Electron-Neutrino Angular Correlation in the Decay of He^6†

JOSEPH B. VISE AND BRICE M. RUSTAD
Columbia University, New York, New York
and
Brookhaven National Laboratory, Upton, New York
(Received 18 July 1963)

The energy spectra of recoil lithium ions in coincidence with beta particles of selected energy have been measured for the beta decay of He^6. The beta-particle energy was determined with a well-type beta scintillation detector; and the energy and charge of the recoil ions were measured with an electrostatic spectrometer and time-of-flight analyzer. The electron-neutrino angular-correlation coefficient determined from the observed energy distributions of recoil ions is $\lambda = -0.319 \pm 0.028$. The ratio of the tensor to axial vector coupling constants calculated from this measurement is $(|C_T|^2+|C_T'|^2)/(|C_A|^2+|C_A'|^2)=0.022\pm0.044$. A new measurement of the He^6 beta spectrum was made with a thin-lens magnetic spectrometer, and the maximum energy is 3.508 ± 0.015 MeV.

INTRODUCTION

THE measurement of the electron-neutrino angular correlation in allowed beta transitions is one of the methods by which experimental evidence may be obtained on the form of the beta-decay interaction. Because He^6 is the only known monatomic gas which decays by a simple superallowed Gamow-Teller transition, this isotope has been used in several different types of electron-neutrino angular correlation experiments to determine the ratio of the tensor to axial vector coupling constants.[1–8] The results of these measurements, however, have not all been consistent.

After parity violation was demonstrated in the weak interactions,[9] many new experiments were performed to obtain information on the new coupling constants which had to be introduced into the beta-decay interaction.[10] The results of these experiments and of a measurement[11] of the electron-neutrino angular correlation in the decay of Ar^{35} were in disagreement with certain previous angular correlation experiments. Reevaluation of one of the principal measurements[3] on He^6 revealed serious instrumental discrimination,[4] and several investigations were started to remeasure this correlation coefficient.[6–8] The experiment described in this paper was undertaken at that time to redetermine the He^6 electron-neutrino angular correlation by a new method, which is not subject to the instrumental effects found in the previous measurements and which is more sensitive to the value of the angular correlation coefficient.

Because the cross sections for neutrino reactions are extremely small, the angular correlation coefficient, λ, between the beta particle and the neutrino is obtained in recoil experiments by measurement of distributions of decay events in a beta-active source as a function of one or more of the three observable quantities: the energy (or momentum) of the recoil nucleus, the energy of the beta particle, and the angle between the directions of emission of these particles.[12] The simplest way to determine λ is by measurement of the energy spectrum of the recoil nucleus. Experiments of this kind have been performed with He^6 by Allen *et al.*,[6] and by Johnson *et al.*[8] Experiments in which the beta particle and the recoil nucleus are detected in coincidence have been performed in two ways with He^6. Rustad and Ruby[3] and also Csikai and Szalay[5] have measured coincidence rates as a function of beta-particle energy and angle between the beta particle and recoil nucleus; and Allen *et al.*[2] and Ridley[7] used the energy of the beta particle and the time-of-flight of the recoiling nucleus, the latter with no discrimination in angle between the beta particle and the recoil nucleus.

The experiments which seem to have been most prone to instrumental discrimination are those in which angular measurements were made.[3,5] In the experiment reported by Rustad and Ruby, a change in the angular orientation of the beta detector caused a corresponding change in both the beta-energy distribution and the

† This work was supported by the U. S. Atomic Energy Commission.

[1] J. S. Allen, H. R. Paneth, and A. H. Morish, Phys. Rev. **75**, 570 (1949).
[2] J. S. Allen and W. K. Jentschke, Phys. Rev. **89**, 902 (1953).
[3] B. M. Rustad and S. L. Ruby, Phys. Rev. **97**, 991 (1955).
[4] B. M. Rustad and S. L. Ruby, Post-deadline paper, New York meetings, American Physical Society, January 1958 (unpublished); C. S. Wu and A. Schwarzschild, Columbia University Report CU-173, 1958 (unpublished).
[5] J. Csikai and A. Szalay, Zh. Eksperim. i Teor. Fiz. **35**, 1074 (1958) [translation: Soviet Phys.—JETP **8**, 749 (1959)].
[6] J. S. Allen, R. L. Burman, W. B. Herrmannsfeldt, P. Stahelin, and T. H. Braid, Phys. Rev. **116**, 134 (1959). J. S. Allen, Rev. Mod. Phys. **31**, 791 (1959).
[7] B. W. Ridley, Nucl. Phys. **25**, 483 (1961).
[8] C. H. Johnson, F. Pleasonton, and T. A. Carlson, Bull. Am. Phys. Soc. **8**, 333 (1963).
[9] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956). C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. **105**, 1413 (1957).
[10] For reviews on beta decay during this period, see E. J. Konopinski, Ann. Rev. Nucl. Sci. **9**, 99 (1959). C. S. Wu, in *Theoretical Physics in the Twentieth Century, A Memorial Volume to Wolfgang Pauli*, edited by M. Fierz and V. F. Weisskopf (Interscience Publishers, Inc., New York, 1960), p. 249; O. Kofoed-Hansen and C. J. Christensen, *Handbuch Der Physik* (Springer-Verlag, Berlin, 1962), Vol. 41, Chap. 2.
[11] W. B. Hermannsfeldt, D. R. Maxson, P. Stahelin, and J. S. Allen, Phys. Rev. **107**, 641 (1957).
[12] O. Kofoed-Hansen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **28**, No. 9 (1954); Phys. Rev. **74**, 1785 (1948).

effective size of the source volume.[4] In the cloud chamber experiment of Csikai and Szalay,[5] there appears to be the possibility of discrimination against the observation of beta-recoil events for which the recoil-ion energy was low. The principal disadvantage of the measurement of the recoil energy spectrum, which permits the use of an intense source, is that the change in shape of the predicted spectrum for variations in the value of λ is smaller than the change obtainable in certain types of coincidence experiments.

