum for an electron is

$$\frac{P}{I} \text{ electron orbital motion} = \frac{e}{2m_e c} \cong 0.9 \times 10^{7} \tag{8}$$

and the ratio of these two quantities is

$$\frac{(P/I) \text{ astronomical bodies}}{(P/I) \text{ electron}} \simeq 10^{-22} \tag{9}$$

This dimensionless ratio is nearly equal to the dimensionless constant

$$\frac{G^{\frac{1}{2}}\, m_e}{e} = 4 \times 10^{-22} \tag{10}$$

Blackett considered it unlikely that this approximate numerical equality should occur accidentally. Therefore he proposed that it should be true in general that

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(5) P. M. S. Blackett, Nature 159, 658 (1947).

$$(P/I)_{\text{astronomical body}} = (P/I)_{\text{electron}} \frac{G^{\frac{1}{2}} m_e}{e} = \frac{G^{\frac{1}{2}}}{2c} \tag{11}$$

It was found subsequent to Blackett's paper that the magnetic field of the sun is nearer to 1 gauss than to 50 gauss which was the value he used, so the ratio P/I for the sun actually does not have the value given in equation (7). There are many more stars whose magnetic fields have been determined by now and it would be interesting to compare these new data with equation (11).

The relation (11) is consistent with the model of a rotating charged earth that Einstein proposed. However, the simplest model of a rotating charged body gives very much too high an electric field at the surface of the earth so that the theory must be modified to include surface charge as well as volume charge in order to give a reasonable value for the electric field as well as for the magnetic field.

A third general area in which an electron-proton charge inequality might have some interesting implications is cosmology. Lyttleton and Bondi [6] suggested that the observed expansion of the universe might be understood in terms of a slight charge difference as an electric repulsion.

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(6) R. A. Lyttleton and H. Bondi, Proc. Roy. Soc. A 252, 313 (1959).

They discussed this suggestion first in the context of simple Newtonian theory using the model of a smoothed out, spherical universe composed of hydrogen atoms with a mass density σ and a corresponding charge density σ, where

$$\sigma = \rho \frac{ye}{m_H} \tag{6}$$

and y is assumed to be positive. (See Figure 1.) The electrostatic force on a hydrogen atom at a distance r from the center of this charge distribution is

$$F_{el.} = \frac{(ye)^2}{r^2 \; m_H} \; M_r \tag{12}$$

where M_r is the total mass within the radius r.

The gravitational force is

$$F_{grav.} = \frac{M_r \; m_H G}{r^2} \tag{13}$$

We define the ratio of the electrostatic repulsive force to the gravitational attractive force to be

$$\mu = \left(\frac{ye}{m_H \quad \sqrt{G}} \right)^2 = (1.12 \times 10^{18} \; y)^2 \tag{14}$$

which is the same as equation (3). The net repulsive force is then

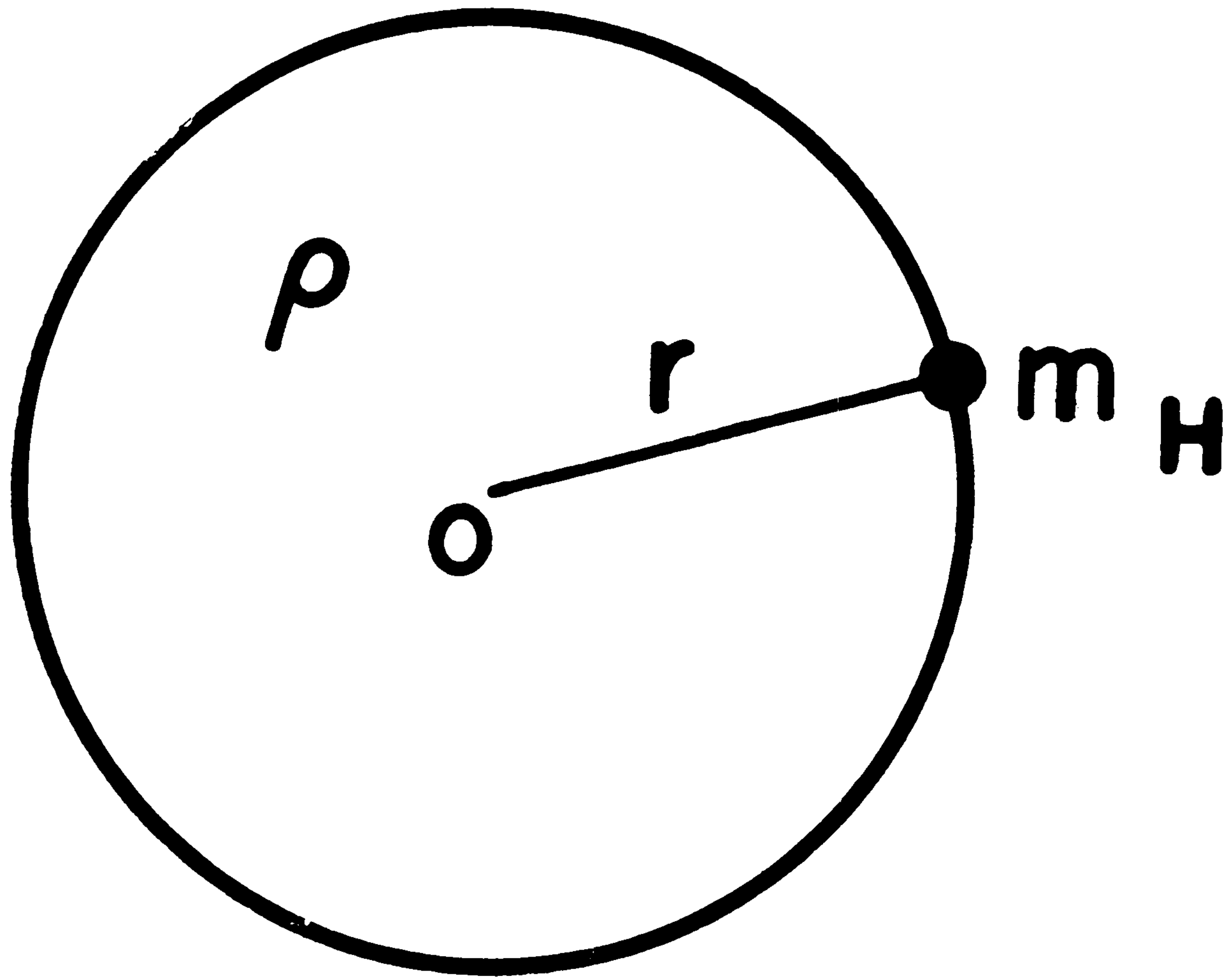

Figure 1. Model of a uniformly charged universe.

$$F = F_{el.} - F_{grav.} = (\mu - 1)\, F_{grav.}$$

$$F = (\mu - 1)\, \frac{4}{3} \pi \rho \, m_H \, Gr = kr \qquad (15)$$

If $\mu - 1 > 0$, there will be a repulsive force which is proportional to r and which will lead to an expansion of the universe.

In order to achieve constant matter density in the universe despite the expansion, Lyttleton and Bondi propose the continuous creation of matter (hydrogen atoms) and hence necessarily also then the creation of charge. They propose a modification of Maxwell's equations to allow for the nonconservation of charge and solve the problem of a steady-state expanding universe with mass and charge creation. They obtain the following relationship between the mass density ρ, the Hubble constant T^{-1}, and the rate of matter creation Q :

$$\rho = \frac{1}{3} m_H \, Q \, T. \qquad (16)$$

Using $T = 3 \times 10^{17}$ sec and $\rho = 10^{-29}$ gm/cm^3, they obtain

$$Q = 6 \times 10^{-23} \; \frac{\text{H atoms}}{\text{cm}^3\text{-sec}}$$

which corresponds to a creation rate of one hydrogen atom per second in a cube of 250 kilometers on an edge.

