The Measurement of e/M by Cyclotron Resonance

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The cyclotron resonance frequency of the proton has been measured using a new method. By measuring the spin precessional frequency of the proton in the same magnetic field, the proton magnetic moment in nuclear magnetons has been determined as $\mu_p=2.79276\pm0.00006$. In combination with other data this result can be used directly to determine the charge-to-mass ratio of the proton $e/M_p=9579.4_2\pm0.3$ emu/g, the faraday $F=9652.0_3\pm0.3$ emu/g (physical scale), and the ratio of the proton mass to the electron mass $M_p/m_e=1836.12\pm0.05$. A preliminary value for the H_2-D doublet is given.

INTRODUCTION

THE cyclotron resonance phenomenon has appeared to be an attractive method of measuring the charge-to-mass ratio of ions ever since the development of the cyclotron. In contrast to the usual mass spectroscopic method, stringent geometrical conditions other than the uniformity of the magnetic field are not required. For relative measurements, such as the determination of packing fractions, it is only necessary to measure frequency.

Until recently this application of cyclotron resonance had not been successfully exploited, but activity in this field during the last year or so has resulted in important advances.[1–7] A major portion of this paper describes a method of measuring the ratio of the spin precessional frequency of the proton $\omega_n=\gamma_p B$ to the cyclotron frequency of the proton $\omega_c=eB/M$ in the same magnetic field by a device which we have called the omegatron. From this ratio one can obtain* the proton moment in nuclear magnetons,[8] the faraday,[5] and, in combination with the result of Gardner and Purcell,[4] the ratio of the mass of the proton to the mass of the electron. This paper also describes the measurement of the mass difference of the (H_2-D) doublet.

In the note describing the omegatron,[5] a preliminary value for the faraday was given as an illustration of the potentialities of the method. Subsequent studies revealed shifts in the resonance frequency due to the presence of weak electric fields. One section of this paper describes the success that has been attained in measuring the magnitude of the shifts attributable to this cause.

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* *Note added in proof:* The authors combined the result of this experiment with several selected atomic constants recently determined in related experiments to illustrate the relationship of this new measurement with previous values. Since this manuscript was submitted, this relationship has been described more completely in the reports of J. A. Bearden and H. M. Watts [Phys. Rev. **81**, 73 (1951)] and J. W. M. DuMond and E. R. Cohen [A least-squares adjustment of the atomic constants as of December, 1950 (privately distributed)].
[8] L. W. Alvarez and F. Bloch, Phys. Rev. **57**, 111 (1940).

PART I. THE OMEGATRON

Principle of Method

It is not surprising that the cyclotron has been considered as an instrument for precise mass measurement. However, significant measurements have not been made with conventional cyclotrons because of the difficulty of attaining adequate resolution. In order to get high resolution, it is necessary for the ions to make a large number of revolutions. This requires that the applied rf voltage and the resulting radial increment per cycle be small. Since the ordinary cyclotron depends upon rf focusing, as well as magnetic focusing, the rf voltage cannot be reduced sufficiently to obtain the required resolution. The omegatron effectively overcomes this limitation.

As shown in Figs. 1 and 2, the ions are produced within the analyzer region of the omegatron by an axial electron beam (in the direction of the magnetic field). A positive trapping voltage applied to the guard rings produces an electric field which retards the loss of ions in the axial direction so that the rf field can act

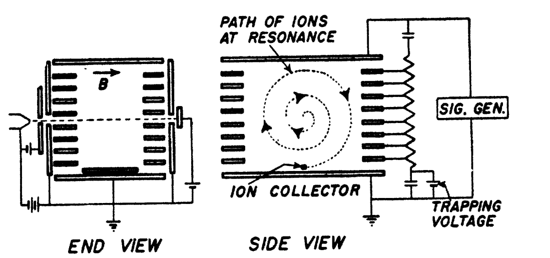

FIG. 1. Simplified diagram of the omegatron showing method of applying rf and dc voltages.

