the many channels conspire to prevent a clean separation of the various reactions. The optimum background levels which can be obtained by mass and momentum transfer selections vary from 25 to 75%. The two- and three-body channels are not dominantly peripheral; decay distributions characteristic of resonance production via single meson exchange are not observed in any of the channels. The production rates of the resonant channels are all of the same order of magnitude when detection and phase-space factors are taken into account; this fact may be a reflection of the complexity of the situation.

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Experimental Limit for the Neutron Charge*

C. G. Shull, K. W. Billman, and F. A. Wedgwood†
Massachusetts Institute of Technology, Cambridge, Massachusetts
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A microscopic measurement of the charge on a free, monoenergetic neutron has led to the value of $(-1.9\pm3.7)\times10^{-18}$ electron charges. This is consistent with the usual view that neutrons are electrically neutral. The experiment has exploited the very high angular sensitivity of a double-crystal spectrometer in assessing the angular deflection of a monoenergetic neutron beam under electrostatic deflection conditions. An improvement of about six orders of magnitude in the upper limit of the charge over previously published values obtained by direct experimentation has been attained.

INTRODUCTION

According to present views, the neutron is thought to be an electrically neutral particle. In this paper an experimental test for a minute charge is described in which the angular deviation of a monoenergetic neutron beam under the action of a homogeneous transverse deflecting field is sensed. The absence of such a deflection, coupled with the calibrated sensitivity of the apparatus, confirms the belief of neutron neutrality.

The search for a neutron charge is important in the information it may provide for fundamental-particle theory. Here the charge and mass remain as yet empirical values which theory cannot predict. Indeed, any experiment is of interest which may shed light on the apparent property of all particles to bear integral multiples of the electron charge. The present measurement may be construed as the most precise charge measurement of an elementary particle, and thus sets a severe criterion to be met by any future theory.

In an interesting paper, Feinberg and Goldhaber[1] discuss the necessity and implications of setting accurate experimental limits on the charges of elementary particles. The present belief that the conservation laws of charge, baryon number, and lepton number are independent and absolute leads to the conclusion that known particle processes can only determine the relative magnitudes of charges. Experimental limits on, for example, the neutron charge and the electron-proton charge difference are thus essential. Furthermore, if it were found that the charges of the baryons were all slightly different from their commonly accepted values by a common amount, then the conservation of baryons would follow from the conservation of charge rather than being an independent principle. Similar remarks hold for leptons.

Turning from microscopic to macroscopic considerations, much speculation about the cosmological consequence of a finite electron-proton charge difference, $\Delta q=|q_e|-|q_p|$, has been made. If one assumes charge conservation to hold in the neutron-decay process $n\rightarrow p+e^-+\bar{\nu}$, then Δq is equal to the neutron charge q_n upon the further assumption that the neutrino is

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† Present address: United Kingdom Atomic Energy Research Establishment, Harwell, England.

[1] G. Feinberg and M. Goldhaber, Proc. Natl. Acad. Sci. U. S. **45**, 1301 (1959); also M. Gell-Mann, in *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York, 1960), p. 792.

uncharged. Hence a finite neutron charge would mean that each atom in the universe would bear a net charge $q(\text{atom})=Z\Delta q+Nq_n=(Z+N)q_n$, where Z is the number of atomic electron-proton pairs and N is the number of neutrons. The electrostatic repulsion between such atoms was investigated by Lyttleton and Bondi[2,3] and others.[4–6] It was concluded that a neutron charge of the order of 2 parts in 10^{18} of an electron charge would be necessary to explain the observed expansion rate of the universe. Similarly, some speculation[7] concerning the origin of the magnetic fields of the earth and sun as a result of the revolution of non-neutral atoms about the polar axis has led to a necessary neutron charge of approximately 2 parts in 10^{19} of an electron charge.

Earlier measurements of the neutron charge can be categorized as "direct" and "indirect." The former, into which category the present measurement belongs, includes ionization of gases by neutrons, electrostatic deflection of a neutron beam, and scattering isotropy measurements. A very early study by Dee[8] of the ionization produced in gases by neutron passage gave $q_n<(1/700)|q_e|$. More recently, an experiment on the electric deflection of a thermal-neutron beam by Shapiro and Estulin[9] gave the limit $q_n<6\times10^{-12}|q_e|$. In a similar beam experiment, McReynolds[10] in unpublished work has quoted a value $q_n<2\times10^{-13}|q_e|$. Isotropy of slow neutron scattering by atoms can be used to place a limit on the amount of Rutherford scattering occurring and hence a limit on the neutron charge. Using the isotropy observed by Hamermesh, Ringo, and Wattenberg[11] for xenon gas, one calculates an upper limit of $2\times10^{-11}|q_e|$. The more recent, refined data of Krohn and Ringo[12] reduce this limit by another order of magnitude.

