Direct Comparison of m/e for the Positron and the Electron*

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A relativistic, double-focusing mass spectrometer has been built to operate with 55-kev electrons. It has reversible electric field and fixed magnetic field. Positrons from Na^{22} and electrons from a hot filament alternately follow identical trajectories in opposing directions. The magnitude of the electric field required to focus is used as the measure of m/e. Seventeen positron runs were made intermediate in time between twelve electron runs. The rms deviation of the data lies within the standard deviation associated with positron counting. The result is

$$\frac{(m/e)^- - (m/e)^+}{m/e} = (26\pm 71)\times 10^{-6},$$

where the uncertainty is the standard deviation.

I. INTRODUCTION

EARLY experimental comparisons between m/e for the positron and the electron[1] indicated equality within 15 percent and, later,[2] within 2 percent. Because many atomic constants are known to much greater precision,[3] and because of the possibility of a difference between $(m/e)^-$ and $(m/e)^+$, a number of investigators have recently suggested the need for a direct precision comparison.[4,5] A mass spectrometer built for this purpose is described, as are the results of the experimental comparison.

II. METHOD

If a particle with a mass-charge ratio m/e follows a certain trajectory from point 1 to point 2 under the influence of fields **E**, **H**, then a particle with a mass-charge ratio $-m/e$ will follow the same trajectory from point 2 to point 1 under the influence of fields $-\mathbf{E}$, **H**. In the present experiment a family of trajectories between points 1 and 2 is furnished representing the focusing in angle and energy of a source at 1 on a detector at 2 or vice versa. If, however, the particles have slightly different magnitudes of m/e, correspondingly different magnitudes of **E** will be needed to achieve focus. One has

$$\frac{\delta(m/e)}{m/e} = -\left(1-\frac{v^2}{c^2}\right)^{-1}\frac{\delta E}{E},$$

for the case where the particle speed v is constant along the central trajectory.

III. DESCRIPTION OF APPARATUS

A simplified plan view of the mass spectrometer is shown in Fig. 1. An electromagnet, with rectangular poles between which the rectangular part of the vacuum chamber is clamped, provides a nearly uniform vertical magnetic field over the volume of the chamber. Electrostatic deflector plates CC (stainless steel with adjacent planes lapped flat and parallel) have a potential difference between them, the average potential being near ground. These act as a velocity selector. The purely magnetic deflection between D and E defines the momentum. It will be shown below that by suitable choice of λ, ρ, and ϕ the apparatus is made double-focusing. The controls for varying ρ and ϕ are not shown.

At A there is a line source of positive β-rays (0.5 mC Na^{22}). A portion of the positron spectrum entering the mass spectrometer through slit B is brought to a focus on slit E by adjusting the electric field between plates CC. This selects a velocity to match the momentum defined by the magnetic field, which is held fixed. In terms of the fractional change in voltage across the velocity selector, the beam has a width at half-maximum approximately equal to the defining slit width divided by ρ ($\sim$0.009 in./3 in.=0.003). The horizontal angle range and the fractional energy range accepted are of the order of magnitude of the velocity-selector plate spacing divided by ρ ($\sim$0.115 in./3 in.=0.038). Vertical angles are limited by the height of aperture H and of slit B, and are the same for electrons and for positrons.

The situation for a positron run is indicated in Fig. 1. A bundle of positron trajectories from slit B to slit E is schematically represented. The trajectories emerging from the spectrometer at E are stopped down at aperture H, pass through the housing I, and terminate at the end-window Geiger-Mueller counter GMC. Aperture H limits the width of the beam to the usable width of the counter window.