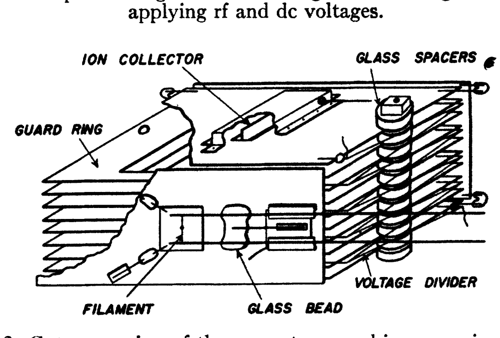

FIG. 2. Cut-away view of the omegatron used in measuring ν_n/ν_c.

on the ions over a greater number of cycles. The rf voltage is applied to two parallel electrodes and also to the guard rings through a bleeder to establish a uniform rf field, although a uniform field is not necessary except for the purpose of checking the theoretical equations. If the frequency of the applied voltage is the same as the cyclotron frequency, the ions will be accelerated in orbits of increasing size (Archimedes' spiral) and eventually strike the collector, thus producing an indication of resonance.

An analysis of the motion of a charged particle having a charge-to-mass ratio e/M, starting from rest under the influence of an rf electric field $E=E_0 \sin\omega t$ which is applied at right angles to a steady magnetic field B, shows that the particle will describe a spiral path with an angular velocity of $(\omega+\omega_c)/2$ and with a radius given by

$$r=(E_0/B\epsilon)\sin(\epsilon t/2), \qquad (1)$$

where $\epsilon=|\omega-\omega_c|\ll\omega_c$ and $\omega_c=eB/M$. Thus, for $\epsilon\neq 0$, the radius r will "beat"—i.e., it will go through successive maxima and minima at an angular frequency of $|(\omega-\omega_c)/2|$. At resonance, $\epsilon=0$, and Eq. (1) becomes

$$r=E_0 t/2B. \qquad (2)$$

If a collector is placed at some fixed distance R_0 from the origin, the charged particles or ions will never reach the collector if $(E_0/B\epsilon)<R_0$. Thus, for any fixed value of E_0/B, there is a critical value $\epsilon'=E_0/R_0B$ for which the ions will just reach the collector. If the resolution $M/\Delta M$ is defined as $(M/\Delta M)=(\omega_c/2\epsilon')=(\nu_c/\Delta\nu)$, where $\Delta\nu$ is measured at the base of the resonance peaks, then it follows that

$$\frac{M}{\Delta M}=\frac{\omega_c R_0 B}{2E_0}=\frac{R_0 B^2 e}{2E_0 M}. \qquad (3)$$

In practical cgs units,

$$(M/\Delta M)=4.8\times 10^{-5}(R_0B^2/E_0M), \qquad (4)$$

where M is measured in atomic mass units. Since the time required for the ions to reach the collector when $\epsilon=\epsilon'$ is $t'=\pi/\epsilon'$, it follows that

$$(M/\Delta M)=(\omega_c/2\epsilon')=(\omega_c t'/2\pi)=n', \qquad (5)$$

where n' is the number of revolutions the ions make before reaching the collector when $\epsilon=\epsilon'$. The time required for the ions to reach the collector at resonance is $t=2t'/\pi$. Thus, we can write

$$M/\Delta M=\pi n/2, \qquad (6)$$

where n is the number of revolutions the ions make at resonance.

The maximum radius r_m attained by nonresonant ions differing in mass by the amount ΔM from the resonant ions of mass M can be obtained from Eqs. (1) and (2) and is given by

$$r_m=2MR_0/(n\pi\Delta M).$$

For a fractional mass separation of only 1/1100 and for $n=7000$ revolutions, $r_m=R_0/10$. Thus, the non-resonant ions remain very near the center.

The total length of path L of the resonant ions can be determined by resolving the rf field into two rotating components each of which has half the applied amplitude. Since the ions obtain their final energy V from that component which always acts in the direction of motion, it follows that $L=V/(\frac{1}{2}E_0)$. From this equation, it can be shown that

$$L=n\pi R_0.$$

Although the rf voltage applied to the omegatron is only a fraction of a volt, the final energy of the ions is relatively large. For example, the H^+ ion attains a final energy of about 1000 ev in a magnetic field of 4700 gauss for $R_0=1$ cm. For a resolution of 10,000 the rf field as calculated from Eq. (4) is $E_0=0.1$ volt/cm. At resonance, the time required for the ions to reach the collector as obtained from Eq. (2) is one millisecond; and since the frequency $\omega_c/2\pi$ is about 7 Mc, the ions make about 7000 revolutions before reaching the collector with a total path length of 220 meters. Since the radius increases linearly with the number of revolutions, the increment per cycle is R_0/n or approximately 1.4 microns. The optimum trapping voltage has been found to be of the order of 0.1 volt.