Indirect measurements, i.e., charge measurements on un-ionized atoms and molecules, lead to values of q_n much lower than are presently established by direct techniques. In an extensive and careful investigation carried out by King,[13] the upper bound for the charges of three representive molecules might be cited, that of molecular hydrogen, deuterium, and sulfur hexafluoride, which are all found to be neutral, possessing an upper charge bound of $\pm3\times10^{-20}|q_e|$. Using the usual formula $q\ (\text{atom})=Z\Delta q+Nq_n$, the expressions for $q(H_2)$ and $q(D_2)$ may be solved simultaneously to give a value of q_n independent of Δq. This gives a limit of $q_n<\pm3\times10^{-20}|q_e|$. Assuming $\Delta q=q_n$, $q(SF_6)$ gives $q_n<2\times10^{-22}|q_e|$. These limits surpass very considerably those which are obtained with the present direct measurements. Of course the possibility of a free charge being slightly different in magnitude, at this small level of charge difference when particles are amalgamated into an atom, does exist. In fact this possibility gives further impetus to improving direct methods on fundamental particles to the point where the two methods overlap in sensitivity and meaningful intercomparisons can be made which might point out just such an effect.

EXPERIMENT DESCRIPTION

The present experiment exploits the very high angular sensitivity of a pair of perfect crystals in double Bragg reflection with parallel orientation in assessing the effect of an electric field on a monochromatic neutron beam. Past deflection experiments on particle neutrality have generally utilized highly collimated particle beams with *linear* deflection sensitivity being obtained by sensing intensity changes at a narrow detector judiciously positioned on the side of the beam. With the double-crystal method, the intensity from the second crystal can respond in a very sensitive fashion to changes of *angular orientation* of the particle beam between the two crystals irrespective of the degree of collimation of the geometric beam. Thus the beam intensity need not be sacrificed to acquire high collimation. This is important in the case of neutron beams, with their relatively low quantum intensity. In passing between the two crystals, the neutrons experience the effect of an intense, homogeneous, transverse electric

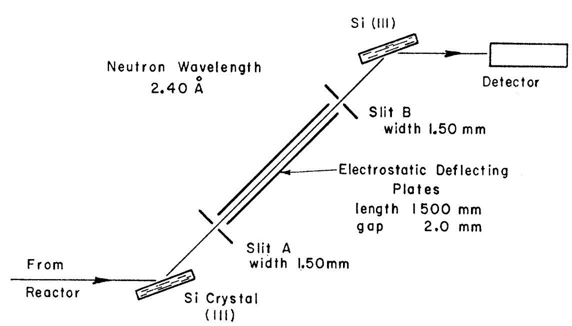

FIG. 1. Schematic diagram of double-crystal spectrometer and electrostatic-deflection system which has been used in the search for a neutron charge.

[2] R. A. Lyttleton and H. Bondi, Proc. Roy. Soc. (London) **A252**, 313 (1959).
[3] R. A. Lyttleton and H. Bondi, Proc. Roy. Soc. (London) **A257**, 442 (1960).
[4] F. Hoyle, Proc. Roy. Soc. (London) **A257**, 431 (1960).
[5] W. F. G. Swann, Astrophys. J. **133**, 738 (1961).
[6] L. G. Chambers, Nature **191**, 1082 (1961).
[7] A. Piccard and E. Kessler, Arch. Sci. Phys. Nat. (Geneva) **7**, 340 (1925); W. F. G. Swann, Phil. Mag. **3**, 1088 (1927); P. M. S. Blackett, Nature **159**, 658 (1947); V. A. Bailey, J. and Proc. Roy. Soc. (N. S. Wales) **94**, 77 (1960).
[8] P. I. Dee, Proc. Roy. Soc. (London) **A136**, 727 (1932).
[9] I. S. Shapiro and I. V. Estulin, Zh. Eksperim. i Teor. Fiz. **30**, 579 (1956) [English transl.: Soviet Phys.—JETP **3**, 626 (1957)].
[10] A. W. McReynolds, Brookhaven National Laboratory Reports, 1951 (unpublished).
[11] M. Hamermesh, G. R. Ringo, and A. Wattenberg, Phys. Rev. **85**, 483 (1952).
[12] V. E. Krohn and G. R. Ringo, Phys. Letters **18**, 297 (1965).
[13] J. G. King (private communication). For earlier measurements see J. G. King, Phys. Rev. Letters **5**, 562 (1960); A. Picard and E. Kessler, Ref. 7; A. M. Hillas and T. E. Cranshaw, Nature **184**, 892 (1959); **186**, 459 (1960); V. W. Hughes, Phys. Rev. **76**, 474 (1949); **105**, 170 (1957); J. C. Zorn, G. E. Chamberlain, and V. W. Hughes, Phys. Rev. **129**, 2566 (1963).