In the present determination of the He^6 electron-neutrino angular correlation coefficient, the energy distribution of singly charged recoil ions from a defined gaseous source volume was measured in coincidence with beta particles of fixed energy. This experiment has the following features which contribute to its reliability: (1) A large change in the predicted distribution as a function of the correlation coefficient. (2) An experimental arrangement in which the observed parameters may be varied while the geometry of the apparatus remains fixed. (3) A coincidence measurement in which sufficiently large amounts of information are collected so that the internal consistency of the experimental data and of the background subtraction procedure may be analyzed to test the behavior of the apparatus. (4) A background counting rate less than or comparable with the true counting rate. (5) A method of separating singly charged lithium ions from doubly charged ions and scattered neutral recoil ions with an electrostatic spectrometer and time-of-flight analyzer.

It is shown by Eq. 3 in the following section that the recoil-ion energy spectrum is a linear function of the ion energy when the ions are observed in coincidence with beta particles of fixed energy. The slope of this spectrum is proportional to the angular correlation coefficient, being positive for the case of pure tensor interaction ($\lambda=+\frac{1}{3}$) and negative for pure axial vector interaction ($\lambda=-\frac{1}{3}$). Since the spectrum is linear, the observed slope is independent of the shape of the resolution curve of the spectrometer used to measure the recoil-ion energy. The coincidence feature of the experiment permits an evaluation of the background subtraction procedure by measurement of delayed coincidence rates. Finally, it is possible to test the behavior of the apparatus by comparison of the shapes of the observed and predicted spectra with either the beta energy or the recoil-ion energy held fixed.

THEORY

In the theory of allowed beta decay, the probability for the emission of a beta particle with total energy, E, in a direction which makes an angle θ with respect to the direction of the emitted neutrino is given by

$$P(E,\theta)dE\,d\Omega=kF(Z,E)E(E_0-E)^2(E^2-1)^{\frac{1}{2}}\times\left(1+\lambda\frac{v}{c}\cos\theta+\frac{b}{E}\right)dE\,d\Omega, \quad (1)$$

where E is the total energy of the beta particle in units of mc^2, v is the velocity of the electron, $F(Z,E)$ is the Fermi Coulomb function, and E_0 is the total energy available to the transition. The Fierz interference term, b, has been found to be zero within an experimental error of a few percent from spectral shape measurements,[13] K capture to positron ratios,[14] and electron helicity measurements.[10]

The decay from the 0^+ ground state[15] of He^6 to the 1^+ ground state[16] of Li^6, which has an ft value of 815 sec,[17] is a pure, allowed Gamow-Teller transition. The angular correlation coefficient for this case is given by

$$\lambda=-\frac{1}{3}\left(1-\frac{|C_T|^2+|C_T'|^2}{|C_A|^2+|C_A'|^2}\right)\bigg/\left(1+\frac{|C_T|^2+|C_T'|^2}{|C_A|^2+|C_A'|^2}\right), \quad (2)$$

where the terms $|C_T|^2$, $|C_T'|^2$, $|C_A|^2$ and $|C_A'|^2$ signify the squares of the magnitudes of the parity conserving and nonconserving coupling constants for the tensor and axial vector interactions. There are two additional terms in λ which have not been included in Eq. (2). The first is a Coulomb correction term,[18] which is negligibly small in the case of He^6. The contribution to λ due to the second term, which arises from higher order matrix elements in the theory of the conserved vector current in beta decay, is also well within the accuracy of the present experiment.[19]

The theoretical expression for the energy coincidence spectrum for the beta particle and recoil ion is obtained by transforming Eq. (1) into the distribution $P(E,R)$ where R is the kinetic energy of the recoil ion in mc^2 units. This distribution is given by

$$P(E,R)dE\,dR=2\pi kMF(Z,E)\{E(E_0-E)+\lambda[MR+E(E_0-E)-\tfrac{1}{2}(E_0^2-1)]\}dE\,dR, \quad (3)$$

where M is the mass of the recoil ion in units of the electron rest mass.

APPARATUS

A diagram of the apparatus used for the measurement of the distribution, $P(E,R)$, is shown in Fig. 1. The source volume was defined for the events measured in this experiment by the well in the beta-scintillation detector and by an aperture and shutter at the mouth

[13] A. V. Pohm, R. C. Waddell, and E. N. Jensen, Phys. Rev. **101**, 1315 (1956). A. Schwarzchild, B. M. Rustad, and C. S. Wu, Bull. Am. Phys. Soc. **1**, 336 (1956); A. Schwarzchild, Doctoral thesis, Columbia University Report CU-167, 1957 (unpublished).
[14] R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954).
[15] E. D. Commins and P. Kusch, Phys. Rev. Letters **1**, 208 (1958).
[16] J. H. Manley and S. Millman, Phys. Rev. **51**, 19 (1937).
[17] C. S. Wu, B. M. Rustad, V. Perez-Mendez, and L. Lidofsky, Phys. Rev. **87**, 1140 (1952).
[18] M. Morita and R. S. Morita, Phys. Rev. **107**, 139 (1957).
[19] M. Gell-Mann, Phys. Rev. **111**, 362 (1958); M. Morita, Phys. Rev. **114**, 1080 (1959); Y. K. Lee, L. W. Mo, and C. S. Wu, Phys. Rev. Letters **10**, 253 (1963).

