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Method for Eliminating Omegatron Radial Field Errors or for Direct Measurement of Mass Ratios*

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An omegatron having two pairs of ion-accelerating plates instead of one and using resonance absorption detection has been used successfully to obtain simultaneous cyclotron resonances of two different ion species in the same field. When used in conjunction with a nuclear resonance probe, the method effectively eliminates errors due to perturbing radial electric fields in the omegatron; alternatively, if radial electric fields are considered negligible, the method permits the direct measurement of mass ratios.

I. INTRODUCTION

A COMPACT mass spectrometer utilizing cyclotron resonance for mass separation was first successfully employed by Sommer, Thomas, and Hipple[1,2] for the precise measurement of the faraday. The instrument, referred to by them as the omegatron, provides for the trapping of positive ions formed along an axis in a uniform magnetic field parallel to that axis. Lateral drift of the ions is prevented by the magnetic field itself and axial drift by an electric field whose potential over any plane through the axis is saddle-shaped with minimum curves corresponding to lines parallel to the axis. An rf electric field of angular frequency ω_0 transverse to the magnetic field affects the ion orbits appreciably only when the cyclotron angular frequency $\omega = eB/m$ is in the neighborhood of ω_0. At resonance, $\omega=\omega_0$, the ion orbits expand continuously, and the ions may be collected at a suitably placed electrode; or this resonance condition may be determined by the absorption of power from the rf electric field.[3]

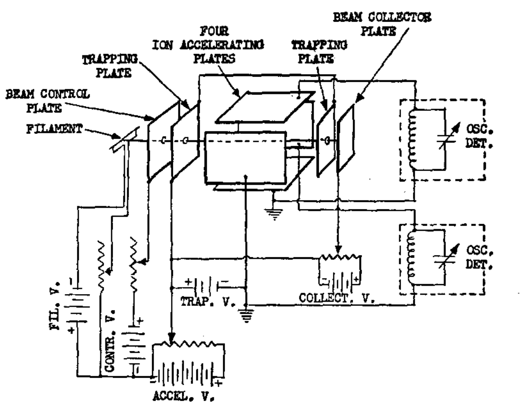

Fig. 1. Arrangement of the omegatron electrodes and the electrical connections to them.

In contrast to the conventional mass spectrometers, in the omegatron the ions must be produced in the analyzing region. This has necessitated the presence of an ionizing electron beam along the axis of the magnetic field; and this, in turn, gives rise to a radial electric field which perturbs the cyclotron frequency. More serious, perhaps, is the necessity for the presence of a radial component of the trapping field. It occurred to the authors that these fields could be measured and thus effectively eliminated if the perturbed cyclotron frequencies of two different ions could be simultaneously measured in the same magnetic and electric field. This paper describes the instrument which has proved capable of accomplishing this.

II. PRINCIPLE OF OPERATION OF THE FOUR PLATE OMEGATRON

The two different ion species, created by bombardment by electrons from a tungsten filament, are accelerated by separate pairs of electrodes arranged as the four sides of a box as indicated in Fig. 1. These plates are dc ground potential and two "trapping" plates forming the top and bottom of the box are maintained at a small positive potential relative to these. The ions execute helical paths as they move back and forth along the axis of the magnetic field. Each pair of electrodes forms a part of the capacitance of the resonant circuit of an oscillator. Resonance is detected as a drop in the level of operation of the oscillator caused by the absorption of energy in the condenser by the expansion of the orbits of the cycling ions.

The equation of motion yields the two resonance conditions

$$\omega_1{}^2 = \frac{e_1}{m_1}B\omega_1 - \frac{e_1}{m_1}\frac{E}{r},$$

$$\omega_2{}^2 = \frac{e_2}{m_2}B\omega_2 - \frac{e_2}{m_2}\frac{E}{r},$$

where

$e_1/m_1, e_2/m_2$ = specific charge of ions of type 1 and 2, respectively,

B = magnitude of the axial magnetic field,

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[1] Hipple, Sommer, and Thomas, Phys. Rev. **76**, 1877 (1949).
[2] Sommer, Thomas, and Hipple, Phys. Rev. **82**, 697 (1951).
[3] H. Sommer and H. A. Thomas, Phys. Rev. **78**, 806 (1950).