With constant matter density ρ the repulsive force given in equation (15) is consistent with a velocity which increases linearly with distance

$$v = \sqrt{K} \; r \tag{17}$$

where

$$K = (\mu - 1) \frac{4}{3} \pi\rho \, G$$

The observed expansion of the universe is

$$v = r/T \tag{18}$$

Equating (17) and (18) gives

$$T = \frac{1}{\left[(\mu - 1)\frac{4}{3}\pi\rho \, G\right]^{\frac{1}{2}}} \tag{19}$$

and hence $\mu = 5$

and $y = 2 \times 10^{-18}$. (20)

This is the charge inequality that Lyttleton and Bondi proposed to explain the observed expansion of the universe with a theory in which they allow for charge creation and a modification of Maxwell's equations. They also formulated their theory in the more general terms of de Sitter space-time to satisfy the cosmological principle that the universe appears the same as viewed from any position. The more general theory introduced no essential modifications of the basic conclusions of the Newtonian picture.

When ionization occurs, electrically neutral units will grow from the background of smoothed-out, un-ionized matter. These units are identified with galaxies or clusters of galaxies. Ions--primarily protons--which are expelled from these units by the electrostatic forces are identified with the hard component of the cosmic rays.

Hoyle [7] pointed out an error in the treatment of the modified Maxwell theory of Lyttleton and Bondi. The principal difference in conclusion reached by Hoyle is that the potential due to a charge will be of the form

$$\varphi = \frac{e}{r} \cos \left[(-\lambda)^{\frac{1}{2}} r \right] \qquad (21)$$

where r is the distance from the charge and λ is a cosmological quantity

$$(-\lambda)^{\frac{1}{2}} \approx \frac{1}{\text{Radius of the Universe}}$$

(7) F. Hoyle, Proc. Roy. Soc. A 257, 431 (1960).

From equation (21) it is clear that the potential will change sign at sufficiently large distances, and thus the force between two like charges will change from repulsive to attractive.

Hoyle's interpreation then is that the electrostatic force would not be repulsive on a cosmological scale and lead to an expansion of the universe in the manner Lyttleton and Bondi proposed, but would rather be primarily attractive. Hoyle noted however that if matter and antimatter are both created at the same rate, if a hydrogen atom has a charge ye, and an antihydrogen atom a charge $-ye$, and if matter and antimatter become sufficiently separated, then repulsion of matter and antimatter will occur according to equation (21) and expansion of the universe would occur. Hoyle's theory also requires that $y \simeq 2 \times 10^{-18}$.

3. Experimental Evidence on Charge Difference.

Now I would like to discuss what terrestrial laboratory experiments have established about the electron-proton charge difference.

One of the earliest experiments was the Millikan oil drop experiment [8]. Millikan studied the motion of droplets of various liquids which had been charged by different means

(8) R. A. Millikan, The Electron (University of Chicago Press, Chicago, 1917), 1st ed. pp. 80-83.

such as by friction, by use of x-rays, or by capture of ions from the air. From the observation of the motion of these droplets under the forces of gravity, of viscous drag, and of an electric field, Millikan was able to show that in all cases every droplet had a charge which was an integral multiple of the smallest unit. He studied charges of both signs and he found that

$$\frac{\text{positive charge unit}}{\text{negative charge unit}} = 1 \pm 1/1500$$

A macroscopic interpretation of this result can be given in terms of the electron-proton charge difference [9]. A typical oil droplet is a sphere with a radius of about 10^{-4} cm and a density of 1 gm/cm^3. The number, N, of proton-electron pairs in one of these droplets is then $N \simeq 2.5 \times 10^{12}$. Millikan's observations require that

$$Nye < e/1500$$

and hence

$$y < 3 \times 10^{-16}$$

Another macroscopic experiment by a gas efflux method

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(9) V. W. Hughes, Phys. Rev. 76, 474 (1949) (A), ibid., 105, 170 (1957).

was first done by Piccard and Kessler [4] and will be discussed later.

I should like to discuss next an atomic beam experiment which has recently been done by Zorn, Chamberlain, and Hughes [10, 11, 9]. The method of the experiment is to study the deflection of a molecular beam in a homogeneous electric field. If an atom is neutral, it will not be deflected, but if there were a difference between the electron and proton charge magnitudes then an atom would have a net charge and it would be deflected.

We used a classic molecular beam technique [12] as illustrated in Figure 2.

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(10) J. C. Zorn, G. E. Chamberlain and V. W. Hughes, Bull. Am. Phys. Soc. 6, 63 (1961); Proceedings of the Tenth Annual International Conference on High Energy Physics (Interscience Publishers, New York, 1960), p. 790.

(11) J. C. Zorn, G. E. Chamberlain and V. W. Hughes, Bull. Am. Phys. Soc. 5, 36 (1960).

(12) P. Kusch and V. W. Hughes, "Atomic and Molecular Beam Spectroscopy" in Handbuch der Physik 37/1. S. Flügge, ed. (Springer-Verlag, Heidelberg, 1959), p. 6.

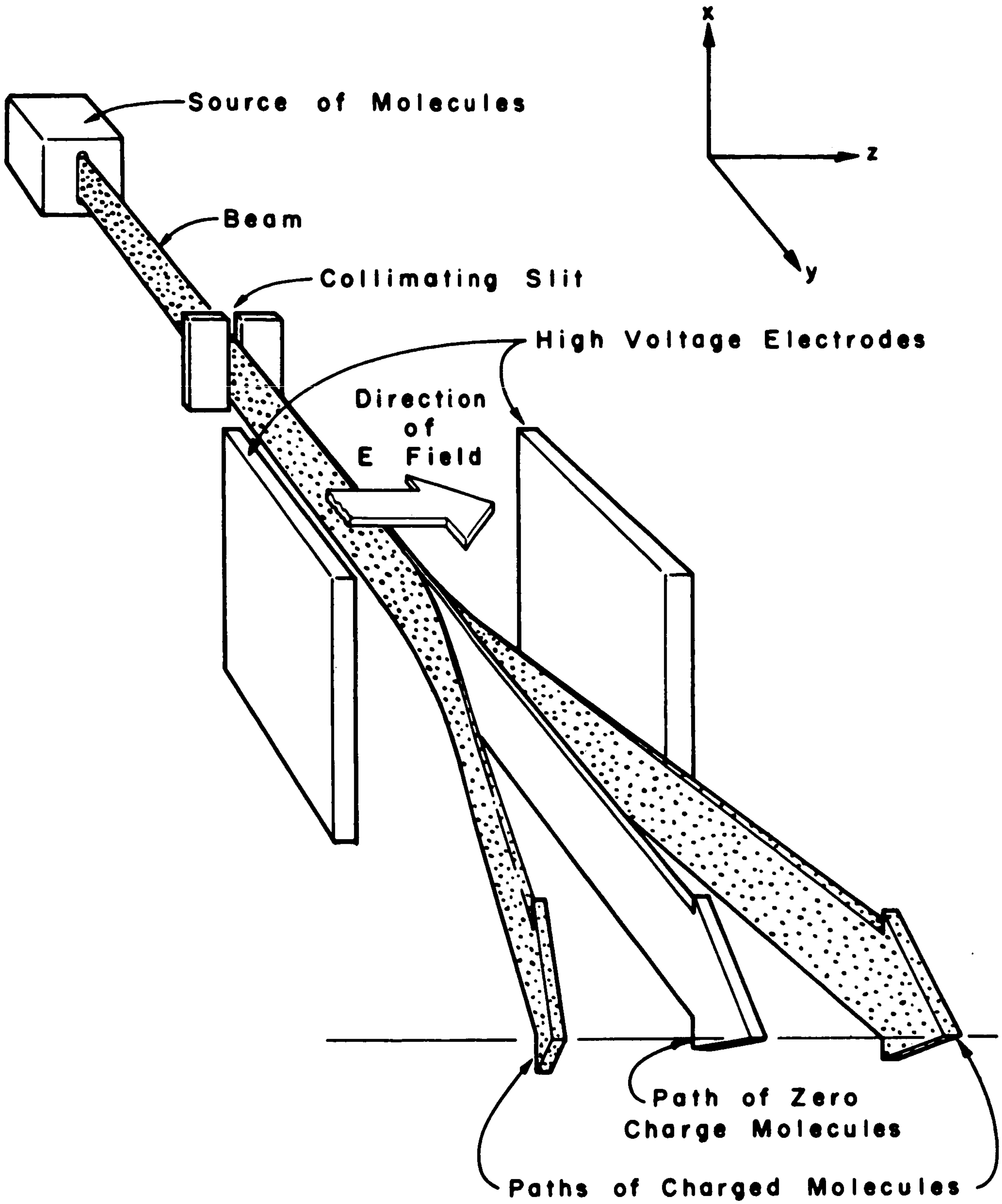

Figure 2. Molecular beam measurement of atomic or molecular charge.