Equation (4) indicates that for constant B the resolution varies inversely with the mass; but if E_0 is decreased as the mass is increased in such a manner that the number of revolutions remains the same, then the resolution will be constant. This, however, requires that the ions of higher mass be trapped longer, and the maximum length of time that the ions can be trapped imposes a limit on the attainable resolution.

Experimental Arrangement

The original omegatron shown in Fig. 2 consists of two 3×5 cm parallel plates (rf plates), two centimeters apart, with eight parallel guard rings of the same outer dimensions equally spaced between the plates. A tungsten filament 0.007 cm in diameter produces the electrons which are collimated by the 0.05-cm aperture in the draw-out electrode. The accelerated electron beam passes midway between the rf plates and falls on an electron collector which is used to monitor the beam current. An ion collector, inserted through a slot in one of the rf plates, is used to measure the resonant ion current. The whole assembly, including the voltage divider for the guard rings, is enclosed in a glass tube 4.7 cm in diameter.

The omegatron and the entire vacuum system as well as the electrometer tube are mounted so that they can be easily removed from the magnet gap. Thus, the magnetic field in the space normally occupied by the omegatron can be readily measured by inserting a nuclear resonance probe. The magnet, nuclear resonance regulator, and nuclear resonance probe used with the omegatron have already been described[9] in connection with the measurement of the gyromagnetic ratio of the proton.

The resonance peak can be scanned by varying the frequency or the magnetic field. For high resolution operation, it is convenient to use a crystal controlled oscillator and to scan by varying the magnetic field. In order to scan magnetically, a small pair of Helmholtz coils is mounted on either side of the regulator probe. A small current through these coils tends to change the field at the sample, but the regulator action changes the main field to keep the net field at the sample constant. Thus, the field can be shifted very smoothly and precisely over a range of $\pm 1/5000$.

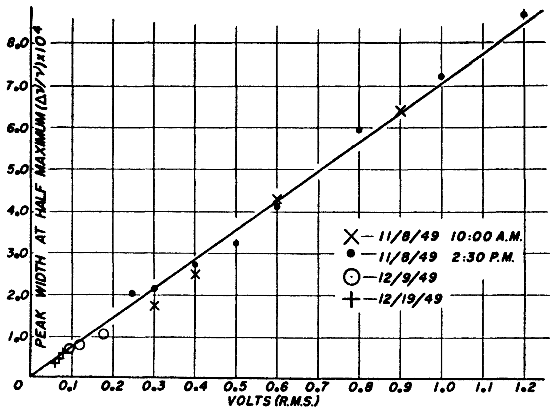

FIG. 3. Variation of resolution with rf voltage.

Performance

There are relatively few adjustments to make in operating the omegatron. The electron accelerating voltage is normally held fixed at 67.5 volts. The electron beam current is controlled by a simple regulator circuit similar to the one described by Winn and Nier.[10] In general, the trapping voltage and electron current are adjusted for maximum peak height as the rf voltage is decreased in magnitude while operating at fixed pressure. Highest available resolution is attained when minimum convenient peak height is reached. Figure 3 shows the variation of resolution with rf voltage. A normal working peak usually corresponds to an ion current of about 3×10^{-14} amp whereas electrometer fluctuations are about 4×10^{-16} amp. A high resolution peak is shown in Fig. 4.

The operating pressure as indicated on the ionization gauge located on the pumping arm was usually of the order of 10^{-7} to 10^{-6} mm Hg; however, several measurements of H^+ and H_2O^+ were made at an indicated background pressure of 3×10^{-8} mm Hg, the best attainable vacuum. The omegatron is extremely sensitive; and, by sacrificing resolution, virtually all the resonant ions produced can be collected. This is indicated by the fact that the ion current does not increase indefinitely as the rf voltage is increased and flat-topped peaks are obtained.

Although nearly all measurements with the omegatron up to the present time have been made with the very light masses, the spectrum up to mass 100 has been roughly scanned on several occasions. In particular, measurements at higher masses have been restricted to a few checks at mass 28, where a maximum resolution of 5000 was obtained.