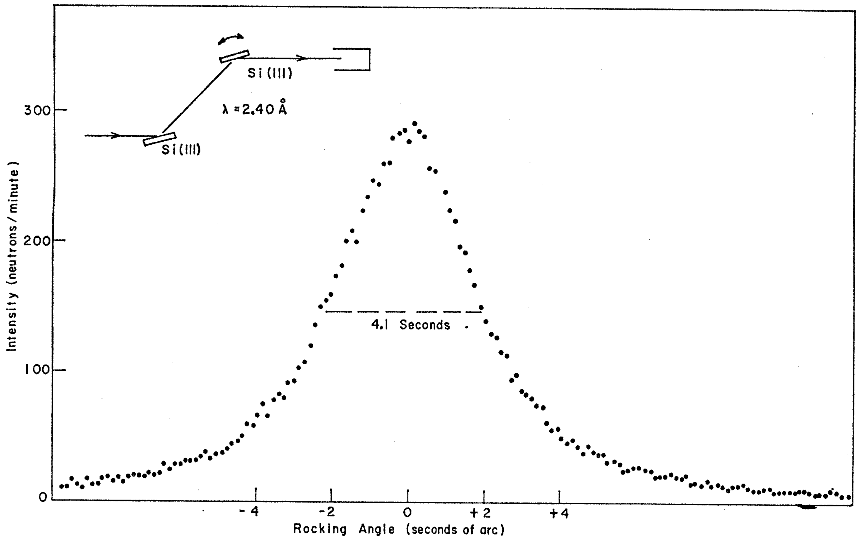

FIG. 2. Typical rocking curve of intensity versus angular orientation of second crystal in double-crystal spectrometer. Very fine angular stepping is available with a torsion-bar goniometer.

field as shown in the schematic diagram of Fig. 1 with consequent angular deflection if a charge were present.

In the double-crystal arrangement the first crystal is irradiated by full-spectrum neutron radiation from the reactor source and a semimonochromatic neutron beam is produced by Bragg reflection. If the crystal were perfect with no mosaic structure, this beam would be perfectly dispersed with a one-to-one correspondence between angular orientation and wavelength for individual rays. A second crystal of matched perfection and Bragg reflecting planes would exhibit in second diffraction of this beam a very sharp angular rocking curve because all rays from the first crystal would automatically satisfy Bragg conditions for the second one. The narrow angular width of the rocking curve is obtained independent of the geometrical collimation or wavelength spread of the rays in the beam. These effects have been recognized for a long time, and frequently exploited, in x-ray technology.

There exists, however, a limiting narrowness to the rocking curve, arising from a fundamental angular width associated with the three-dimensional diffraction process. This limit, called the Darwin limit, can be associated with the finite depth of penetration of the coherent radiation into the crystal and is given by the expression

$$\delta=\lambda^2 N F_{hkl}/\sqrt{2}\pi \sin 2\theta, \qquad (1)$$

where λ is the radiation wavelength, N is the density of unit cells in the crystal, F_{hkl} is the crystal-structure factor per unit cell in absolute units of scattering, and θ is the Bragg scattering angle. In this expression for the Darwin width, δ represents the full width at half-maximum (FWHM) intensity in the intensity distribution as a function of rocking angle of the second crystal as affected by diffraction broadening at both crystals. This width can be approached with crystals of high perfection, provided that great care is given to ensuring parallel alignment of the crystal planes.

The present experiments have been performed with two crystals of silicon prepared[14] to minimize dislocation density and mosaicity. They have been used in (111) Bragg reflection from etched reflection faces with a radiation scattering angle of 45° corresponding to a mean neutron wavelength of 2.40 Å. Typical of the rocking curves obtained with such crystals is that shown in Fig. 2, where the FWHM intensity is determined to be 4.1 sec of arc. For comparison, the Darwin width of Eq. (1) for the conditions of the experiment is calculated to be 2.3 sec of arc. Presumably the difference arises from incomplete crystal perfection or incomplete alignment of the crystals.

In studying these very narrow rocking curves it is necessary to have very refined angular control of the supporting spectrometer. The usual control in diffraction spectrometers is useless for this purpose and various refinements were attempted, leading to the construction of a special torsion-bar spectrometer containing no bearing or gears. This is shown schematically in Fig. 3.