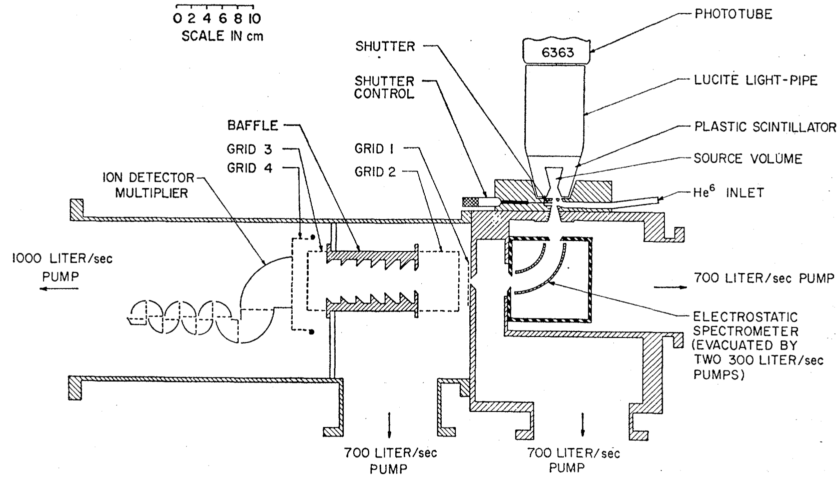

FIG. 1. Schematic diagram of the apparatus.

of the well. The recoil-ion detector system consisted of a collimator which defined a beam of recoil ions from the source volume, an electrostatic spectrometer to determine the energy of the recoil ions, a set of accelerating grids, and a secondary emission multiplier detector. The mechanical shutter was located immediately below the source volume to permit the determination of background from decays originating in regions outside the source volume. To prevent variation in He^6 concentration when the position of the shutter was changed, the He^6 gas was introduced into the system below the shutter and allowed to diffuse freely into the source volume before passing into the remainder of the system. Five stages of differential pumping were used to reduce the He^6 concentration near the recoil-ion detector. The output pulses from the two detectors were recorded on a five-channel pulse-height by six-channel time-of-flight analyzer. The beta-particle energy was selected by pulse-height analysis. Since the electrostatic spectrometer resolved lithium ions with a double electronic charge, which have an abundance[20] of about 10%, as if they were singly charged ions of half the energy, time-of-flight coincidence analysis was performed on the output pulses of the two detectors to separate events corresponding to the variously charged ions. The energy and time-of-flight spectrometers defined the momenta of the beta particle, neutrino, and recoil nucleus in each decay event recorded.

In this type of experiment, it is essential that the beta detector should have a constant efficiency and that the resolution should be a known function of the beta energy for all values of E and R selected for the measurement. It was decided that these requirements could best be realized with a beta detector designed to have uniform characteristics for beta particles emitted within the solid angle cone between $\phi=135°$ and $\phi=180°$ from the direction of the recoil ion. The relation between E and R for various values of the angle ϕ, calculated from the conservation laws of energy and momentum, is shown in Fig. 2. The experiment was performed in the region between the curves for $\phi=135°$ and $\phi=180°$.

He^6 Production

The He^6 source gas was produced in a manner similar to that described previously.[3] Three hundred grams of high-purity, highly emanating beryllium hydroxide powder, contained in an aluminum box, were irradiated in the Brookhaven Graphite Research Reactor; and the He^6 produced by the $Be^9(n,\alpha)He^6$ reaction was carried into a gas purification system through 40 ft of tubing with a sweep gas of ethyl alcohol vapor. The ethyl alcohol and other condensable vapors were removed

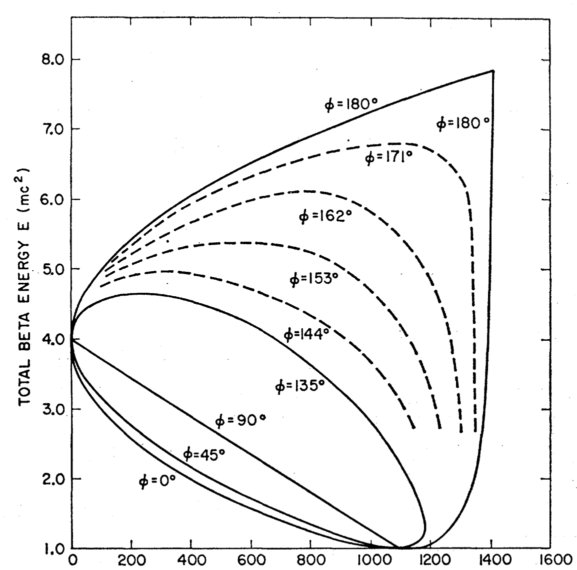

FIG. 2. Beta-particle energy E versus recoil-ion energy R for selected values of the angle ϕ between the directions of the beta particle and the recoil ion for the decay of He^6.