For an electron run the velocity-selector voltage is reversed. The injector housing I is held at a negative potential so that electrons from the hot tungsten filament J are accelerated toward the aperture H. An aluminum scattering foil G (0.2 mg/cm²), retracted during positron runs, is now placed across H. The foil

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[1] J. Thibaud, Phys. Rev. **45**, 781 (1934).
[2] A. H. Spees and C. T. Zahn, Phys. Rev. **58**, 861 (1940).
[3] Jesse W. M. DuMond and E. Richard Cohen, Phys. Rev. **82**, 555 (1951); Muller, Hoyt, Klein, and Du Mond, Phys. Rev. **88**, 775 (1952). We are indebted to Professor DuMond for communicating some recent results prior to publication.
[4] J. W. M. DuMond, Phys. Rev. **81**, 468 (1951).
[5] Arne Hedgran and David A. Lind, Phys. Rev. **82**, 126 (1951).

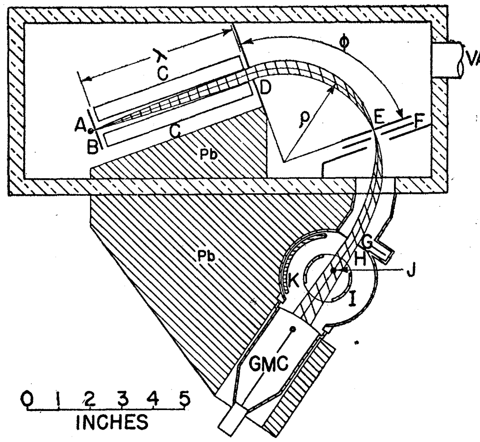

FIG. 1. Plan view of double-focusing mass spectrometer. Spacing between plates CC and the widths of slits B, E, and rough-slit D are grossly exaggerated in order to show a bundle of particle trajectories. The magnetic field is uniform over the rectangular part of the vacuum chamber and is out of the paper. The vacuum chamber height between magnet pole faces is $1\frac{1}{8}$ in.

is bombarded uniformly by electrons from the injector and thus, through multiple scattering, provides trajectories of acceptable angles at each point of the aperture. All acceptable energies are provided by modulating the injector voltage at an audiofrequency, the amplitude being large compared with the range of acceptable energies. The current provided by the injector is monitored by measuring the current collected at rough-slit F. During electron injection the counter window is protected by closing the nonmagnetic gate K.

Electrons arrive at slit B twice during each modulation cycle and are collected on the positron source-holder A. The signal is amplified and detected on a heterodyne analyzer. The average injector voltage is adjusted to give a null first-harmonic response. This means that the modulation voltage is centered about

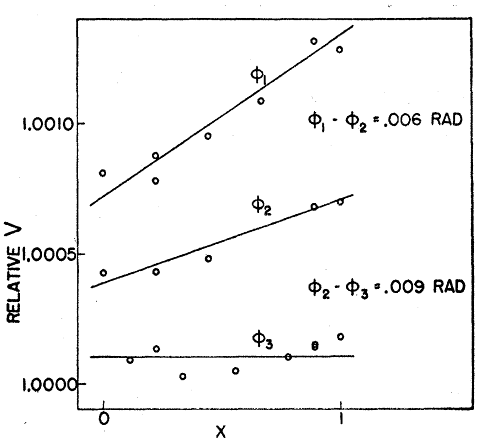

FIG. 2. Velocity-selector voltage V to focus electrons as a function of scanning-slit position x for three different values of momentum-selector angle ϕ. (The aperture H has unit width in x on this plot.)

the mean acceptable energy. The second-harmonic signal is then taken as a measure of the electron beam.

The magnet is excited by current from an electronically regulated 300-volt supply.[6] Fluctuations in current are detected by balancing the potential difference across a precision resistor against a standard cell and are compensated by hand adjustment. To allow the magnet yoke to reach equilibrium it is found necessary to permit magnet-coil current to flow continuously for several days. The field in the spectrometer is approximately 100 gauss.

Fluctuating magnetic fields due to dc machinery in the city (streetcars, etc.) were so large relative to the field in the spectrometer that final adjustment and runs had to be made in a magnetically quiet location outside the city. The improvement in magnetic-field stability was a hundredfold.