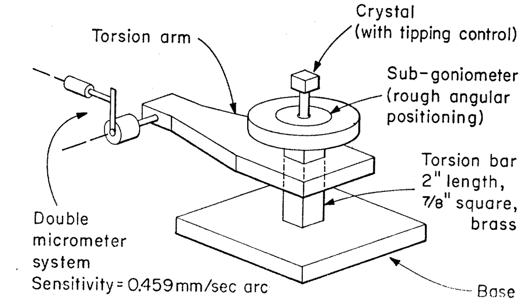

FIG. 3. Schematic diagram of the torsion-bar spectrometer used in controlling the angular orientation of the second crystal in the double-crystal spectrometer.

[14] We are indebted to Dr. B. W. Batterman of the Bell Telephone Laboratories for supplying these crystals.

A short brass bar of length 2 in. and $\frac{7}{8}$-in. square cross section is twisted within its elastic range by a torsion arm through a double micrometer system. This system was found to work very well and permitted easy scanning over the peak and positioning at selected regions on the rocking curve. It should be mentioned that the limited range over which the torsion bar may be elastically twisted is not adequate in the initial searching for the Bragg reflection. Accordingly, a less refined subgoniometer with extended range has been mounted on top of the torsion-bar assembly, which can be used in finding the reflection following which it is disengaged. Also, the initial search for the fine reflection can be very greatly aided by "redispersing" the radiation between the crystals through introduction of a small-angle scattering agent, such as a colloidal powder or an unmagnetized iron plate with random magnetic-domain structure.

It is obvious that the high sensitivity to relative angular orientation of the two crystals calls for sophisticated means of mechanically supporting the two spectrometers. Ideally, this would be best accomplished by having both crystal goniometers supported by one massive supporting agent with minimization of localized temperature variation throughout the complete assembly. Because of the relatively large separation between the two crystals in the present charge experiment, it was necessary that these be supported separately, one being attached effectively to the reactor face and the other with independent support from the reactor floor. This design limitation resulted in considerable drifting of the neutron intensity throughout the course of the day and from one day to another when the second crystal was positioned on the sensitive side slope of the rocking curve (see Fig. 5). Strong correlation was found between the magnitude of this drifting and atmospheric conditions both inside the reactor building (air-conditioned) and outside the building with particular dependence upon the temperature. In order to lessen this, a room was constructed around the whole spectrometer unit in which the temperature was controlled to ±0.1°C, with additional thermal lagging around critical spectrometer parts. This helped greatly in reducing the drifting but not to the point of elimination. Strong indications were obtained that the whole reactor experiment floor was being shifted with outside atmospheric changes. In assessing the intensity effect of a periodic reversal of the electric-field direction on the neutron intensity it was necessary to apply drift corrections to the data, as will be discussed later. Because of the large time constant of this drift, however, as compared with the data sampling period of 5 min, the drift could in no way mask a real neutron-charge effect.

ELECTRIC DEFLECTION OF NEUTRON BEAM

If the neutron were to possess an electric charge ze, with z being the fractional electron charge, a neutron ray in passing along a length L in a transverse electric field E would be deflected an angle β given by

$$\beta = z\frac{e}{m}E\frac{L}{v^2}\,, \tag{2}$$

where m is the neutron mass and v is its velocity. With the previously published[9] upper limit to the residual charge of 6×10^{-12} electron charges and with the values of $E=225\,000$ V/cm, $L=150$ cm, and $v=1650$ m/sec attained in the present experiment, the deflection angle β is calculated to be 980 sec of arc. Such a violently large angular deflection would of course be readily observed with an angle detecting system of the sensitivity suggested by the rocking curve of Fig. 2. Moreover, the angular shift to be measured with field reversal, rather than just on-off, becomes 2β, and if the intensity effect is studied on both sides of the rocking curve, then the difference between observations on the high-angle side and low-angle side becomes 4β. Necessary criteria for the presence of a real charge effect lie in having an intensity difference upon field reversal coupled with a *reversed sign* effect on the two sides of the rocking curve. Thus if I_{+H} is the intensity measured with (+) field direction in the high-angle side of the rocking curve, then the quantity

$$(I_{+H}-I_{-H})-(I_{+L}-I_{-L})$$

is to be associated with an angular shift 4β. The necessity for satisfying the double criteria automatically removes from the data analysis a number of experimental effects which might produce a broadening of the neutron beam rather than a directional shift. Among these are: (1) passage of the neutron through the electric-field gradient regions either at the fringing ends or between the deflection plates through interaction with the polarized electric dipole moment or the permanent magnetic moment of the neutron, (2) interaction of the neutron magnetic moment with magnetic fields resulting from any corona current between plates, and (3) scattering of the neutrons by gas evolution from the plates caused by electric discharge.