[20] A. Winther, Kgl. Danske Vid. Sel. Mat. Fys. Medd. **27**, No. 2 (1952); T. A. Carlson, F. Pleasonton, and C. H. Johnson, Phys. Rev. **129**, 2220 (1963).

from the gas stream with dry ice and liquid nitrogen traps. The gas was further purified in an activated charcoal trap maintained at liquid nitrogen temperature and then concentrated by a small, two-stage oil diffusion pump. Condensable oil vapors at the output of the pump were removed by a liquid nitrogen trap, and the reamining gas passed to the experimental apparatus through a short length of tubing. The delivery of He^6 to the apparatus was controlled by diverting part of the He^6 flow to a separate diffusion pump. The system was capable of delivering 2×10^9 atoms of He^6 per sec, which was nearly one hundred times the quantity required for the experiment.

The purity of the He^6 was determined by measurements of the half-life and of the beta spectrum. The observed half-life for beta particles with energy greater than 1.0 MeV is 0.83 ± 0.02 sec, and the logarithmic decay curve is linear over a period of eight half-lives. This may be compared with the value of 0.797 ± 0.003 sec reported by Bienlein and Pleasonton,[21] the weighted mean of half-life measurements of 0.813 ± 0.007 sec of Ajzenberg-Selove and Lauritsen,[22] and the value of 0.862 ± 0.017 sec recently reported by Malmskog and Konijn.[23] The beta spectrum of the gas was measured with a thin-lens magnetic beta spectrometer. The Fermi plot of the spectrum has an endpoint of 3.508 ± 0.015 MeV, which agrees with the value, 3.50 ± 0.05 MeV reported by Wu *et al.*[17] and with the value of 3.508 ±0.004 MeV recently obtained from the recoil-ion spectrum by Johnson *et al.*[24] In addition, no activities with a higher endpoint were observed in the beta spectrum. The decay rates of monoenergetic beta rays selected by the thin-lens magnetic spectrometer from a source of He^6 were also measured at several beta-particle energies. A search was made for gamma rays from the He^6 gas, and none were found other than the bremsstrahlung spectrum. An evaluation of all the above measurements yielded an upper limit of 0.2% for the activity contributed above a beta energy of 0.7 MeV by possible contaminants with half-lives greater than five seconds.

Source Volume and Beta Detector

The beta scintillation detector was designed to have uniform pulse-height response for monoenergetic beta particles emitted in the source volume at angles between 135° and 180° from the direction of the collimated recoil-ion beam. The detector was machined from "Pilot-B" scintillation plastic to a shape shown in cross section in Fig. 1. The source volume well in the detector was shaped so that a particle scattering from the side surfaces of the well could not pass directly through the collimating apertures of the recoil-ion spectrometer. The scintillation plastic was fastened to a Lucite light pipe, 12.7 cm in length by 7.6 cm in diameter, with an epoxy cement,[25] and a Dumont type 6363 photomultiplier tube was mounted at the end of the light pipe. All surfaces of the detector and light pipe were highly polished and covered with an aluminum foil reflector. The well of the detector was lined with aluminum foil, 0.00063 cm thick, which was grounded to prevent accumulation of static charge on the walls.

The beta detector was tested with a monoenergetic pencil beam of beta particles obtained from a magnetic spectrometer. The characteristics of the detector were determined as functions of the energy and incident angle and position of the beam. Pulse-height spectra showed that the response of the detector was proportional to the beta-particle kinetic energy to within 2% and that the full width at half maximum of the peak varied as the square root of the energy. The resolution of the detector was 14% at 1.4 MeV. An investigation was made of the variation in the efficiency and pulse-height response of the detector for a representative selection of incident positions and angles of the beta-particle beam into the detector. The mean variation in the detection efficiency for the range of angles used in the experiment was 1.4% and the mean variation in the pulse-height response was 1.0%. The data from these measurements were used to compute the error introduced into the experimental results by beta-detector nonuniformities.

A pulse-height spectrum and the corresponding Fermi plot obtained from the beta detector with He^6 flowing into the experimental apparatus are shown in Fig. 3. The nonlinearity at the high energy end of the curve arises from resolution effects. The curvature below 1.4 MeV results from detection of electrons, degraded in energy, which originated below the brass collimator

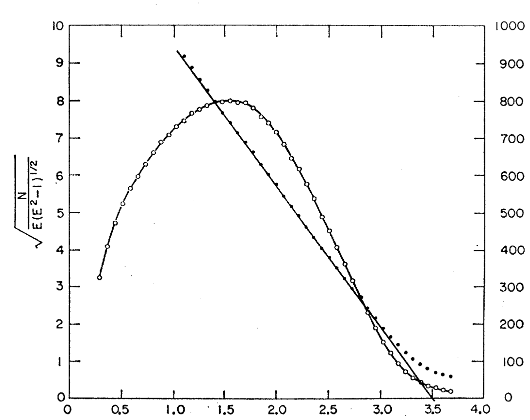

FIG. 3. Beta-particle energy spectrum (open circles) and Fermi plot (closed circles) measured with the well-shaped beta detector.

[21] J. K. Bienlein and F. Pleasonton, Nucl. Phys. **37**, 529 (1962).
[22] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[23] S. Malmskog and J. Konijn, Nucl. Phys. **38**, 196 (1962).
[24] C. H. Johnson, F. Pleasonton, and T. A. Carlson, Nucl. Phys. **41**, 167 (1963).
[25] Epoxy resin—Bonding Agent R 313, C. H. Biggs Co., Los Angeles, California.

at the neck of the source volume. It should be noted that these degraded-energy electrons do not contribute to the measured coincidence events in the correlation experiment.