The velocity-selector voltage is provided by a 4-kv regulated rf power supply immersed in oil.[7] The output appears across an 8-meg chain whose center point is grounded. The regulating signal is obtained by comparison of the potential at a point on this chain with that across a type 5651 voltage regulating tube. For measuring the velocity-selector voltage, an independent 16-meg potential divider is connected across the output terminals. The center of this chain is also grounded. A precision potentiometer measures the potential difference between ground and either the plus or minus 1-volt (nominal) points on the potential divider. The measured potential differences are designated by a symbol V (with or without a subscript) in the remainder of the paper. These readings are a measure of both the potential difference between the velocity-selector plates and the average potential of the plates with respect to ground. This latter voltage acts longitudinally and therefore enters only relative to the beam energy and not to the velocity-selector voltage, thus being reduced in effect by a factor of about fifteen.

The electron-injector voltage is provided by an rf voltage quadrupler immersed in oil. The maximum output is 60 kv dc. Because the injector potential is modulated, no regulation is necessary. The audiofrequency modulation (75 cps) is impressed by a transformer whose output is 10 kv peak. The injector power supply is not operated during positron runs, but it is so arranged that the same direct current flows in the primary of the rf transformer during electron and positron runs. This circuit is the only one in the immediate vicinity of the spectrometer whose operation is different for electron and positron runs.

IV. FOCUSING PROCEDURE

Elementary considerations show that a linear, crossed-field velocity selector in series with a magnetic momentum selector, operating in a common magnetic

[6] Hausman, Bender, and Reilley, Phys. Rev. **82**, 773 (1951).

[7] We are indebted to Professor R. S. Bender for the design of this circuit.

field, focuses a nonrelativistic particle to first order in initial angle when the total transit time is half a cyclotron period. The combination also focuses to first order in initial energy provided the path lengths in the two selectors are equal. Thus, in Fig. 1 one would have $\phi=\frac{1}{2}\pi$ and $\rho=2\lambda/\pi$ nonrelativistically.

Because of the paucity of low energy positrons it was necessary to run at slightly relativistic energies (~55 kev). Under these circumstances the focusing conditions are altered. For example, time-dilation during velocity selection necessitates lengthening the velocity selector. In addition the angle ϕ must be decreased from $\frac{1}{2}\pi$. These effects are of order v^2/c^2.

The values of the parameters for best focus are determined experimentally using the electron beam. Criteria for good focus are: (a) The line width should be consistent with the geometry; (b) if the width of aperture H is subdivided, the focusing potential of the velocity-selector should be the same for all subdivisions. When these criteria are satisfied, besides having a narrow line, the location in voltage V of the line does not depend on the details of the electron energy spectrum.

To find the best focus, the following procedure was used.

(a) For given ρ and ϕ the electron-injector assembly is moved until the central trajectory enters D in a direction parallel to the plates CC.

(b) For the same ρ and ϕ the focusing potential V is determined as a function of the position x of a scanning slit, one-fourth the width of H and temporarily installed at H.

For suitable ρ, $V(x)$ is an essentially linear function, the slope depending on ϕ. The value of ϕ can then be adjusted to make this slope vanish. Figure 2 shows $V(x)$ for three values of ϕ in the neighborhood of a good focus. A check on the focus so obtained is afforded by offsetting the injector voltage from the usual value which gives a null first-harmonic response. Offsets of ± 3.5 kv induce no significant change in $V(x)$.

After achieving a focus as described, the scanning slit at H is removed from the apparatus. With this slit removed, a check on the state of the focus is made from time to time by running electrons with the foil G retracted. This alters the spectrum of energies provided. No change in location in V of the electron line, or in its width, has ever been observed for the two positions of foil G.

The curve of zero slope in Fig. 2 indicates the state of focus used in taking the final data.

V. EXPERIMENTAL PROCEDURE

Using the electron beam, the resolution function, beam *versus* velocity-selector voltage V, was found to be a gaussian. Positron counts were then taken at various values of V. Figure 3(a) shows the results of these runs superimposed on the electron line-shape. It is concluded that the positron line-shape is the same as that for electrons. Secular drifting of the line position in V was allowed for by frequent locations of the half-beam points with electrons. This drift is a smooth function of time and can be largely attributed to the temperature dependence of the 16-meg potential divider.