QUANTITATIVE CHECK ON ANGULAR SENSITIVITY BY PRISM BENDING OF NEUTRON BEAM

It was decided to test the angular sensitivity of the double crystal system through introduction of a known deflection signal before attempting the charge experiment. A convenient means of doing this is by refractive bending of the beam in passage through a prism judiciously placed between the two crystals in such a way as to give a deflection similar to a charged neutron in an electric field. The index of refraction n for neutron radiation in passing through matter is given by the expression

$$1-n=Mb\lambda^2/2\pi\,, \tag{3}$$

where M is the atomic density, b is the coherent neutron-scattering amplitude per atom, and λ is the neutron wavelength. Thus for a prism of apex angle 2α the refractive bending β of a ray is given by

$$\beta = 2(1-n)\tan\alpha, \quad (4)$$

with the bending direction being toward the apex for material with amplitude of conventional positive sign. A small-angle prism of aluminum with apex angle 3.20 ± 0.07 deg was selected for study and this was placed in the beam on a device which periodically reversed the apex direction in synchronism with the neutron counting intervals. Thus the change of intensity is to be associated with a deflection angle 2β. Using the accepted value of $+0.35\times10^{-12}$ cm for the coherent scattering amplitude of aluminum, the quantity $(1-n)$ is calculated to be 1.93×10^{-6} and β becomes 22.2 ± 0.7 msec of arc with the uncertainty arising from uncertainties in the prism angle and in the coherent scattering amplitude value for aluminum. Intensity changes with prism reversal were made on both sides of the rocking curve, with the expected reversal of sign, and these intensity effects were combined with the measured slope of the rocking curve in the regions of measurement to give an experimental value of β of 23.1 ± 1.1 msec arc. This agrees within experimental error to that expected by calculation and illustrates that angular deflections in the range of 1 msec of arc can be measured. In treating the prism-intensity data, corrections for intensity drift and for higher order wavelength components in the neutron beam were incorported. These are discussed in succeeding sections.

It should be noted that this check on apparatus sensitivity calibrates the apparatus in a very definitive way for the present charge measurement. By eliminating the wavelength in (4) by means of the de Broglie relation, one finds the prism deflection angle to have the same velocity dependence as the charge deflection angle predicted by (2). Thus, this calibration is a very real and quantitative demonstration of the sensitivity of the apparatus not only to detect small angular beam deviations, but specifically those which could arise from charge deflections. Such a calibration of apparatus sensitivity is, of course, essential in any "null" experiment and a serious effort to provide a quantitative one should always be made.

EFFECT OF HIGHER ORDER NEUTRON WAVELENGTHS

In Bragg reflecting a monochromatic beam of primary wavelength λ_0 from a crystal it is also possible to have simultaneous reflection of higher order wavelength components whose intensity will depend upon the incident spectral intensity and upon the reflectivity of higher indexed Bragg reflections. In all of the present experiments the crystal orientation was such that a 2.40-Å primary wavelength was reflected from (111) silicon planes. With full spectrum radiation falling on the first crystal however, higher order wavelengths λ_0/n are simultaneously reflected from $n(h,k,l)$ planes. The crystal structure of silicon prohibits second-order reflection (for $n=2$) but the third order is permitted as well as some higher ones, and hence a 0.80-Å component is possible. Such a component would receive an electrostatic (or prism) angular deflection only one-ninth that of the primary wavelength component according to Eqs. (2) and (4). This serves to dilute the angular sensitivity by a noticeable factor which must be considered.

For a two-component beam, with λ_0 and $\frac{1}{3}\lambda_0$, it can be easily shown that the true angular displacement $d\theta$ accompanying the primary component when an observed intensity change dI is measured is given by

$$dI/d\theta = M_T - (8/9)M(\lambda_0/3), \quad (5)$$

where M_T is the slope of the total intensity rocking curve and $M(\lambda_0/3)$ is the slope if only the contaminant wavelength were present. Thus it is necessary to establish the intensity slope for the contaminant wavelength. This has been done by determining the transmission of a calibrated Cu–1% Gd filter at various positions across the rocking curve. The very large absorption cross section of gadolinium is strongly sensitive to neutron energy or wavelength in this region and such measurements can yield the relative intensities of the components.