The Shutter and the Insertion of He^6

The source volume for the experiment was defined by an aperture plate and a shutter mechanism located at the open end of the scintillation detector well. This was necessary since the lithium-recoil ions, which have a maximum energy of only 1418 eV, cannot penetrate a window. The shutter consisted of a 180 $\mu g/cm^2$ aluminum foil supported on two fine aluminum wires which could be positioned mechanically from outside the vacuum system. The foil was opaque to the recoil lithium ions but transparent to the beta rays detected in the experiment. It was intended that the opening and closing of the shutter should not affect the He^6 concentration in any part of the apparatus. To achieve this, the He^6 was introduced into the system below the source volume aperture plate; and two holes were machined into this plate to permit the gas to diffuse freely into the source volume. The central hole was coaxial with the beta detector and also served as the entrance slit of the electrostatic spectrometer. The second hole, which also opened directly into the source volume, was located off the axis of the beta detector so that lithium ions passing through this hole would not have a direct path into the electrostatic spectrometer. The shutter mechanism was located in such a way that the central hole could be covered, while the side hole remained open at all times. Measurements of He^6 concentrations made with a small gas probe connected to a beta counter showed that the He^6 intensity below the shutter region changed by less than 0.1% with change of shutter position. The counting rate of the beta detector, however, increased by 2.1% when the shutter was closed. The explanation for this increase is that when the shutter was open, the source volume sampled both the higher concentration regions near the He^6 inlet and the lower concentration regions of the recoil-ion detector system; but when the shutter was closed, the source volume did not open directly into the latter region. The data obtained in the correlation measurement were corrected for this small variation in source activity.

The Ion Detector System

The ion detector system consisted of three principal components: the electrostatic spectrometer, the accelerating grids, and the secondary emission multiplier. The spherical electrostatic spectrometer was designed according to theory developed by Purcell[26] and by Browne *et al.*[27] The field edge effects were minimized by guard rings as described by Herzog.[28] The entrance "slit" for the spectrometer was the central hole in the source volume aperture plate, and the image of this "slit" was focused on the circular aperture adjacent to grid 1 in Fig. 1. The aluminum deflecting plates were shaped as truncated segments of a sphere and supported on polystyrene spacers. The potentials of the inner and outer plates were made equally negative and positive with respect to ground; and the potential between the plates was measured with a precision potentiometer.

The grid system, grids 1, 2, 3, and 4, was used to accelerate the ion beam before it entered the multiplier detector. Each grid consisted of a tungsten mesh woven to 12.7×15.7 wires/cm from wire 0.0025 cm in diameter. The spacings between grids 1 and 2 and grids 3 and 4 were 1.4 cm. The transmission of the mesh was 93%. The grids were supported by stainless steel frames which were smoothly rounded and highly polished to reduce field emission effects. Grid 1 was electrically grounded, and grid 4 was connected to the first dynode of the multiplier. For the correlation measurements, grids 2 and 3 and the baffle were electrically connected to grid 4; however, during some calibration tests of the apparatus, various acceleration potentials were applied to grids 2 and 3 and the baffle.

The electron multiplier for the detection of the recoil ions contained 14 multiplying dynodes which had sensitized magnesium-silver alloy surfaces. The structure of the multiplier was a modification of the design used in the Dumont type 6363 photomultiplier tube. The entrance aperture of the multiplier measured 6.3 by 6.3 cm; and the entire beam from the electrostatic spectrometer, which had a maximum transverse dimension of 5 cm at grid 4, was incident on the sensitive surface of the first dynode.

The ion detector system was tested and calibrated with a monochromatic beam of lithium ions. The ions were produced and focused in an electron-gun assembly from a 5CP1 cathode ray tube in which the cathode had been replaced by a lithium surface-ionization source. During tests, the gun was enclosed in a vacuum envelope that was connected by a flexible metal bellows to the main vacuum system just above the source volume aperture plate. The energy of the ions was determined from potentiometer measurements of the accelerating potential. The position of the ion beam incident on the spectrometer "slit" was adjusted with the ion-gun deflecting plates, and the angle of incidence of the beam was set mechanically by tilting the ion gun.

The resolution characteristics of the electrostatic spectrometer were determined in two ways. First, resolution curves were measured with stationary pencil beams of monoenergetic ions. These curves had a rectangular shape with a width of 4.5% in agreement with predictions. The spectrometer voltage settings for the center of these curves were proportional to the ion

[26] E. M. Purcell, Phys. Rev. 54, 818 (1938).

[27] C. P. Browne, D. S. Craig, and R. M. Williamson, Rev. Sci. Instr. 22, 952 (1951).

[28] R. Herzog, Z. Physik 97, 596 (1935).

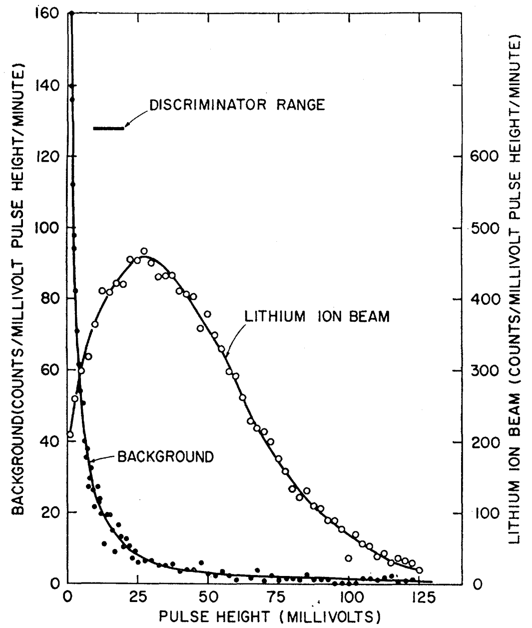

FIG. 4. Pulse-height spectra from the recoil-ion detector. A spectrum measured with 6000-eV lithium ions from the ion gun is shown together with the background which was subtracted from the ion spectrum.

energy over the range of 200 to 2000 eV. The second set of tests, which was used to determine the energy calibration of the spectrometer, was designed to simulate the extended gas source in the source volume. Alternating voltages were applied to the deflecting plates of the ion gun so that the beam uniformly scanned the entrance "slit" of the spectrometer. Individual curves were measured for 24 representative angular positions of the ion gun. The effective resolution curve for the spectrometer was obtained from a numerical summation of these measurements. The full width at half maximum of the resulting resolution curve was 7.6%. The estimated accuracy of this energy calibration is $\pm 1.0\%$.