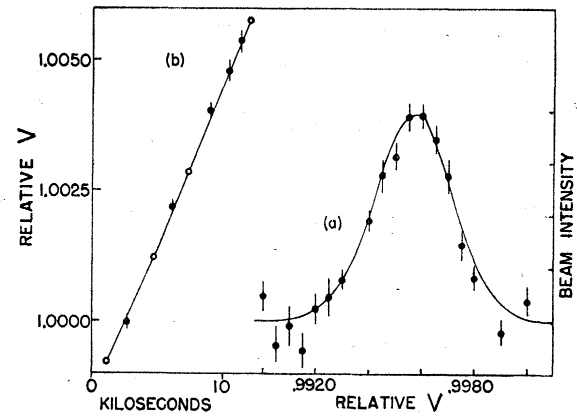

FIG. 3(a). Comparison between observed electron and positron line-shapes. The curve (Gaussian) is for electrons. The points are positron counting rates with standard counting errors attached. (b). Preliminary sequence of runs showing electron points as circles (V^- *versus* time) and positron points as dots (V^+ *versus* time). The errors attached to the latter are standard deviations due to counting N_R-N_L. Straight line segments connect electron points.

After showing that the electron and positron line-shapes are identical, the procedure is to sandwich pairs of positron runs between electron runs. During a sequence of runs, the magnetic-field current is continuously monitored as described previously, and the balance is held within three parts per million.

Electron Runs

Gate K (Fig. 1) is closed to protect the counter. Scattering foil G is inserted across aperture H. The average injector voltage is adjusted to give a null first-harmonic signal from the electron collector; then the second-harmonic signal is detected. Values V_L and V_R of the velocity-selector voltage are found which pass half the peak electron beam. During this process the current from the injector to rough-slit F is monitored. If it fluctuates more than 1 percent, the reading of V is discarded. Each half-beam point is located once or twice. The total elapsed time during the readings is about one minute. The location V^- of the electron line is then $(V_L+V_R)/2$.

The ratio of peak beam current to noise was 80:1. The dc beam current was $\sim 10^{-10}$ amp.

Positron Runs

Gate K is opened, scattering foil G is retracted from aperture H. The leads from the velocity-selector plates CC are disconnected from the ends of the resistor

TABLE I. Results for two sequences of positron and electron runs.

Particle[a]	Elapsed time kilosec	Potentiometer volts V_L	V_R	Counts in 800 sec N_L	N_R	Volts to focus V^-	V^+	δV volts
First sequence of runs								
−	2.3	0.9301	0.9334	···	···	0.93175	···	···
+	3.6	0.9301	0.9333	592	613	···	0.93181	−0.00009
+	5.2	0.9301	0.9333	559	701	···	0.93242	+0.00032
−	6.4	0.93055	0.93395	···	···	0.93225	···	···
−	10.8	0.93113	0.93463	···	···	0.93288	···	···
+	12.1	0.9315	0.9347	619	625	···	0.93313	0.00000
+	13.8	0.9315	0.9347	625	671	···	0.93333	−0.00013
−	15.0	0.93195	0.93545	···	···	0.93370	···	···
+	16.3	0.9325	0.9350	632	736	···	0.93427	+0.00028
+	18.5	0.9330	0.9362	677	623	···	0.93433	−0.00016
−	19.8	0.9330	0.93658	···	···	0.93479	···	···
+	21.0	0.9334	0.9366	602	647	···	0.93523	+0.00015
+	22.6	0.9334	0.9366	559	678	···	0.93560	+0.00012
−	23.8	0.93405	0.93746	···	···	0.93576	···	···
+	26.0	0.9345	0.9377	646	680	···	0.93627	−0.00001
−	27.1	0.93478	0.93832	···	···	0.93655	···	···
Second sequence of runs								
−	2.6	0.92543	0.9288	···	···	0.92711	···	···
+	3.8	0.9254	0.9286	598	645	···	0.92724	−0.00007
+	5.6	0.9257	0.9289	567	589	···	0.92741	−0.00021
−	6.9	0.9262	0.9295	···	···	0.92785	···	···
+	8.6	0.9264	0.9296	600	659	···	0.92830	+0.00015
+	10.7	0.9266	0.9298	582	649	···	0.92854	+0.00002
−	12.0	0.92705	0.93048	···	···	0.92876	···	···
+	13.2	0.9273	0.9305	618	681	···	0.92922	+0.00021
+	14.8	0.9278	0.9310	633	598	···	0.92922	−0.00012
−	15.8	0.9278	0.9313	···	···	0.92955	···	···
+	16.9	0.9284	0.9316	674	625	···	0.92975	+0.00001
+	18.6	0.9284	0.9316	674	662	···	0.92994	−0.00010
−	19.6	0.9285	0.93193	···	···	0.93021	···	···
+	20.8	0.9290	0.9322	648	607	···	0.93039	···
+	22.5	0.9290	0.9322	657	628	···	0.93045	···
−	23.6	0.92875	0.93205	···	···	0.93040	···	···
+	24.9	0.9288	0.9320	710	659	···	0.93014	···
+	26.6	0.9284	0.9316	563	711	···	0.93074	···
−	27.6	0.92883	0.93227	···	···	0.93055	···	···
−	28.1	0.9288	0.9323	···	···	0.93055	···	···