The beam is defined by a source slit and a collimating slit so that it has a ribbon-like cross section which is narrow in the transverse horizontal direction and long in the vertical direction. This beam passes through a homogeneous electric field which would deflect the beam if the atoms were charged.

Figure 3 shows a horizontal cross section of the apparatus in greater detail. In terms of the geometry of Figure 3, the deflection that a charged molecule of velocity v would experience due to the electric field is given by

$$s_v = \frac{qE}{2mv^2} L_1 (L_1 + 2L_2) \tag{22}$$

where q, m, and v are the charge, mass and velocity of the particle in the beam and E is the electric field strength. In particular, a molecule with the most probable velocity α of molecules in the source $(\alpha = \sqrt{2kT/m})$ is deflected by the amount

$$s_\alpha = \frac{qE}{4kT} L_1 (L_1 + 2L_2) \tag{23}$$

where T is the source temperature and k is Boltzmann's constant.

In our recent experiment

$$L_1 = 200 \text{ cm}, \quad L_2 = 30 \text{ cm}$$

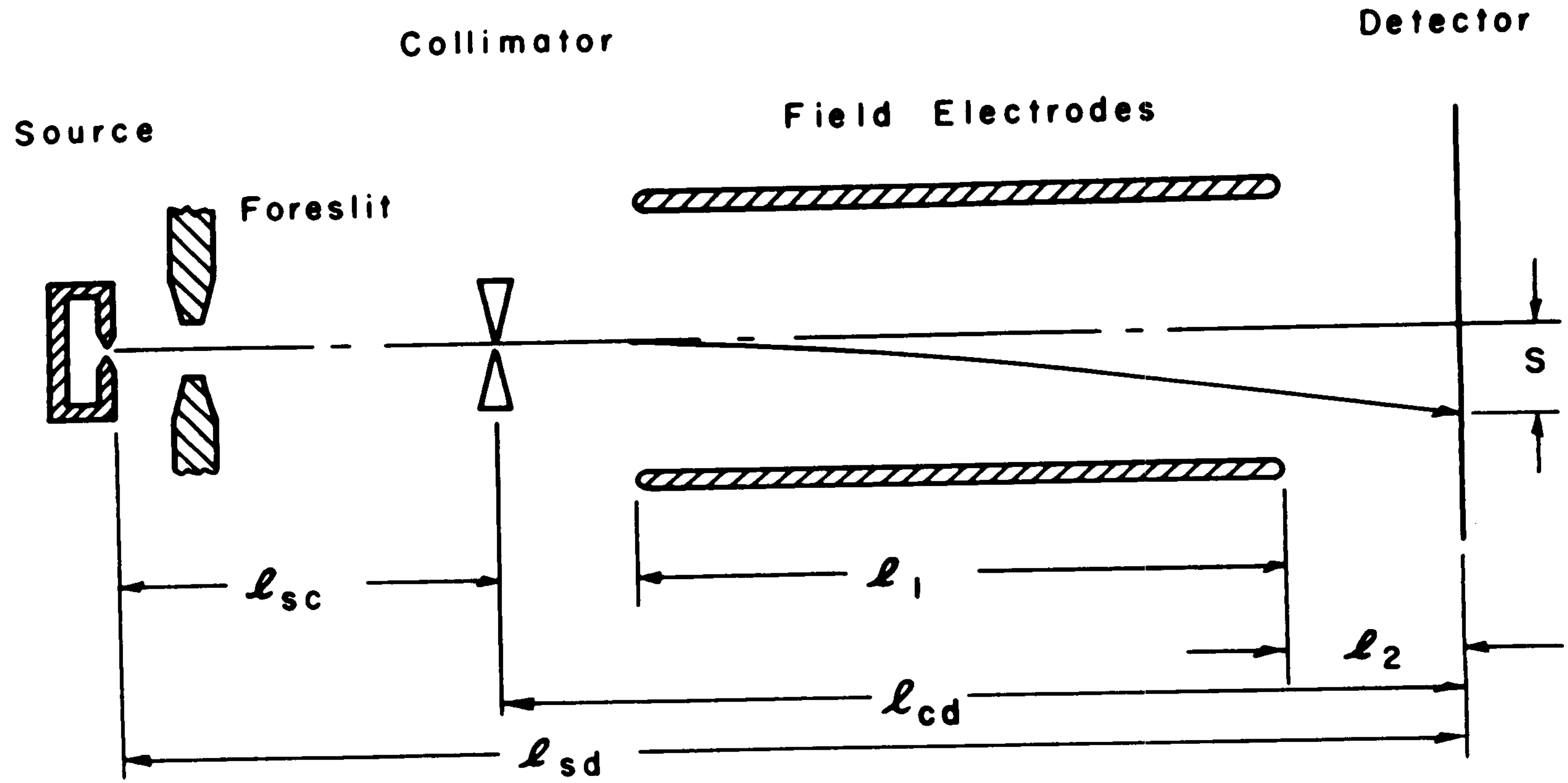

Figure 3. Geometry of apparatus, showing trajectory of an atom which has been deflected by the electric field.

and $$E = 10^5 \text{ volts/cm.}$$

The experiment was done for cesium and potassium atoms and the oven temperature was about 500 $^{\circ}$K. Our detector sensitivity was such that a deflection of 10^{-5} cm could be detected. Hence the minimum detectable atomic charge was

$$q \simeq 3 \times 10^{-17} e$$

For cesium the atomic number is 55; so the minimum detectable charge on an electron-proton pair, δq, is smaller by a factor of 55:

$$\delta q \sim 6 \times 10^{-19} e$$

This sensitivity is in the range of interest for the Lyttleton-Bondi theory.

There are some complications which are important to the experiment. Because of the smallness of the deflections being observed, electric field inhomogeneities can produce comparable deflections associated with the polarization of the atoms. The atoms have no permanent electric dipole moments, but in an electric field an electric dipole moment is induced. If the field is inhomogeneous, there will be a force on this induced electric dipole moment. In our experiment such field inhomogeneities arise at the ends of the field region. If the energy of the atom in the field is $W(E)$, then the force due to the induced dipole moment is

$$\vec{F} = -\nabla W(E) = -\frac{\partial W}{\partial E} \nabla |E| \tag{24}$$

It is apparent from the form of equation (24) that the direction of the force does not change with the direction of the field. Hence by reversing the polarity of the potential across the electrodes, we can distinguish between this dipole polarizability force and the force on a net atomic charge.

Another complication in interpreting the deflection measurements is the spread in velocities of the atoms. The velocity distribution is a Maxwellian one for particles effusing through an opening in the oven:

$$I_v \, dv = \frac{2I}{\alpha^4} v^3 e^{-v^2/\alpha^2} \, dv \tag{25}$$

where I is the total beam intensity. The observed deflection is given by an average over this velocity distribution.

Figure 4 illustrates a third complicating factor which must be considered. The source and detector slits have finite widths, so that we obtain a beam intensity distribution in the detector plane which is trapezoidal. In addition, the detector has a finite width.