PART II. APPLICATION TO THE MEASUREMENT OF ATOMIC CONSTANTS

The accurate measurement of the cyclotron resonant frequency of the proton has importance in the field of atomic constants as summarized briefly in the introduction. One of the major problems involved in this application of the omegatron is the displacement of resonance from the true cyclotron frequency.

Frequency Shifts

The observed cyclotron resonance in the omegatron differs from the simple relation, $\omega_c = eB/M$, because of radial electrostatic fields within the tube. These radial fields originate from at least two sources, not altogether independent—from the applied trapping voltage, and from any space charge within the omegatron. Particularly, for the measurement of e/M in absolute units, it is necessary to determine the magnitude of this shift in the resonant frequency

If a radial electric field $E(r)$ is superimposed on an axial magnetic field, then the equation of motion is

$$M\omega^2 r + eE(r) = \omega reB.$$

Thus, we can write

$$\omega \doteq \omega_c\left[1 - \frac{E(r)M}{reB^2}\right]. \tag{7}$$

An approximate analysis of the electric field in the omegatron due to the trapping voltage shows that this field increases linearly with r. It follows from Eq. (7)

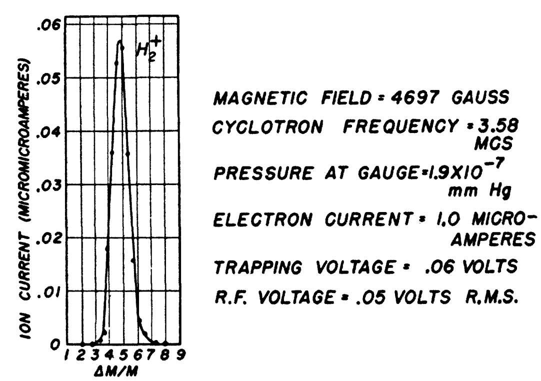

FIG. 4. The H_2^+ peak with a resolution of approximately 1 in 35,000 at half-maximum.

[9] Thomas, Driscoll, and Hipple, J. Research Natl. Bur. Standards **44**, 569 (1950), RP 2104.

[10] E. B. Winn and A. O. Nier, Rev. Sci. Instr. **20**, 773 (1949).

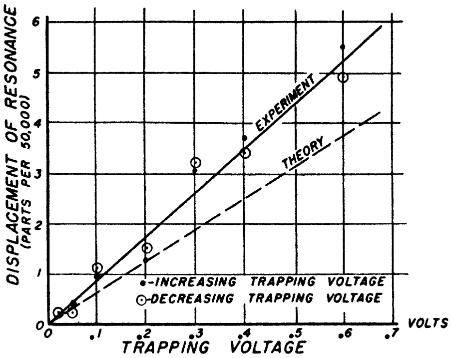

FIG. 5. Effect of trapping voltage on resonant frequency. The trapping voltage normally used is approximately 0.1 volt.

that the shift in resonance is independent of r. This shift has a theoretical magnitude of 1/80,000 per 0.1 volt of trapping voltage. As Fig. 5 shows, experimental investigation shows this effect to be 1/50,000, the additional shift presumably being due to space charge.

Although the shift in resonance could be calculated from the trapping voltage using a constant of proportionality as determined from the slope in Fig. 5, this constant would be a function of space charge condition, and furthermore there would be the difficulty of determining when actual zero trapping voltage exists. A more satisfactory technique has been developed for determining the frequency shift for each measurement.

As Eq. (7) shows, the frequency shift is proportional to the mass. Thus, if resonance is observed at frequency $\nu^{(1)}$ for the proton whose isotopic weight is A_1, and in quick succession under the same operating conditions, resonance is observed at frequency $\nu^{(m)}$ for an ion whose isotopic weight is A_m, then it follows that

$$\nu^{(1)} = \nu_c^{(1)} - A_1 K \nu_c^{(1)}, \tag{8}$$

$$\nu^{(m)} = \nu_c^{(m)} - A_m K \nu_c^{(m)}, \tag{9}$$

where ν_c is the true cyclotron resonant frequency and K is the shift factor determined by the particular operating conditions. A third equation is obtained from the ratios of the true cyclotron frequencies

$$\frac{\nu_c^{(1)}}{\nu_c^{(m)}} = \frac{A_m}{A_1}. \tag{10}$$

These three equations can be used to determine $\nu_c^{(1)}$ given $\nu^{(1)}$ and $\nu^{(m)}$ and the isotopic weights which are known accurately. The correction factor K can be derived from (8) and (9):

$$K = \frac{A_m \nu^{(m)} - A_1 \nu^{(1)}}{A_1 A_m [\nu^{(m)} - \nu^{(1)}]}. \tag{11}$$