ω_1, ω_2 = angular frequencies of the cycling ions,
E/r = ratio of the radial component of the perturbing electric fields to the radius of the orbit of the cycling ion.

For certain conditions of operation E turns out to be roughly proportional to r so E/r is independent of r. Since the term involving E/r is small, the quadratics may be solved approximately to give

$$\omega_1 = \frac{e_1 B}{m_1} - \frac{E}{Br}$$

$$\omega_2 = \frac{e_2 B}{m_2} - \frac{E}{Br}.$$

Subtraction and division by B yields the result

$$\frac{e_1}{m_1} - \frac{e_2}{m_2} = \frac{\omega_1 - \omega_2}{B}.$$

Use of a nuclear resonance probe permits the elimination of B according to the relation $\omega_p = \gamma \cdot B$ where ω_p is the angular frequency of gyration of the proton in the field B and γ is the gyromagnetic ratio. The result is

$$\frac{(e_1/m_1) - (e_2/m_2)}{\gamma} = \frac{\omega_1 - \omega_2}{\omega_p},$$

which gives the difference of the specific charges of the ions in terms of the gyromagnetic ratio of the proton.

III. NATURE OF THE RESONANCES

An analysis of the ion trajectories[4] enables one to compute the resonance shape and hence the resolution that may be expected when resonance absorption detection is used.

In the neighborhood of resonance, if the effect of the initial velocities is neglected, the radius vector to the ion, $x+iy$ in complex notation, may be shown to be approximately

$$x+iy = \{i\alpha/[(2\omega_0+\epsilon)\epsilon]\}(1-e^{-i\epsilon(t-\phi/\omega_0)})e^{-i\omega_0 t},$$

where $\alpha = eE/m$, E here having the peak amplitude of the rf electric field; ω_0 = angular freq of the rf electric field; $\epsilon = \omega - \omega_0$; and ϕ = phase angle relating time of creation of the ion to the phase of the rf electric field. From this one obtains for the time rate of change of the kinetic energy, T, of the cycling ion

$$\frac{dT}{dt} = \frac{\alpha^2 m}{4\epsilon} \sin\epsilon(t - \phi/\omega_0).$$

This expression applies between $t_1 = \phi/\omega_0$ when the ion is created and t_2, the time when the ion makes a collision and is removed from the beam. It is necessary to add up the effect of ions being continuously created and removed from the beam at random phases. If it is assumed that the rate of creation is a constant and as many are destroyed at time t_2 as are created at time t_1, then at any time t the ions contributing to the power are those having phases in the range $\omega_0 t - \psi \leqslant \phi \leqslant \omega_0 t$ where $\psi \approx \omega_0 \tau$, τ being the mean free time for the ion in question.

Hence,

$$\frac{dT}{dt} = \frac{\alpha^2 m}{4\epsilon} \int_{\omega_0 t-\psi}^{\omega_0 t} \sin\epsilon(t-\phi/\omega_0) N d\phi = N\frac{\alpha^2 m \psi^2}{8\omega_0} \frac{\sin^2 u}{u^2},$$

where N is the total number of ions present at any instant and $u = \epsilon\psi/2\omega_0$. From this it is evident that the half power width is approximately

$$\Delta\epsilon \cong 2.8/\tau.$$

The inverse proportionality of $\Delta\epsilon$ to the mean free time is expected but its independence of any other parameter is somewhat surprising and has implications as to the design of the omegatron.

If the rate of creation of the ions shows fluctuations, it can be shown that the resonance curves will show fluctuations along the frequency axis. Difficulties were encountered in precision frequency measurements due to this effect.