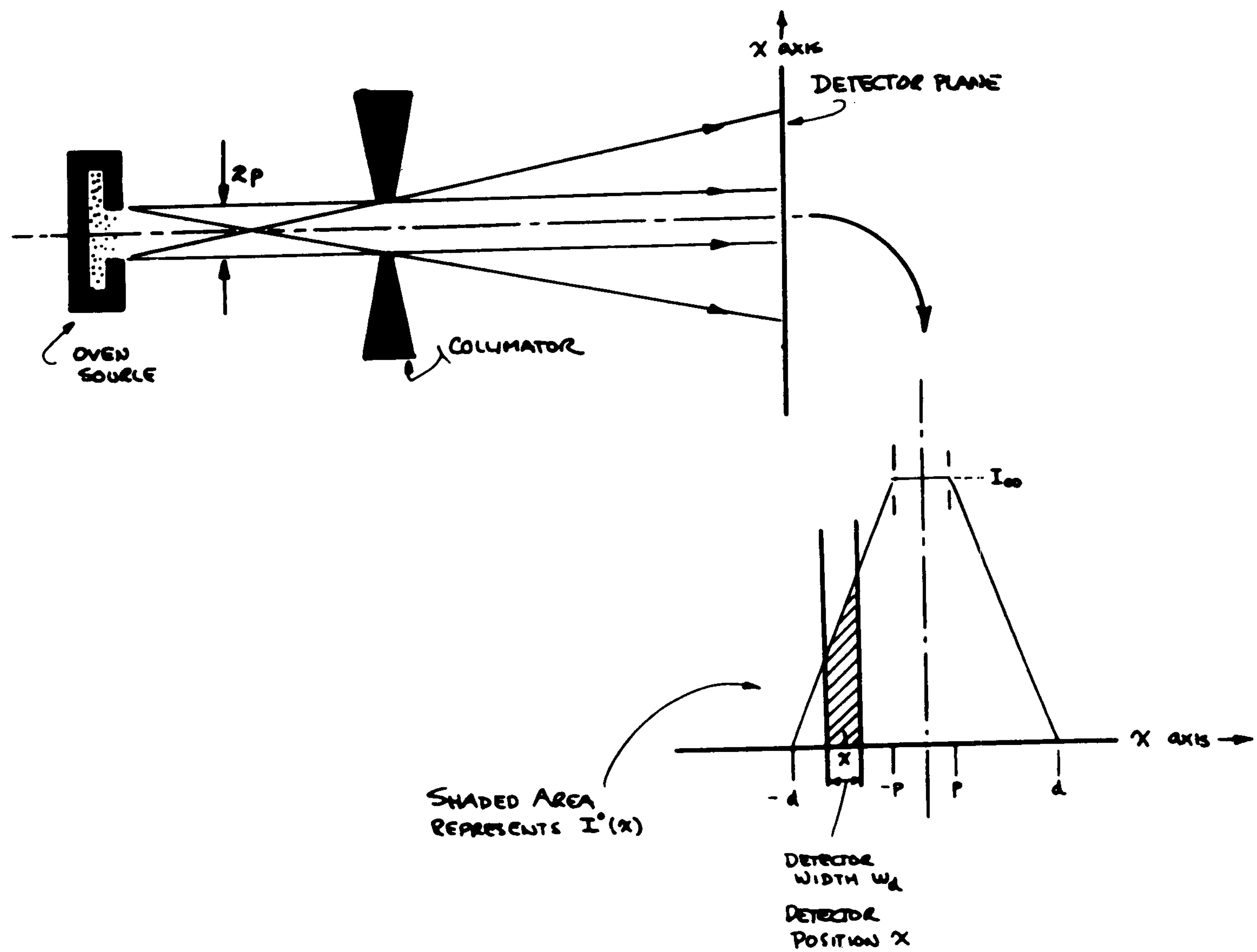

Figure 4. Effect of finite slit widths on beam intensity distribution.

In order to relate the observed intensity pattern to s_α , it is necessary to integrate over the width of the beam path and over the velocity distribution. The relation between s_α and the change in intensity with the detector positioned where the beam intensity has one half its maximum value is given by:

$$\frac{\Delta I}{I} = \frac{2s_\alpha}{d - p} \qquad (26)$$

where d is the half width of the penumbra of the beam in the detector plane and p is the half width of the umbra. The analysis has also been done in another way which does not require an a priori knowledge of the slit geometry and alignment but uses only the observed beam intensity distribution.

Some technical features of the experiment and of the apparatus will now be discussed. The choice of the atom is dictated largely by atomic beam technology. The only property of the atom that appears in the deflection equation (23) is the temperature at which it must be produced. This should be as low as possible. For this experiment we desire an atom containing many electron-proton pairs. Alkali atoms are used because they are produced conveniently in beams at relatively low temperatures and they are detected efficiently with a hot wire surface ionization detector. Figure 5 shows the oven used to produce the beam of potassium or cesium atoms. It is used at a temperature of about 500° K.

Figure 6 shows the observed and calculated beam intensity distribution with oven and collimator slit widths of 0.004 cm. The detector width is also 0.004 cm. The agreement between the two curves is good; the small discrepancy is attributed to atomic beam scattering, slit misalignment, and imperfect knowledge of slit dimensions. The detector is placed at one of the two half-maximum intensity points in order to obtain the maximum change in intensity for a given s_α .

Figure 7 shows the electric field assembly in vertical cross section. The parallel plates are made of aluminum and are about two meters in length with a spacing of 1 or 2 mm. Electric fields of 100 kv/cm are obtained before breakdown occurs.

Figure 8 shows some of the observed data. The change in beam intensity Δ observed with the detector placed at the two half-maximum intensity points (z_1 and z_2) is plotted as a function of electric field for both polarities of the field (A and B).

The deflection of the beam due to a net atomic charge

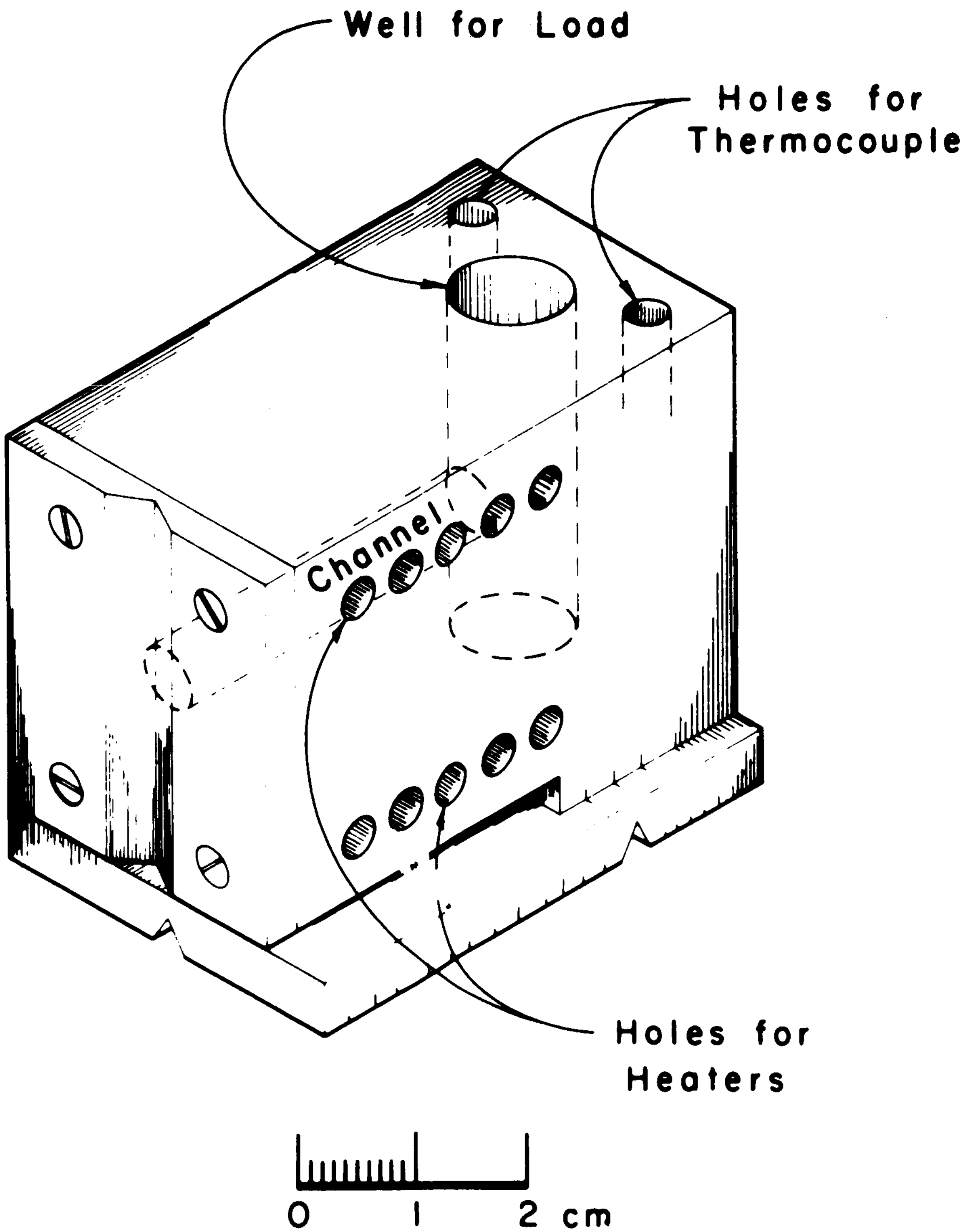

Figure 5. Conventional oven used for alkali atoms.