Then $\nu_c^{(1)}$ can be obtained by rewriting (8) as

$$\nu_c^{(1)} = \frac{\nu^{(1)}}{1 - A_1 K}. \tag{12}$$

This method of correction has been used with measurements made on the three pairs H^+ and H_2^+, H^+ and D_2^+, and H^+ and H_2O^+. As shown in Fig. 6, the correction factors as calculated from either H^+ and H_2^+ or from H^+ and D_2^+ result in values of the ratio of the spin precessional frequency of the proton ν_n to its cyclotron resonant frequency ν_c that agree well within the average deviation of either. The agreement of the correction factors determined from additional measurements made on the trio of masses H^+, H_2^+, and D_2^+ gave added confidence in this method of determining the frequency correction. The effect of space charge on the correction factor was clearly demonstrated in one particular case when a negative pulse was applied to the trapping voltage to sweep out the positive space charge. Under these conditions the sign of the correction factor was reversed, apparently the result of negative space charge. Nevertheless, the corrected value of ν_n/ν_c agreed with the average of the other values.

Measurement of ν_n/ν_c

Because of the frequency shift, each measurement of the ratio ν_n/ν_c for the proton requires the determination of the cyclotron frequency for ions of two different masses. The frequencies of the corresponding crystal oscillators were adjusted so that both cyclotron resonance peaks occurred at about the same magnetic field. The position of each peak was then determined by plotting peak height *versus* Helmholtz coil current, or by recording the coil current corresponding to 85 percent of maximum peak height on each side of the peak. Several sets of readings were usually made. The omegatron was then removed from the gap and replaced by a nuclear resonance probe using a water sample with adjusted relaxation time. (This water sample was subsequently checked against the standard oil sample

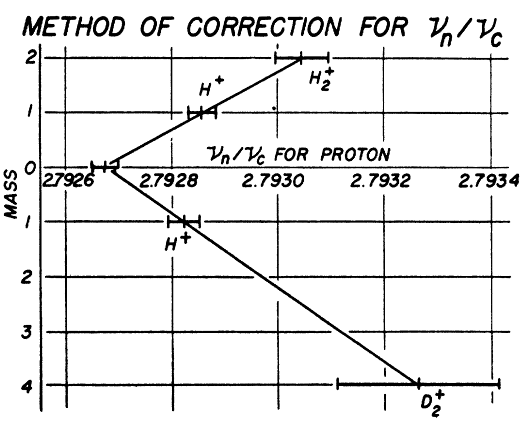

FIG. 6. Determination of the true value of ν_n/ν_c from H^+ and H_2^+ (top portion of figure) and from H^+ and D_2^+ (lower portion of figure). The uncorrected values of ν_n/ν_c for the proton as calculated from measurements on H^+, H_2^+, and D_2^+ are shown as well as the resultant value of ν_n/ν_c when pairs of measurements are combined to determine the correction factor. It is evident that measurements made with H^+ and H_2^+ or with H^+ and D_2^+ converge to the same corrected value of ν_n/ν_c.

used in determining the gyromagnetic ratio.) The coil current necessary to produce nuclear resonance at a frequency ν_n was recorded. The observed cyclotron oscillator frequencies were then reduced to the value corresponding to this coil current. These frequencies $\nu^{(1)}$ and $\nu^{(m)}$ were then substituted into Eqs. (11) and (12) to obtain K and $\nu_c^{(1)}$. The calibration of the Helmholtz coils was not critical, since the oscillator frequencies were initially adjusted to produce resonance near the magnetic field corresponding to ν_n.

The frequencies of the crystal oscillators were measured by using a signal calibrator which was standardized against the standard frequency transmissions of station WWV. This signal calibrator produced reference frequencies throughout the frequency spectrum. The crystal oscillators were usually adjusted so that the beat produced with one of the reference frequencies was some harmonic of the 440 cps or 600 cps modulation of WWV so that direct comparison could be made on an oscilloscope.