The characteristics of the multiplier ion detector were also measured with lithium ions from the ion gun to determine operation conditions most suitable for the measurements. The multiplier was operated with a constant potential of 2600 V between the first dynode and anode; and the amplifier gain and discriminator bias level were selected so that the variation of the detection efficiency of the multiplier itself was less than 2%/keV for ions in the range from 3500 to 7000 eV. During the measurements, the effect of variation in the detection efficiency of the multiplier with ion energy was eliminated by adjusting the potential on grids 2, 3, and 4 and the first dynode so that singly-charged ions passing through the electrostatic spectrometer always arrived at the multiplier first dynode with a kinetic energy of 6000 eV.

A typical multiplier pulse-height spectrum for lithium ions accelerated to 1007 eV in the ion gun and through a potential of 4993 V on the grids is shown in Fig. 4, together with a background spectrum. The discriminator bias levels used during the experiment corresponded to acceptance of 91 to 96% of the total number of counts under the spectral curve.

A possible source of systematic error is a variation in grid transmission as a function of ion energy. Ridley,[2] investigated this effect in a grid structure similar to grids 1 and 2 of this apparatus. From his results, we estimate a change in transmission of grid 1 of $(1.3\pm0.6)\%$ over the maximum range of ion energies, 540 to 1300 eV, used in this experiment; and a correction of $(+0.005\pm0.003)$, calculated from these estimates of variation in transmission, was applied to the final value of the angular correlation coefficient.

Electronics

Data were recorded with a five-channel pulse-height by six-channel time-of-flight analyzer. The time-of-flight analyzer separated events involving singly and doubly charged ions. The pulse-height analyzer permitted simultaneous measurements at various beta energies. To provide accurate timing for time-of-flight analysis, double-delay-line clipped amplifiers (Franklin model 348) were used in conjunction with pulse-height analyzers designed to trigger at the zero cross-over of the amplifier output pulse.[30] The channel widths of the time-of-flight analyzer were variable;[31] but widths of 0.1 or 0.2 μsec were used for most measurements. A recording ratemeter monitored the output of the beta detector so that a continuous indication was obtained of the He^6 activity in the source volume.

Vacuum System

The vacuum envelope for the apparatus was designed to provide five stages of differential pumping in order to minimize the concentration of He^6 decaying in the vicinity of the recoil-ion detector. Each section of the vacuum system was evacuated by a high-speed oil diffusion pump and liquid nitrogen-cooled trap. The highest pressure in the apparatus was 5×10^{-5} mm Hg, measured in the source volume and shutter region when He^6 was flowing. Pressures throughout the rest of the apparatus were approximately 2×10^{-7} mm Hg. The pressure in the ion gun during the calibration tests was less than 10^{-4} mm Hg. At these pressures, the mean free paths of the lithium ions[32] are 570 cm in the source volume and shutter regions, 1.4×10^5 cm in the rest of the apparatus, and greater than 280 cm in the ion gun. In each case, the mean free path was long compared with the corresponding dimensions in the apparatus, which were 7, 43, and 27 cm, respectively. These com-

[29] B. W. Ridley, Nucl. Instr. Methods **14**, 231 (1961).
[30] R. L. Chase, Rev. Sci. Instr. **31**, 945 (1960).
[31] V. Guiragossian, Columbia University Report CU(PNPL)-205, 1960 (unpublished), p. 40.
[32] C. Ramsauer and O. Beeck, Ann. Physik **87**, 1 (1928).

parisons show that the probability of lithium ions being scattered by residual gas molecules in the vacuum system is negligible. The rectangular resolution curves obtained during the calibration of the recoil spectrometer with monoenergetic ions also support this conclusion.

DATA RECORDING AND ANALYSIS

Energy spectra of singly charged recoil ions were measured in coincidence with beta particles of fixed energy. The recoil spectrometer was set for a specific energy, and coincidences between recoil ions and beta particles were recorded on the two-dimensional analyzer, which contained five beta-energy channels and six recoil-ion time-of-flight channels. The individual counting rates in each channel of the analyzer matrix were corrected for background and deadtime, and normalized to the He^6 activity in the source volume. The data associated with each of the five beta channels were summed over those time-of-flight channels which corresponded to the arrival time of singly charged recoil ions. Thus, five coincidence counting rates corresponding to the five beta channels were obtained simultaneously at one recoil-ion energy. This procedure was repeated at five different recoil-ion energies so that five recoil-ion energy coincidence spectra were obtained, each for a selected beta energy. Since $(89.6\pm0.2)\%$ of the recoils from He^6 are singly charged and the abundance variation with energy is less than 0.3% over the range of interest in this experiment,[20] no attempt was made to determine energy distributions for doubly or triply charged ions. Beta energies in the range, 4.1 to 6.5 mc^2, were selected; and the recoil-ion energies were between 540 and 1300 eV.