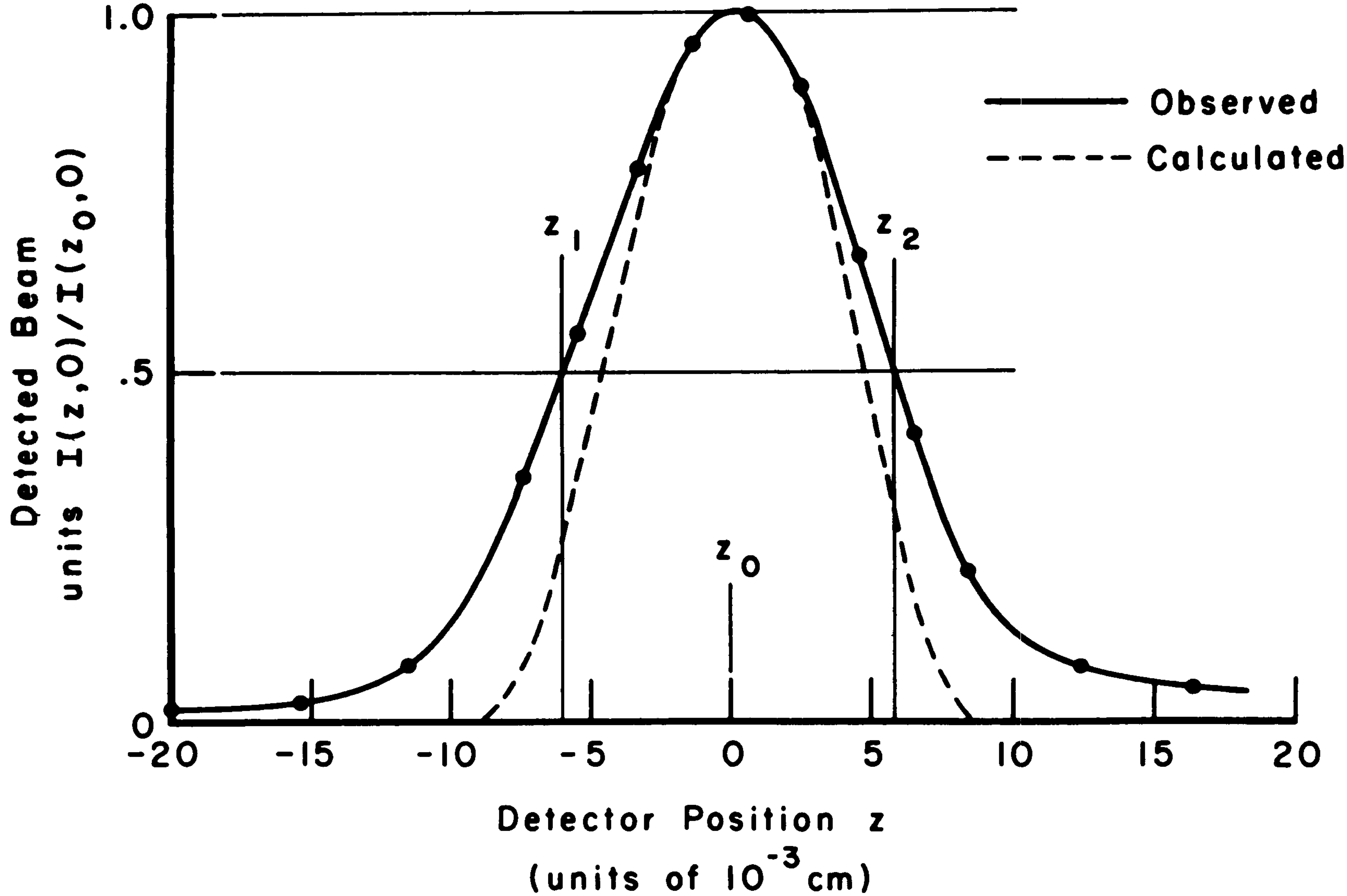

Figure 6. Theoretical beam shape for classical trajectories and ideal geometry compared to an observed zero-field intensity distribution for potassium atoms.

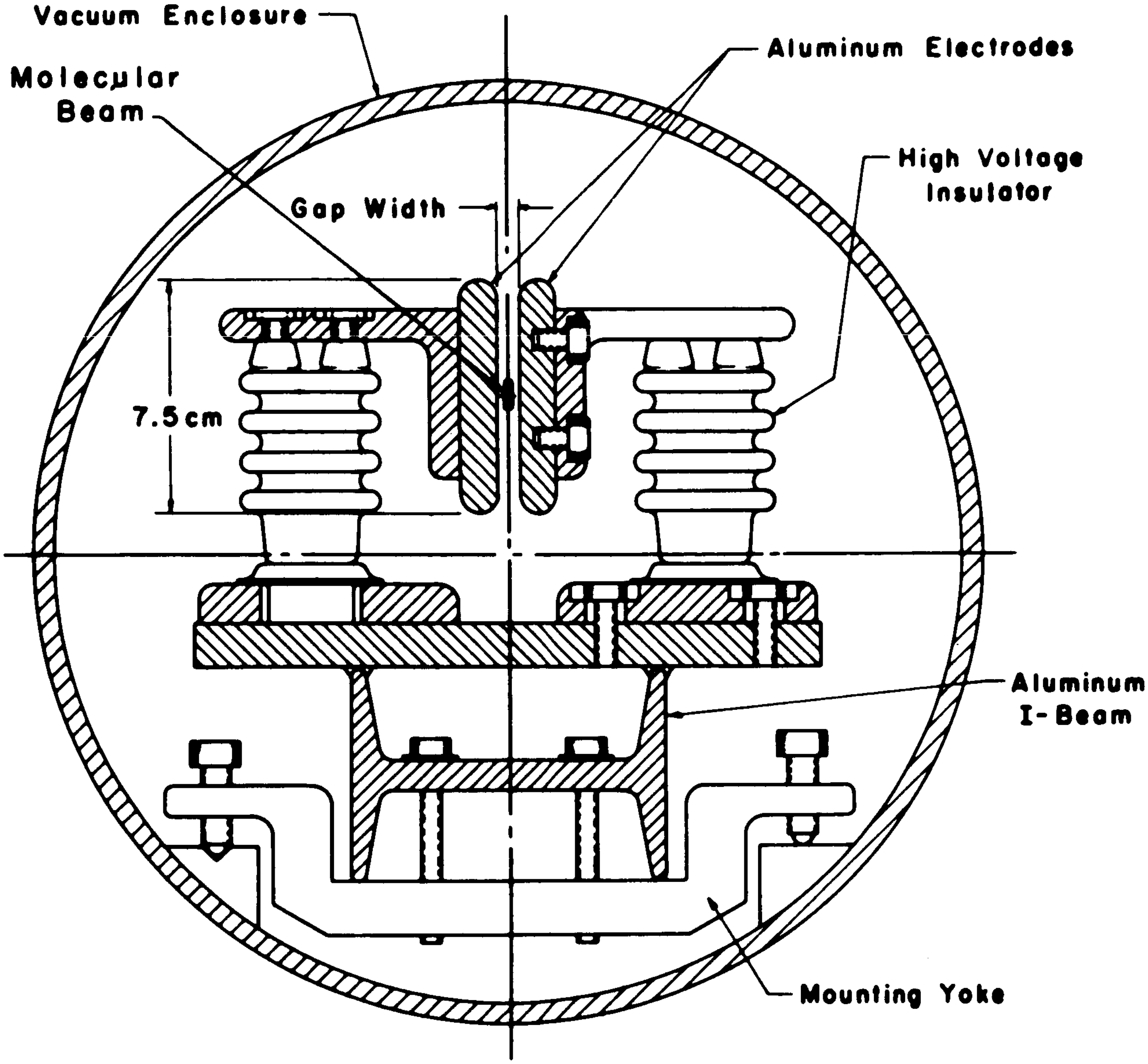

Figure 7. Cross-section of electrode assembly.