Figure 4 shows the intensity distribution across part of the rocking curve for the $\lambda_0/3=0.80$-Å component as evaluated from the transmission measurements com-

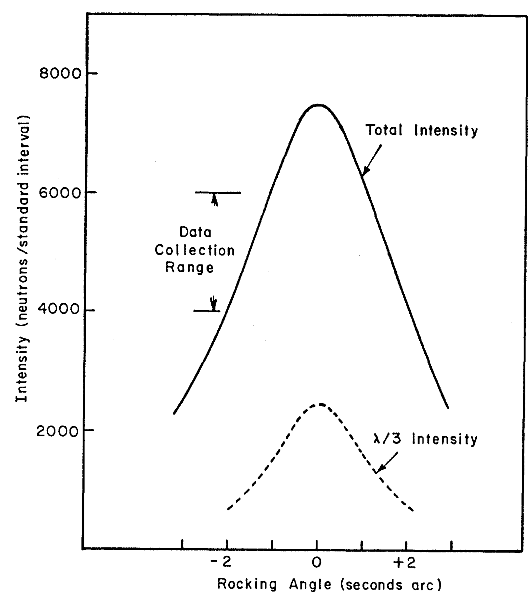

FIG. 4. Rocking curves of the total intensity and the purefied third-order contaminant wavelength $\lambda/3$. The presence of the shorter wavelength contaminant serves to dilute the angular sensitivity of the spectrometer to beam deflection.

pared with the total intensity. Intensities are expressed in terms of a standard counting interval of 25 min referred to a reactor power level of 2 MW. The width of the 0.80-Å curve is less than that for the full intensity but not nearly as narrow as would be predicted from the Darwin formula, Eq. (1). This again implies that residual crystal imperfection and misalignment was responsible for the larger than theoretical limit width as observed. In the data collection for both the prism bending and the electrostatic deflection experiments, observations were restricted to the nearly linear part of the rocking curve where the observed intensity was within the range 0.53 to 0.80 of the peak intensity as shown in the figure. In this region, to good approximation, the pertinent slope values are

$M_T = 2060$ (neutrons per standard interval) per second arc,

$M(\lambda_0/3) = 735$ (neutrons per standard interval) per second arc,

$dI/d\theta = 1405$ (neutrons per standard interval) per second arc.

This represents a correction to the angular sensitivity of about 30%. It has been applied to the small-angle prism data described in the above section and because of the agreement between experiment and calculation for those data, confidence in its validity is obtained. Additional studies of the higher order contaminant intensities were performed by studying the shift in the rocking curve with large-angle prism bending. A double 120° copper prism was used, in which the refracted beams for the two wavelengths are clearly separated. This gave results consistent with those concluded from the filter-transmission measurements. The presence of higher order components larger than the third has been ignored since by calculation they are estimated to contribute at most only 2 or 3% of the third-order intensity.

CORRECTION FOR INTENSITY DRIFT

In assessing an intensity change with periodic reversal of the electrostatic or prism deflection it is necessary to allow for longer period drifting of the measured intensity. All of the present data have been obtained with a basic time interval of 5 min, whereupon the measured effect is reversed. Drifting of the intensity as measured on the side of the rocking curve was encountered as described above and data collection was restricted to those periods when the drift was small for which confident corrections could be applied. Illustrative of the drifting effects are the intensity data shown in Fig. 5, collected over an interval of 24 h with periodic 5 min reversal of the electric-field direction. In order to maintain proper positioning in the linear, high-slope region of the rocking curve, the second crystal orientation was reset (by 1.20 and 0.22 sec arc) at two points during the interval of Fig. 5, as indicated by the discontinuities in the intensity graph. Other independent experiments with high intensity have shown that statistical accuracy can be approached with allowance for intensity drift.

MIRROR REFLECTION OF THE NEUTRON BEAM BY ELECTROSTATIC PLATES

In the electrostatic-deflection experiments there is the possibility that parts of the neutron beam can be totally reflected by the polished surfaces of the electrostatic plates. Limiting slits of width 1.5 mm were positioned just before, and just after the 1.5-m deflection region where a gap separation of 2.0±0.025 mm existed. There exists enough divergence in the neutron beam from the first crystal passing through the entrance slit that rays can approach the plate surfaces within the critical angle for total reflection. In first approximation, rays which are totally reflected either once or twice from the surfaces would experience a cancellation of the electrostatic deflection so that a real effect would be unmeasurable with such rays. Thus it is important to know to what extent this reflected intensity is contributing to the measured intensity on the side of the rocking curve of the second crystal. It can be seen that those rays which have been singly reflected will fortunately make no contribution to the observed intensity, since they will have been deflected far off the rocking