Data were measured for equal time periods in the sequence: shutter open—shutter closed—shutter closed—shutter open (or vice versa). The coincidence counting rates measured with the shutter closed constituted the principal background correction. These were subtracted from the shutter-open counting rates. Additional small corrections were made for the shutter position

TABLE I. Typical counting rates.

Instrument	Counting rate
Beta detector	27 000 counts/sec
Recoil-ion detector	
1. Decays originating in the source volume	0.1 count/sec
2. Decays in the remainder of the apparatus	2.6 counts/sec
3. Background from other sources	2.0 counts/sec
Total	4.7 counts/sec
Coincidence counting rates per beta channel	
1. True coincidences	0.33 count/min
2. Background coincidences from He^6 decaying below the shutter region	0.08 count/min
3. Random accidental background coincidences	0.35 count/min

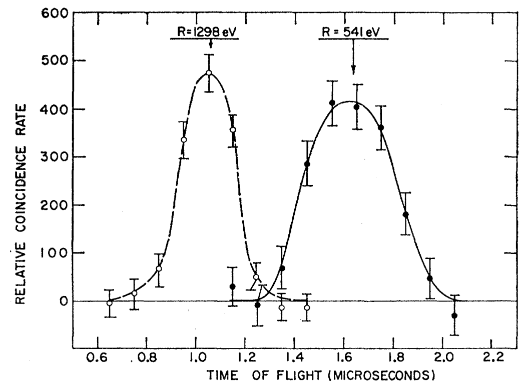

FIG. 5. Typical time-of-flight coincidence spectra for two energy settings of the recoil-ion energy analyzer. The beta-energy range is 5.0 mc^2 to 5.5 mc^2.

effect described previously, for variations in the flow of He^6 into the apparatus, and for changes in the recoil-ion detector counting rate. The shutter position sequence minimized the effect of drift in He^6 source activity.

The time-of-flight spectra of recoil ions, measured with the two-dimensional analyzer for a fixed setting of the recoil-ion spectrometer, contained two peaks corresponding to the flight times of singly and doubly charged recoil ions. The exact channels in which singly charged recoil ions appeared were found from a summation of all the time-of-flight curves measured at each recoil-ion energy. Fig. 5 shows two typical, time-of-flight coincidence curves for singly charged ions measured at the two extreme recoil-ion energies of 541 and 1298 eV. These data, from which background has been subtracted, were taken in one beta channel with total energy from 5.0 to 5.5 mc^2, The time-of-flight channels were 0.1 μsec wide. The positions of the peaks occur at the flight times calculated for the energies selected by the recoil spectrometer and for the flight distance in the apparatus. The base widths of the peaks agree with the calculated variation in flight time arising from the measured resolution of the recoil spectrometer and from the variation in flight path of ions accepted by the detector.

The electron-neutrino angular correlation coefficient was determined by the comparison of the shape of the observed recoil-ion coincidence spectra with the shape predicted by Eq. (3). A weighted, least squares fit of the data to the straight line spectrum of Eq. (3) was used to determine values of λ for the various beta-energy channels selected during the course of the experiment.

The time-of-flight spectra in Fig. 5 are typical of the data taken in the experiment but show coincidences for only one beta channel at two recoil-ion spectrometer settings. Even these limited data are sufficient to determine a value of the correlation coefficient. The value obtained from the summation of counts in each peak is $\lambda=-0.25\pm0.07$. In the actual experiment, coincidence rates were measured at five recoil-ion energies to obtain recoil-ion energy spectra.

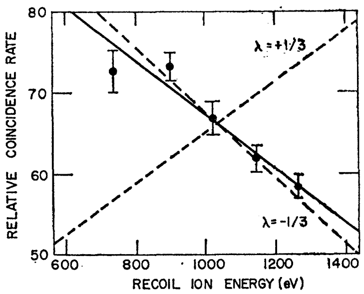

FIG. 6. Recoil-ion energy coincidence spectrum. Data from measurements with different beta-energy channels have been summed, yielding an effective total beta channel of 4.1 to 6.5 mc^2. The solid line is a least-squares fit to the data, and the dashed lines are the predicted spectra for $\lambda=+\frac{1}{3}$ and $\lambda=-\frac{1}{3}$ for $E=5.3$ mc^2.

Typical counting rates during the experiment are listed in Table I. Because coincidence counting rates were low, particular care was exercised to minimize the effects of instrumental drifts. An energy calibration of the beta detector was performed every two hours, and the electronic equipment was calibrated periodically. The delivery of He^6 into the source volume was maintained constant within 10%. Data were collected and analyzed over time intervals of three weeks to minimize error introduced into the experiment from possible long term variations in the characteristics of the apparatus.

EXPERIMENTAL RESULTS

The value of the electron-neutrino angular correlation coefficient was determined from 51 separate measurements of this quantity taken at selected total beta-ray energies between 4.1 and 6.5 mc^2. The measurements were distributed approximately uniformly over this beta-ray energy range, and the corresponding ranges of recoil-ion energy were chosen so that only decay events having values of E and R lying within the area bounded by the curves $\phi=135°$ and $\phi=180°$ in Fig. 2 were accepted. The widths of the beta and time-of-flight channels, the selected values of recoil-ion energy, and the flow of He^6 into the apparatus were varied during the course of the experiment. The weighted average of these measurements is $\lambda=0.319\pm0.027$, where the error is the statistical standard deviation and does not include instrumental error. There was no dependence in the individual values of λ on either the time the data was taken or the beta-particle energy.