[a] Electron runs are designated by the symbol −, positron runs by +.

chains and are reconnected with reversed polarity. The direct current in the primary of the rf transformer of the injector power-supply is set at the value observed during the previous electron run. V is set at a value well off the curve and the background counting rate is checked.

Counts are then taken for 400 sec, at, say, voltage V_L as determined from the previous electron run, or at a value slightly displaced in anticipation of a drift. Then counts are taken for 800 sec at $V_R = V_L + 0.0032$ volt and again for 400 sec at V_L. The total number of counts at V_L is recorded as N_L, that at V_R as N_R. In this way effects of the slope, the curvature, and the rate of change of curvature of the focusing potential as a function of time are eliminated. This procedure is called a "run" and, as will be shown, yields the value of positron focusing voltage V^+ at the center of gravity of the counting time for that run. If, for a given pair of positron runs, V_L is set up first, then for the next pair, one sets up V_R first, and vice versa.

For the final data, two sequences of runs were made. Between these sequences the leads from the velocity-selector power-supply to the resistor chains were reversed, so as to average out any effect of leakage currents and any asymmetry of the velocity-selector voltage about ground. Measured leakage currents never exceeded 10^{-5} of the current in the 8-meg chain.

VI. RESULTS

Table I shows, in the first six columns, the raw data obtained for the final sequences of runs. The values for V^-, the location of the electron peak as obtained directly from columns three and four, are tabulated in column seven and shown in Figs. 4 and 5.

The total number of counts obtained during a run, $N_L + N_R$, should remain constant. In general, however, N_R is not equal to N_L, indicating that the positron focusing potential V^+ differs from the mean potential $(V_L + V_R)/2$ by an amount ΔV. The magnitude of ΔV is derived from the known beam height and width as follows.

If $\langle B \rangle$ is the average number of background counts in 800 sec, then $\frac{1}{2}\langle N_L + N_R \rangle - \langle B \rangle$ is the height of the Gaussian 0.0016 volt from its center. The width of the Gaussian curve is taken to be the average of the electron widths, and is 0.00343 volt. The peak height of the Gaussian is then $1.828[\frac{1}{2}\langle N_L + N_R \rangle - \langle B \rangle] = 239.8$ counts/800 sec. The slope of the Gaussian at the ± 0.0016-volt points is 9.908 counts/(800 sec$\times$0.0001 volt). Thus, since

$$\Delta V = \tfrac{1}{2}(N_R - N_L)dV/dN,$$

we have

$$\Delta V = (N_R - N_L)/19.82.$$

The uncertainty in ΔV arises from the uncertainty in $N_R - N_L$ and also from that in the quantity 19.82, while the uncertainty in the latter arises from that in the electron line width, that in $\langle N_R + N_L \rangle$, and that in $\langle B \rangle$. The rms deviation of the line width is 2.6 percent. The standard deviation of $\frac{1}{2}\langle N_R + N_L \rangle - \langle B \rangle$ is 17.1 percent, so that the uncertainty in the quantity 19.82 is 17.3 percent. The uncertainty in $(N_R - N_L)$ is $\langle N_R + N_L \rangle^{\frac{1}{2}} = 35.6$ counts/800 sec, or 0.00018 volt in each V^+.