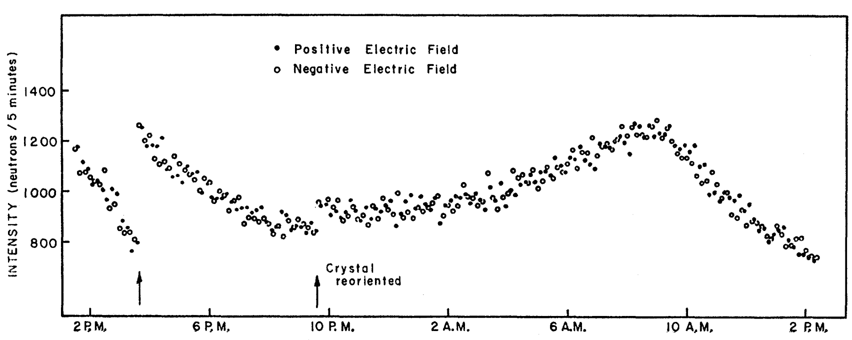

FIG. 5. Intensity measured with second crystal positioned in high-slope region as a function of time of day. Intensity drifting associated with long period angular shifting is to be noted. The electric-field direction is reversed after a 5-min counting interval. The second crystal was repositioned by angles of 1.20 and 0.22 sec of arc at two points during this run.

curve of the second crystal. On the other hand, it is possible that a ray which has been doubly reflected from strictly parallel sections of both plate surfaces can be maintained on the rocking curve. Triply reflected radiation from the plate surfaces can be excluded from consideration because of geometrical restrictions.

Experiments were performed which served to sense the fraction of the observed intensity arising from the doubly reflected radiation. With the second crystal set in normal operating orientation on the steep-slope region of the rocking curve, the intensity was studied as the deflecting-plate system was purposely mistipped relative to the entrance and exit slits over a range not permitting direct shadowing of the slits. This serves to change the fraction of doubly reflected radiation relative to direct transmitted radiation by changing solid-angle factors and the local regions of reflection. No intensity change was measured in the normal operating region of the rocking curve by this tipping procedure, and it was concluded that the measured intensity was to a high degree composed of direct transmitted radiation through the slits which would then be susceptible to real electrostatic deflection. For doubly reflected radiation to stay within the rocking-curve limits necessitates a very high degree of parallelism at the two points of reflection and apparently this is too restrictive for our plate surfaces.

Additional observations that were made also suggest the absence of mirror-reflected radiation contributing to the rocking-curve intensity. Measurements of the peak intensity showed no change before and after insertion of the deflecting plates between the two limiting slits. A study of the peak intensity when the deflecting-plate system was translated across the beam axis showed the characteristic trapezoidal shape, with a flat top and width between sides agreeing excellently with that expected from the dimensions of the end slits and the plate separation. Perturbations in both of these measurements would be expected if mirror-reflected rays were being sensed in the intensity delivered by the second crystal.

RESULTS ON CHARGE DEFLECTION EXPERIMENTS

Intensity data were collected for three values of electric field strength 50 000, 150 000, and 225 000 V/cm, with most data at the highest field strength. As the experiment progressed, less trouble with voltage sparking was experienced because of improved plate conditions. Sparking was most pronounced during a short interval of a few seconds following polarity reversal and for this reason a time delay of 10 sec before activating the counting interval was introduced. Vacuum in the deflecting system was maintained by an oil diffusion pump with a liquid-nitrogen molecular-sieve cold trap with an intermediate vacuum of 4×10^{-5} Torr. The nonmagnetic 305 stainless-steel plates were

TABLE I. Summary of data collection on two sides of rocking curve with electric field reversal (field strength 225 000 V/cm).

Run number	Nominal reactor power	Total intensity I_+ (neutrons	Total intensity I_- counted)	Number of standard intervals	Intensity difference per standard interval
High-angle side of reflection					
12	2*MW*	439 151	439 934	84.6	− 9.26
14	2	458 972	458 732	92.6	+ 2.59
16	2	377 370	378 372	75.2	−13.32
18	2	447 085	447 336	85.8	− 2.93
24	3	383 826	382 726	79.1	+13.91
26	5	835 220	836 527	180.0	− 7.26
	Total	2 941 624	2 943 627		
Average intensity difference per standard interval = −3.35 neutrons				±4.05 (over all statistics); ±3.65 (mean-square deviations)	
Low-angle side of reflection					
13	2	458 299	457 788	93.4	+ 5.47
15	2	568 331	567 725	119.6	+ 5.07
17	2	410 858	410 618	82.4	+ 2.91
22	2	241 396	241 303	50.4	+ 1.85
23	3	382 534	381 953	79.9	+ 7.27
25	4	950 023	951 926	201.0	− 9.47
	Total	3 011 441	3 011 313		
Average intensity difference per standard interval = +0.20 neutrons				±3.86 (over-all statistics); ±3.05 (mean-square deviations)	

preconditioned by "baking-in" with an external 0.01-μF capacitor connected in the voltage-supply circuit.[15] Measurement of the voltage was checked by means of a calibrated electrostatic voltmeter connected directly across the electrodes.