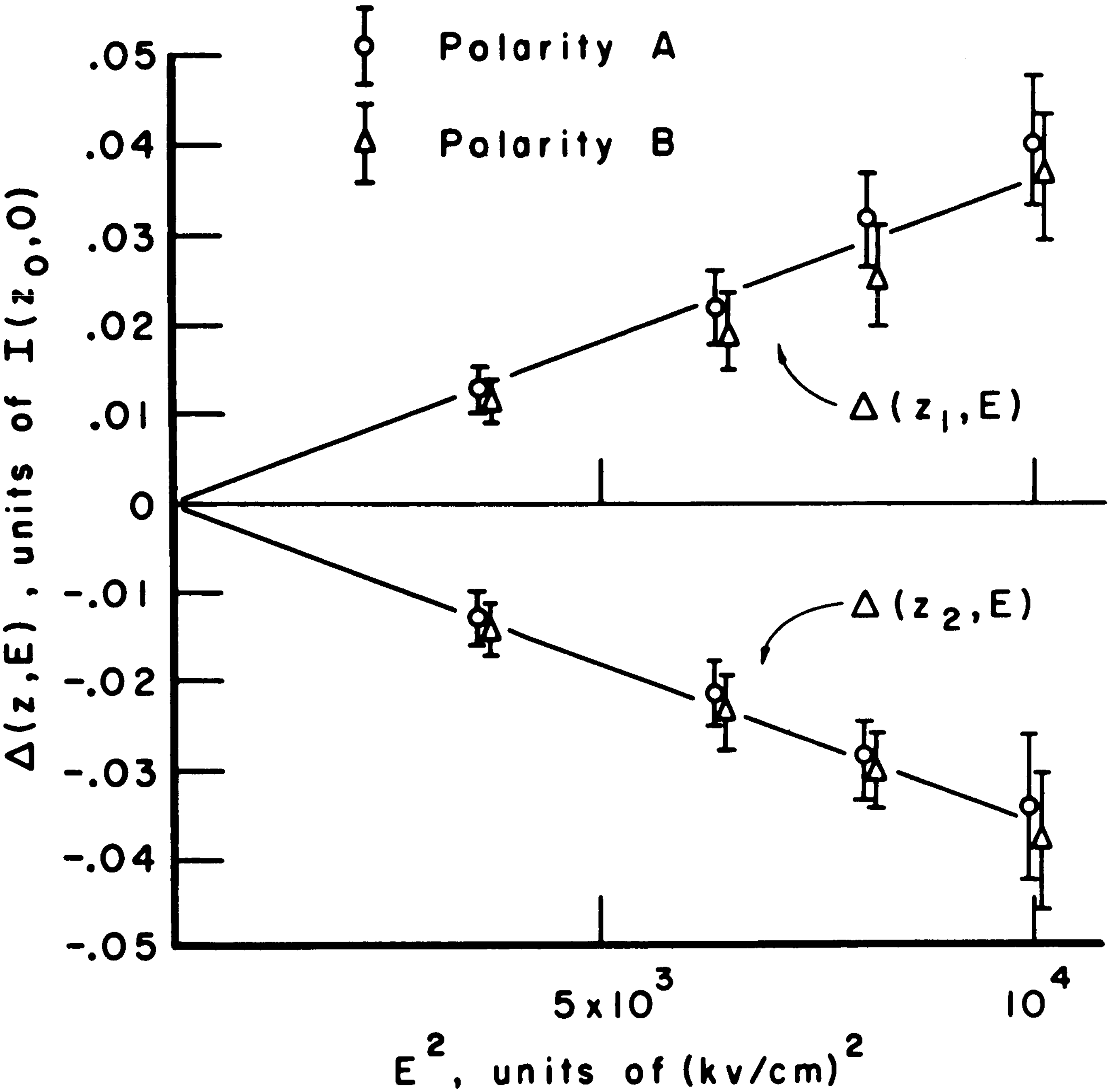

Figure 8. Beam intensity as a function of electric field at half-maximum intensity points (z_1 and z_2).

is directly proportional to E and, at the field strengths used in this experiment, the deflection from the induced dipole moment is proportional to E^2. The observed dependence of Δ (z_i,E) is shown in Figure 8. It is seen that Δ (z_i,E) is linearly proportional to E^2 up to a field E of about 10^5 v/cm, as expected for deflections due to dipole polarizability alone. At still higher fields Δ is no longer proportional to E^2; indeed both $\Delta(z_1,E)$ and $\Delta(z_2,E)$ decrease with an increase of E at sufficiently high values of E. This behavior is not consistent with deflection due to a net atomic charge and a dipole polarizability but rather is explained by an attenuation of the atomic beam at the higher fields. The beam appears to be attenuated in proportion to the gap current, and this gives rise to a field dependent signal change $D(z_i,E)$ not associated with an electric deflection of the beam atoms.

Table I shows the results deduced from such measurements on Potassium and Cesium atoms and on hydrogen and deuterium molecules. The upper limits for the charges are given. The upper limits on the charge are considerably higher for hydrogen and deuterium than for the alkalis. This is due to the fact that the Pirani detector for hydrogen is not as efficient as

TABLE I.

RESULTS	INTERPRETATION
Gases:	
$q(H_2) < \lvert 2 \rvert \times 10^{-15}\ q_e$	$\delta q < \lvert 1 \rvert \times 10^{-15}\ q_e$
$q(D_2) < \lvert 2.8 \rvert \times 10^{-15}\ q_e$	$q_n < \lvert 1.7 \rvert \times 10^{-15}\ q_e$
Alkalis:	
$q(K) = (-3.8 \pm 11.8) \times 10^{-17}\ q_e$	$q(K) = 19\ \delta q + 20\ q_n$
$q(Cs) = (+1.3 \pm 5.6) \times 10^{-17}\ q_e$	$q(Cs) = 55\ \delta q + 78\ q_n$
	If the value of δq is considered to be independent of q_n, the above are a pair of equations in two unknowns; solution gives the limits
	$\delta q = (-.85 \pm 2.7) \times 10^{-17}\ q_e$
	$q_n = (+.61 \pm 2.0) \times 10^{-17}\ q_e$
	But the neutron decay: $n \rightarrow p + e^- + \bar{\nu}$ indicates $\delta q = q_n$, so
	$\delta q = (1.0 \pm 4.2) \times 10^{-19}\ q_e$

δq: electron-proton charge difference
q_n: neutron charge
q_e: absolute value of electron charge

the hot wire surface ionization detector for the alkalis so that the gas apparatus was shorter and less sensitive to small deflections than the alkali apparatus.

The charge of an atom or molecule is assumed to be completely given by the scalar sum $q = Z\delta q + Nq_n$, where Z is the number of electron-proton pairs, $\delta q = q_p - q_e$ is the electron-proton charge difference, N is the number of neutrons, and q_n is the neutron charge. The most direct determination of a limit for δq is obtained from the measurement of the net charge of the hydrogen molecule:

$$|\delta q| = \frac{|q\ (H_2)|}{2} < 1 \times 10^{-15}\ q_e \qquad (27)$$

In addition, the result from deuterium gives a limit for q_n :

$$q_n < 2.4 \times 10^{-15}\ q_e \qquad (28)$$

Smaller limits than the above can be obtained from the experimental values for the charges of cesium and potassium.

$$q(Cs) = 55\ \delta q + 78\ q_n = (13 \pm 56) \times 10^{-18}\ q_e \qquad (29)$$

$$q(K) = 19\ \delta q + 20\ q_n = (-38 \pm 118) \times 10^{-18}\ q_e \qquad (30)$$

As simultaneous equations in δq and q_n, the solution gives

$$\delta q = (-8.5 \pm 27) \times 10^{-18} q_e \tag{31}$$

independently of the value of q_n , and

$$q_n = (6.1 \pm 20) \times 10^{-18} q_e \tag{32}$$

independently of the value of δq.