The values of V^+ so obtained (with only the 0.00018-volt error attached), together with the values of V^-

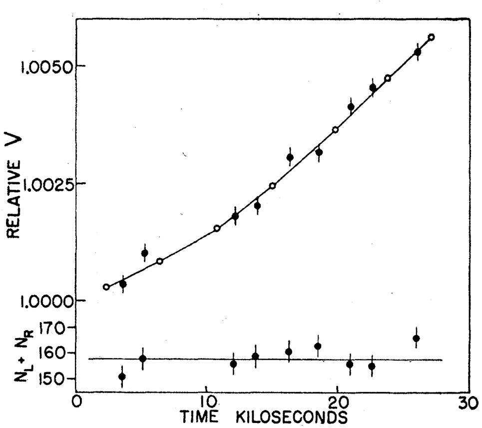

FIG. 4. Final data, first sequence of runs. Electron points are shown as circles, and are joined by straight line segments. Positron points are shown as dots with standard deviations arising from the counting errors in $N_R - N_L$. Also shown is $N_L + N_R$ for each positron run (here expressed as counts per 100 sec) with a standard statistical error.

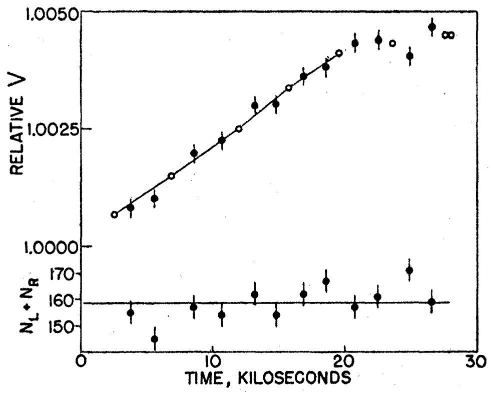

FIG. 5. Final data, second sequence of runs. Same notation as in Fig. 4. Data beyond 20 ksec is not used for final result (see Table I).

are plotted in Figs. 4 and 5 for the final sequences of runs. The sum N_R+N_L is plotted on the same time scale. The results of a preliminary sequence, observed when V^- and V^+ varied rapidly with time, are plotted in Fig. 3(b). These preliminary results are not used in subsequent computations and are shown only to indicate the validity of the method used to locate the positron points in time. Results shown in Fig. 5 for times exceeding 20 ksec also are not used in subsequent computations since a heat source was removed and returned to the laboratory during this period.

The value of V^- corresponding to the time of each positron point is found by linear interpolation between adjacent electron points. The difference δV between V^+ and the interpolated value of V^- is tabulated in the last column of Table I. The average δV is 53×10^{-6} volt for the first sequence and -14×10^{-6} volt for the second sequence. These in turn are averaged with equal weights.

Attached to this final average is a standard deviation compounded from the statistical uncertainties of the individual points and the uncertainty in the average of ΔV stemming from the quantity 19.82.

The seventeen values of δV have an rms deviation of 0.00015 volt which compares favorably with the standard deviation associated with counting (N_R-N_L), namely 0.00018 volt.

The difference of the mass-charge ratios is connected with the difference in focusing potentials δV through the factor $(1-v^2/c^2)^{-1}$. This is evaluated from the magnitude of voltage V, the known ratio of the potential divider used to measure the velocity-selector voltage, and the geometric parameters. The factor is 1.23.

The final result is

$$\frac{(m/e)^- - (m/e)^+}{m/e} = (26\pm71)\times10^{-6}.$$

VII. ACKNOWLEDGMENTS

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