The three significant instrumental errors for the experiment are those associated with the beta energy calibration, the recoil-ion energy calibration, and the change in grid 1 transmission as a function of ion energy. The corresponding errors in λ are ±0.005 for the beta calibration, ±0.003 for the recoil calibration and ±0.003 for grid 1 transmission. When these are combined with the statistical error, the standard deviation of the measured value of λ becomes ±0.028.

From Table I, it may be seen that true coincidences originating from the region outside the source volume amount to only 24% of the true coincidences contributed by the source volume. Errors due to fluctuations in He^6 concentration below the shutter region were therefore similarly reduced. The estimated maximum error in λ due to the 0.1% maximum He^6 concentration fluctuation below the shutter caused by shutter motion is ±0.0003 a negligible quantity compared to other errors in the experiment.

The validity of the background subtraction procedure was tested by summing all coincidence counts in those time-of-flight channels corresponding to times during which it was impossible to observe true coincidence events originating in the source volume. The total number of counts from time-of-flight channels for which there could be no true coincidences, normalized to the same width of time channels covered by the singly charged peak, is (0.8 ± 1.1)% of the total number of true counts in the coincidence peak. The stated error is the statistical standard deviation.

Two further internal consistency tests of the data were made. The first test concerned the linearity of the recoil-ion energy coincidence spectrum shown in Fig. 6. This spectrum was obtained by summing data from the separate recoil-ion coincidence measurements which were recorded simultaneously in five beta-energy channels in the range from 4.1 to 6.5 mc^2 and at values of the recoil-ion energy indicated in the figure. Data for six spectra, which were measured under different conditions over a longer recoil-ion energy range, were not included in this summation. The solid line in the figure was obtained from a weighted least-squares fit of the points to a straight line. The chi-squared test showed that the probability of the deviation of the experimental points from this line is 22%. Predicted curves for $\lambda=+\frac{1}{3}$ (pure tensor interaction) and $\lambda=-\frac{1}{3}$ (pure axial vector interaction), calculated for the mean beta energy of 5.3 mc^2, are also shown. In the second test, coincidence data corresponding to a particular recoil-ion energy were selected from the total set of measurements and plotted as a function of beta energy. These experimental points are compared with the theoretical prediction, $P(E,R=1021 \text{ eV})$ for $\lambda=+\frac{1}{3}$ and $\lambda=-\frac{1}{3}$ in Fig. 7. The error bars shown in the figure include both the statistical error and the error from the variation in width of the beta channels. The chi-squared test yielded a 53% probability for the fit of the points to

FIG. 7. Beta-energy coincidence spectrum for a recoil-ion energy of $R=1021$ eV. The curves are the predicted spectra for $\lambda=+\frac{1}{3}$ and $\lambda=-\frac{1}{3}$.

the theoretical curve for $\lambda=-\frac{1}{3}$. Figures 6 and 7 present results of the experiment graphically. The tests demonstrate the linear response of the apparatus, since the probability of the deviations of the experimental points from the curves is well within the usually accepted limits of the chi-squared test.

SUMMARY AND CONCLUSIONS

The beta-neutrino angular correlation coefficient in the decay of He^6 was determined from recoil-ion energy spectra measured with the ions in coincidence with beta particles of fixed energy. Particular care was taken in the design and calibration of the apparatus to minimize and evaluate systematic errors. The internal consistency of the experimental data was analyzed to investigate the behavior of the apparatus. Tests of the background subtraction procedure and of the shape of the observed coincidence spectra, measured for fixed beta particle or for fixed recoil-ion energy, show that the apparatus functioned in the manner predicted, within the evaluaged precision of the angular correlation measurements.

The beta-neutrino angular correlation coefficient for He^6 determined from the recoil-ion energy coincidence spectra is $\lambda=-0.319\pm0.028$ where the error quoted is the standard deviation. This leads to the conclusion that the Gamow-Teller interaction in the decay of He^6 is predominantly axial vector. The admixture of the tensor interaction calculated from this measurement is $(|C_T|^2+|C_T'|^2)/(|C_A|^2+|C_A'|^2)=0.022\pm0.044$.

The results are compared with other recent measurements on He^6 in Table II. Accurate values of the half-life and of the decay energy of He^6 were required to determine the He^6 purity. The half-life obtained from these measurements is 0.83 ± 0.02 sec; and the maximum energy of the beta spectrum, measured with a thin-lens magnetic spectrometer, is 3.508 ± 0.015 MeV in agreement with previous measurements.

TABLE II. Recent measurements on He^6.

Author	λ	Method
Allen *et al.*[a]	$-0.39\ \pm0.05$	Recoil spectrum
Johnson Pleasonton and Carlson (private communication)	-0.3343 ± 0.0030	Recoil spectrum
Ridley[b]	$-0.353\ \pm0.022$[c] $+0.011$[d] -0.021[d]	Beta-recoil coincidence
Present work	$-0.319\ \pm0.028$	Beta-recoil coincidence

[a] See Ref. 6.
[b] See Ref. 7.
[c] Statistical error.
[d] Systematic error.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Professor W. W. Havens, Jr. and Professor C. S. Wu for their advice and many helpful suggestions. For the design and testing of the beta detector, we are grateful to Dr. O. C. Kistner. The valuable assistance of G. G. Everly throughout the experiment was greatly appreciated. We wish to acknowledge the contribution of Vahe Guiragossian and Robert Chase who designed and constructed the electronic circuits. The Alan B. Dumont Company generously provided their facilities for the preparation of the recoil-ion detector.