The results of measurements made in July and August 1950 are tabulated in Table I. These measurements were made under considerably varied operating conditions and with resolutions between 5000 and 10,000 (resolution measured at approximately 5 percent of maximum peak height). All measurements were made with the guard rings grounded for rf. The value of K was usually of the order of 6 parts per 100,000. If some measurements extending back to February, 1950, are included, there is no appreciable change in the value of ν_n/ν_c although these earlier runs were made at lower resolution and with less favorable techniques.

Suspected sources of systematic errors were checked whenever possible. The magnetic effect of the filament current was determined by reversing the current between several of the measurements. The net result indicated that the error from this source is less than 5 parts per million. The magnetic shielding effect due to the electrodes (55 Cu–45 Ni) was checked at the conclusion of this series of runs by carefully removing the rf electrode and replacing it after a proton resonance sample was placed within the omegatron. It was found that the field within the omegatron was the same as the field in the magnet gap with the omegatron removed to within 2 parts in a million. There remains a slight asymmetry in the cyclotron resonance peak whose meaning is still undetermined. However, we feel that the ratio of ν_n/ν_c lies within the range

$$\nu_n/\nu_c = 2.79268_5 \pm 0.00006,$$

where ν_n is the observed nuclear resonance frequency in the standard oil sample. The assigned error is several times the estimated probable error.

Proton Moment

The experimentally determined ratio ν_n/ν_c is the uncorrected value of the proton moment in nuclear magnetons.[8] Since the total diamagnetic correction for

TABLE I. Summary of data.

Basis	No. of values	ν_n/ν_c	Av. dev.
Mass 1 and Mass 2	20	2.792684	$\pm 27\times 10^{-6}$
Mass 1 and Mass 4	18	2.792682	$\pm 22\times 10^{-6}$
Mass 1 and Mass 18	7	2.792701	$\pm 9\times 10^{-6}$
Average	45	2.792685	$\pm 25\times 10^{-6}$

our standard oil sample as reported by Thomas[11] is 28.1 parts per million, the resultant value of the proton moment in nuclear magnetons is

$$\mu_p = 2.79276 \pm 0.00006.$$

Thomas used the magnetic shielding constant for H_2 calculated by Ramsey[12] in obtaining the above diamagnetic correction. If the more recent value reported by Newell[13] is used, the value of the proton moment as reported is unchanged. Using the value given by Hylleraas and Skavlem,[14] the proton moment becomes $\mu_p = 2.79277 \pm 0.00006$. Bloch and Jeffries[15] have recently reported a value of the proton moment using an inverted cyclotron. If we apply a diamagnetic correction of 28.1 parts per million, their value becomes

$$\mu_p = 2.79252 \pm 0.0002.$$

Specific Charge of the Proton

The charge-to-mass ratio of the proton is given by the relation,

$$e/M_p = \gamma_p(\nu_c/\nu_n).$$

Taking into consideration the errors associated with ν_n/ν_c and with γ_p, the gyromagnetic ratio without diamagnetic correction,[12] the result is

$$e/M_p = 9579.4_2 \pm 0.3 \text{ emu/g}.$$

Faraday

The faraday can be calculated from e/M_p and the isotopic weight of the proton A_1 using the formula

$$F = A_1(e/M_p) = A_1\gamma_p(\nu_c/\nu_n),$$
$$F = 9652.0_3 \pm 0.3 \text{ emu/g (physical scale)}.$$

Craig and Hoffman[16] have recently reported the value $F = 9651.93$ with an average deviation of 0.26 using the electrochemical method with sodium oxalate.

Ratio of the Proton Mass to the Electron Mass

If the value of ν_n/ν_c for the proton is multiplied by the ratio of the cyclotron frequency of the electron to the precessional frequency of the proton as measured by Gardner and Purcell[4] (both ratios without diamagnetic correction), M_p/m_e can be calculated.

$$M_p/m_e = 1836.12 \pm 0.05.$$

[11] H. A. Thomas, Phys. Rev. **80**, 901 (1950).
[12] N. F. Ramsey, Phys. Rev. **78**, 699 (1950).
[13] G. F. Newell, Phys. Rev. **80**, 476 (1950).
[14] E. Hylleraas and S. Skavlem, Phys. Rev. **79**, 117 (1950).
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[16] D. N. Craig and J. I. Hoffman, Phys. Rev. **80**, 487 (1950).