Table I summarizes the data collected at the highest field strength. As mentioned earlier, the field polarity was reversed in 5-min counting intervals and it was convenient to group these respective intensities into larger parcels of a 25-min standard interval. During the period of data collection extending over a four-month interval, the reactor power level was elevated from 2 to 5 MW, as seen in the table entries. For convenience in statistical analysis of the data, the number of standard intervals studied in the various runs has been normalized to that corresponding to the lower reactor power of 2 MW. This has been done through use of the measured peak intensity of the rocking curve for the different power values. The entries I_+ and I_- represent the total number of neutrons counted during the individual runs, with the latter value having been corrected for intensity drift. Data are presented in the table for the measurements made on both sides of the rocking curve with a total count of nearly 12 million neutrons being made at this field strength.

[15] B. H. Smith and H. A. Grunder, UCRL Report No. 10654, 1963 (unpublished).

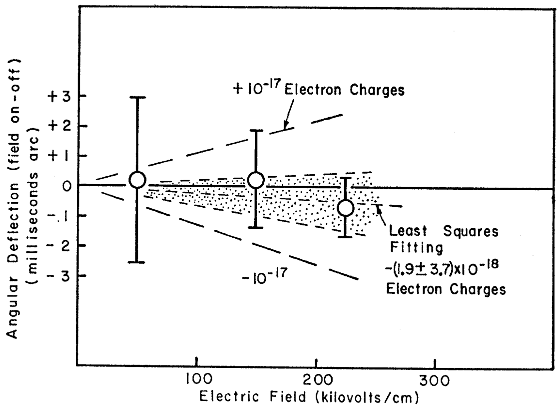

FIG. 6. Angular deflection of neutron beam by electrostatic deflection as a function of electric-field strength. Deflection values to be expected for a neutron charge of 10^{-17} electron charges are shown for comparison with the experimental data points.

The errors on the average intensity difference (upon polarity reversal) per standard interval are quoted in two ways, from the over-all statistical error assessed from the total number of random events being counted and from the mean-square deviations of the results for the individual runs. The errors are given as standard errors, corresponding to the 68% confidence level and the two methods used for their evaluation seem reasonably consistent with the deviation spread being more confined than suggested from the over-all statistics. Subtracting the intensity effects on the two sides of the rocking curve yields -3.55 ± 5.60 neutrons per standard interval and this corresponds to an angular shift of 4β. Using the slope values quoted above, the angular deflection of the neutron beam for this field strength of 225 000 V/cm becomes -0.63 ± 0.99 msec of arc.

Similar data collection has been obtained at the lesser field strengths and the measured angular deflections are summarized in Fig. 6. The calculated deflections as a function of field strength for neutron charge values of $\pm10^{-17}$ electron charges are shown in the figure for comparison with the measured deflections. A least-squares fitting to all of the data points yields the final value of $(-1.9\pm3.7)\times10^{-18}$ electron charges as the neutron charge. Thus *the experimental result is consistent with a value of zero charge within the experimental uncertainty*. Stated more specifically, the experimental result indicates the neutron charge to fall within the algebraic limits of $+1.8$ and -5.6×10^{-18} electron charges with 68% probability. This range places the established charge value as being about six orders of magnitude smaller than previous direct experiments.

DISCUSSION OF RESULTS

The present measurement provides a clear and unambiguous determination of the neutron's neutrality without assumptions about charge conservation, the additivity of charge in atoms and molecules, or the exact neutrality of the neutrino. In addition, all the neutrons investigated possessed a well defined velocity and interaction time in the electric field.

Unfortunately, the present method is not yet sensitive enough to provide a fruitful intercomparison between it and the indirect method, which could permit, for example, a limit to be set on the neutrino charge as a result of a comparison between q_n and $q(\mathrm{H})$. It also falls short of being able to settle the questions about the expanding universe and the magnetism of the earth and sun. However, the technique used here has not yet been extended to its limits and the use of higher beam flux, improved crystals, higher electric fields, and other technical improvements will undoubtedly allow juxtaposition of the indirect and direct charge measurements. Clearly, the present measurement does lend further belief to the apparent exact equality of the charges of elementary particles.

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