A still smaller limit for the electron-proton charge difference can be given if one assumes that $\delta q = q_n$. This relation follows from the usual assumption that charge is conserved in beta decay of the neutron $(N \rightarrow p + e + \bar{\nu})$ and that the charge of the antineutrino is zero (*). Then $\delta q = q\,(\text{atom})/(Z + N)$ and we obtain from $q(\text{Cs})$:

$$\delta q = (1.0 \pm 4.2) \times 10^{-19} q_e \tag{33}$$

With improved vacuum, electric field conditions, and detector stability we believe our atomic beam experiment on the alkalis could be improved in sensitivity by about a

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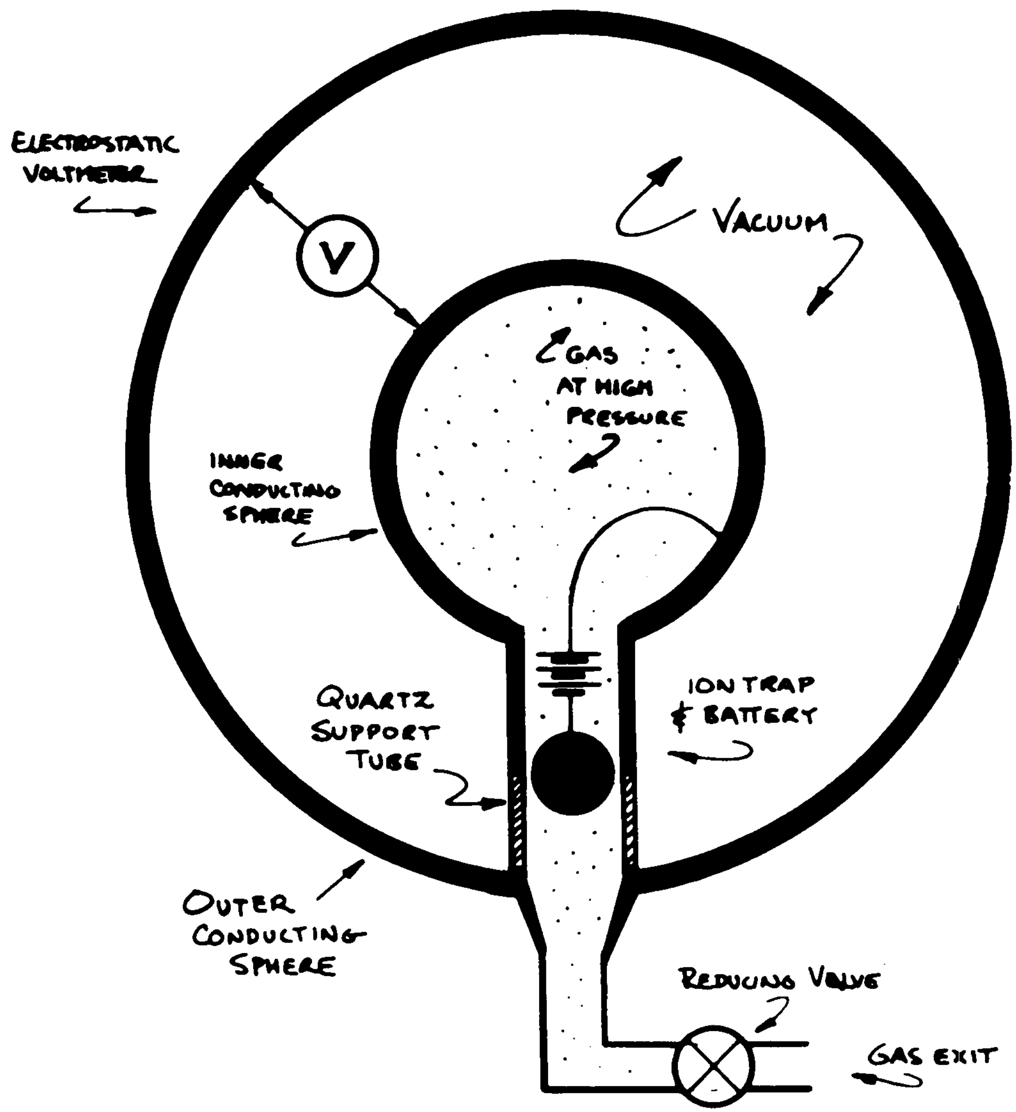
(*) An upper limit to the neutrino charge can be obtained by considering that the neutrino is a Dirac particle with a mass of 500 ev (upper limit to the allowed neutrino mass) and computing the upper limit to the charge that is consistent with neutrino cross-section data (J. S. Allen, The Neutrino (Princeton University Press, Princeton, 1958). The limit found for the neutrino charge in this way is about $10^{-10} q_e$.

factor of 100. An atomic beam experiment on thermal neutrons was done by Shapiro and Estulin who obtained an upper limit for the neutron charge of $6 \times 10^{-12}\ q_e$.

I would like to discuss briefly the macroscopic gas efflux experiment done first by Piccard and Kessler [(4)], which measures the total charge Q of M gas molecules by observing the change in potential of a metal container relative to its surroundings when gas effuses from the container. Figure 9 shows their apparatus consisting of two concentric conducting spheres which form a spherical capacitor. The inner sphere can be filled with a gas. The voltage between the two spheres depends on the capacity, on the surface charge on the inner sphere, and on the volume charge carried by the gas.

Piccard and Kessler filled the inner sphere with 20 to 30 atmospheres of CO_2 or N_2. Then they allowed the gas to effuse from the inner sphere and measured the change in potential across the capacitor. If the gas were neutral and there were no changes in the dimensions of the sphere, then there should be no change in the potential. On the other hand, if the gas had a net charge due to a proton-electron charge difference, then the potential would change when the



$$\Delta Q = C \Delta V$$

CO_2: Piccard & Kessler, Arch Sci Phys et Nat 7, 340 (1925)
N_2, A Hillas & Cranshaw, Nature 184, 892 (1959).

Figure 9. Piccard-Kessler apparatus for gas efflux experiment.

gas leaves the inner sphere. The efflux of ions or electrons was prevented, or at least made difficult, by biasing a small obstacle in the throat of the exhaust tube relative to the inner sphere such that ions are trapped in the inner sphere and are not exhausted with the neutral gas. From their measurements they determined that $\delta q \leq 5 \times 10^{-21}$ e.

Figure 10 shows a modern version of this same experiment by King [13,14]. King did his experiment with hydrogen and on helium.

Conservatively we can interpret his results as setting an upper limit for the charge on H_2 of less than 10^{-19} q_e .

A modern extension of Millikan's oil drop experiment using a small, magnetically suspended metal sphere has been proposed to achieve a higher sensitivity in the determination of δq

Table II presents a summary of experimental information on the electron-proton charge difference.

4. Interpretation of Results.

The atomic beam deflection experiment on the alkali atoms

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(13) J. G. King, Phys. Rev. Let. 5, 562 (1960).

(14) A. M. Hillas and T. E. Cranshaw, Nature 184, 892 (1959), ibid.186, 459 (1960). H. Bondi and R. A. Lyttleton, Nature 184, 974 (1959).