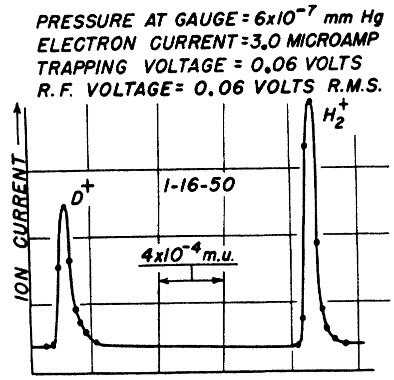

FIG. 7. H_2-D doublet.

PART III. APPLICATIONS IN MASS SPECTROSCOPY

Mass Measurement

One of the most important applications of the omegatron should be in the field of precise mass measurement. Even at this early stage in the development, the omegatron has sufficient resolution for precise measurements at the low masses, and it should be possible to construct an omegatron capable of significant measurements at higher masses. In addition, the omegatron has the advantage of high sensitivity and the measurements can be made in terms of frequency. The shift in resonance due to the trapping field should be relatively unimportant in doublet mass spectroscopy, although space charge conditions may produce some difficulties.

Preliminary measurements of the (H_2-D) doublet have been made. A typical doublet is shown in Fig. 7. Measurements over a period of several days have shown a deviation of less than 1 part per million, although on occasion shifts of several times this amount have been observed. The resultant tentative value is $(15.45\pm0.08)\times10^{-4}$ amu Roberts and Nier[17] have recently reported 15.49×10^{-4} with a somewhat smaller error.

Analytical Applications

Although no effort has been made in this laboratory to develop the omegatron as an analytical instrument, its simplicity and high sensitivity indicate considerable promise in this field. The absence of slits defining the ion beam and the wide choice of travel time suggest the desirability of using the omegatron in studying several aspects of ionization and dissociation of molecules by electron impact.

Although the mass spectrum can be scanned by changing either the frequency or the magnetic field, the latter method seems most advantageous. It can be shown from Eq. (4) that by scanning magnetically ΔM remains constant. This is a definite advantage when a recorder is used, since the width of the recorded peaks remains constant. Thus, the instrument can be set for maximum scanning rate over the entire mass range, and a linear mass scale will be recorded if the magnetic field is made to vary linearly with time.

Variations

Modifications in the original omegatron would undoubtedly improve the performance and eliminate some of the shortcomings reported in this paper. For certain low resolution applications, the design could probably be simplified. Detection by magnetic resonance absorption[18] eliminates the ion collector and associated electrometer.

In order to increase resolution, it is necessary either to increase the number of revolutions or to determine more critically a change in phase of the circulating ions. The number of revolutions corresponding to a minimum detectable ion current may be increased by increasing the magnetic field, by increasing the sensitivity of the detector, or by increasing the trapping efficiency.

In the omegatron with uniform field, the resolution is determined by the number of revolutions required for the ions to get 90° out of phase with the applied voltage. If sensitivity to this phase difference could be increased, the resolution would be improved for the same number cycles. This principle was first applied by Bloch[6] to an "inverted" cyclotron in which harmonics of the resonant frequency are used. The same effect has been obtained in this laboratory with a small cyclotron, using either harmonics or pulses. The idea might be adapted to the omegatron by applying to closely spaced electrodes a sharp pulse which affects only the outer orbits. Although this has been attempted, no significant success has been attained.

Several methods of reducing space charge have been tried and are being considered further. The most direct approach is to pulse periodically the trapping voltage in such a manner that the positive space charge is swept out. However, this results in a decrease in the collected resonant ion current. A more elaborate technique employs a dc bias between the rf plates. This voltage should cause the nonresonant ions to "walk" or drift out of the analyzer region continuously, while the resonant ions attain sufficient radius to strike a displaced collector before drifting out of the analyzer region.

Other variations have been suggested but not critically examined as yet. However, it is probable that the omegatron or some of its variations will find applications in various fields.

Acknowledgment

The authors are indebted to Dr. E. U. Condon for the analysis of the frequency shift due to a radial electric field, to Dr. F. P. Phelps and his associates for the preparation of quartz crystals, to the members of the Bureau Tube Laboratory for the construction of a modified omegatron, and to Dr. R. D. Huntoon for his helpful suggestions.

[17] T. R. Roberts and A. O. Nier Phys. Rev. 77, 746 (1950).

[18] H. Sommer and H. A. Thomas, Phys. Rev. 78, 806 (1950).