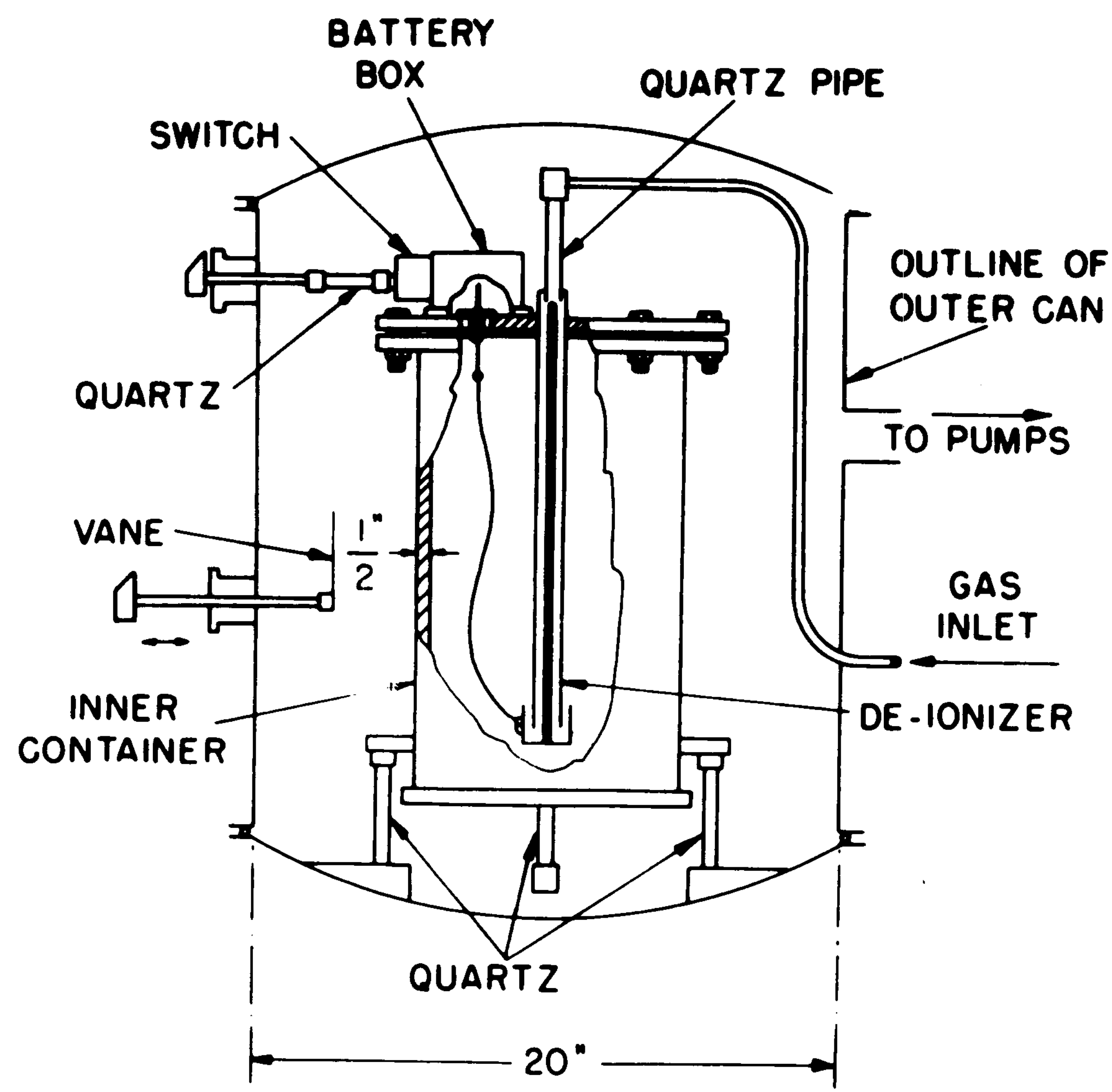

Figure 10. King apparatus for gas efflux experiment.

TABLE II.

Measured Limits for the Charge of Molecules

Method	Molecule	q(Molecule) in units of q_e	$\delta q = q(\text{molecule})/(Z + N)$	Investigators
	CO_2	$<2.2 \times 10^{-19}$	$<5 \times 10^{-21}$	Piccard & Kessler[a]
By	A	$(4 \pm 4) \times 10^{-20}$	$(1 \pm 1) \times 10^{-21}$	Hillas & Cranshaw[b]
Gas	N_2	$(6 \pm 6) \times 10^{-20}$	$(2.1 \pm 2.1) \times 10^{-21}$	Hillas & Cranshaw
Efflux	H_2	$(-2.5 \pm 1.5) \times 10^{-20}$	$(-1.3 \pm 0.8) \times 10^{-20}$	King[c]
	He	$(4 \pm 2) \times 10^{-20}$	$(1 \pm 0.5) \times 10^{-20}$	King
	CsI	$<4 \times 10^{-13}$	$<1.5 \times 10^{-15}$	Hughes[d]
	Free neutron	$<6 \times 10^{-12}$		Shapiro & Estulin[e]
By	CsF	$<2 \times 10^{-14}$	$<1.3 \times 10^{-16}$	Zorn, Chamberlain & Hughes[f]
Beam	KF	$<1 \times 10^{-13}$	$<1.7 \times 10^{-15}$	Zorn, Chamberlain & Hughes[f]
Deflection	H_2	$<2 \times 10^{-15}$	$<1 \times 10^{-15}$	Present work
	D_2	$<2.8 \times 10^{-15}$	$<0.7 \times 10^{-15}$	Present work
	K	$(3.8 \pm 11.8) \times 10^{-17}$	$(1 \pm 3) \times 10^{-18}$	Present work
	Cs	$(1.3 \pm 5.6) \times 10^{-17}$	$(1 \pm 4.2) \times 10^{-19}$	Present work

By Mossbauer effect, a limit of 1×10^{-15} q_e for the charge of the photon has been established[g]

[a] Reference 6 [c] Reference 8 [e] Reference 10

[b] Reference 7 [d] Reference 9 [f] Reference 11

[g] Grodzins, Engelberg & Bertozzi, Bull. Am. Phys. Soc. 6, 63 (1961)

provides a limit for δq of $5 \times 10^{-19}\ q_e$. This limit is about 1/4 the value of δq required by the theory of the expanding universe proposed by Lyttleton and Bondi. Furthermore, the macroscopic experiments by the gas efflux method provide the even smaller limit of $10^{-21}\ q_e$ to $10^{-20}\ q_e$. All of these results provide strong evidence against the form of the Lyttleton-Bondi proposal which requires $\delta q = 2 \times 10^{-18}\ q_e$; they do not test the alternative, though less attractive, form of the Lyttleton-Bondi proposal which requires a greater number of protons than electrons in the universe.

The equality of the electron and proton charge magnitudes has been established with unusually high precision in this and other recent experiments; hence they offer no support for the suggestion that baryon conservation might be simply a consequence of charge conservation. Furthermore, it would seem that any theory of elementary particles should require that the renormalized electron and proton charge magnitudes be equal.

REFERENCES

1. M. Gell-Mann, Proceedings of the Tenth Annual International Conference on High Energy Physics (Interscience Publishers, Inc., New York (1960), p. 792.

2. G. Feinberg and M. Goldhaber, Proc. Natl. Acad. Sci. U. S. 45, 1301 (1959).

3. W. F. G. Swann, Phil. Mag. 3, 1088 (1927); Astrophysical J. 133, 733 (1961).

4. A. Piccard and E. Kessler, Arch. Sci. Phys. et Nat. (Geneva) 7, 340 (1925).

5. P. M. S. Blackett, Nature 159 , 658 (1947).

6. R. A. Lyttleton and H. Bondi, Proc. Roy. Soc. A 252, 313 (1959).

7. F. Hoyle, Proc. Roy. Soc. A 257, 431 (1960).

8. R. A. Millikan, The Electron (University of Chicago Press, Chicago, 1917), 1st ed. pp. 80-83.

9. V. W. Hughes, Phys. Rev. 76, 474 (1949) (A), ibid., 105, 170 (1957).

10. J. C. Zorn, G. E. Chamberlain and V. W. Hughes, Bull. Am. Phys. Soc. 6, 63 (1961); Proceedings of the Tenth Annual International Conference on High Energy Physics Interscience Publishers, New York, 1960), p.790.

11. J. C. Zorn, G. E. Chamberlain and V. W. Hughes, Bull. Am. Phys. Soc. 5, 36 (1960).

12. P. Kusch and V. W. Hughes, "Atomic and Molecular Beam Spectroscopy" in Handbuch der Physik 37/1. S. Flügge, ed. (Springer-Verlag, Heidelberg, 1959), p. 6.

13. J. G. King, Phys. Rev. Let. 5, 562 (1960).

14. A. M. Hillas and T. E. Cranshaw, Nature 184, 892 (1959). ibid., 186, 459 (1960). H. Bondi and R. A. Lyttleton, Nature 184, 974 (1959).