IV. EXPERIMENTAL ARRANGEMENT

The two pairs of ion-accelerating plates (1.7×2.1 cm) were arranged as the four sides of a box symmetrically about a thin collimated beam of electrons emitted by a filament consisting of a single strand of 0.007-cm diam tungsten wire. The radius from the electron beam to the ion-accelerating plates was one centimeter. Collimation of the electron beam was achieved by means of a 0.05-cm hole in the electron beam control plate. Electrons in this beam collided with gas molecules to provide a source of ions at the central axis of the omegatron analyzing region. The metal plates of the omegatron were assembled on mica support plates, and these support plates were used to mount the omegatron on the lid of the containing brass case. The electrical connections to the omegatron and nuclear probe were made through Kovar-to-glass terminal seals mounted on tubular extensions so as to keep the seals out of the magnetic field. The nuclear probe consisted of six turns of No. 12 B & S bare copper wire space wound around a $\frac{3}{8}$-in. diam sealed glass tube containing water. Potentials were applied to the electrodes of the omegatron in the manner shown in Fig. 1.

The measuring technique can be understood by reference to the block diagram of Fig. 2. The magnet, constructed at Brigham Young University, had a two inch air gap between the eight inch diameter pole faces. Helmholtz coils, energized from the 60-cy power line

[4] See, for example, C. E. Berry, J. Appl. Phys. 25, 28 (1954).

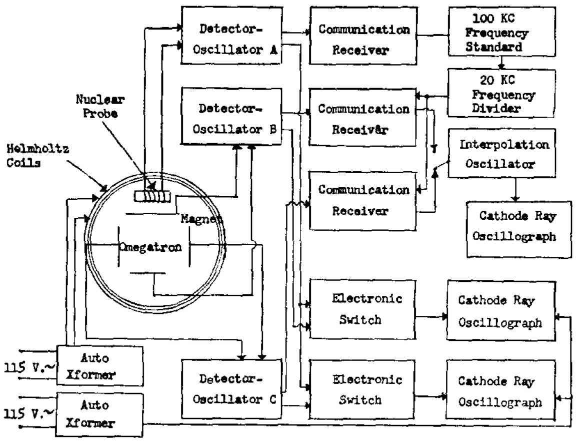

FIG. 2. Block diagram showing the connections to the accelerating and frequency measuring apparatus.

through an auto-transformer, were wound around the ends of both poles of the magnet to provide a means of sweeping the field. The magnet was connected to a bank of storage batteries in series with a resistance, continuous variation of which was achieved by rotating the winding under a contact that was forced to follow the turns by a spring-loaded key engaging the turns. Oscillator-detector A, manufactured by Laboratory for Electronics, Inc., was used with the nuclear resonance probe to obtain the nuclear magnetic resonance frequency of the proton.[5] The output of this oscillator-detector at resonance was fed through two electronic switches to two cathode ray oscillographs. By this means, and by suitable adjustment of the controls of the electronic switches and oscillographs, the one nuclear resonance signal was displayed on both oscillograph screens. This nuclear resonance signal was then used as a reference for the two cyclotron resonance signals, one of which was fed from oscillator-detector B to one oscillograph and the other from oscillator-detector C to the other oscillograph. The cyclotron resonance oscillator-detectors B and C were an adaptation of the circuit for oscillator-detector A. In order to obtain the high tank circuit Q necessary for satisfactory cyclotron resonance signals, the tank coils of these oscillators were made three inches in diameter and larger. A pair of omegatron ion-accelerating plates was connected across each tank coil, thus becoming part of the tank circuit being a capacitor of approximately 50 $\mu\mu$f across the tuning capacitor.

TABLE I. Proton *vs* hydrogen molecule ion signals for 32 v trapping voltage.

f_1	f_2	f(Proton uncorrected)
3700 kc+3663 cy	7460 kc+5496 cy	21 Mc
3700 +3290	7460 +4768	21
3700 +2538	7460 +4672	21
3700 + 273	7460 +2200	21
Average 3702.441 kc	Average 7464.284 kc	21

Electrode Voltages and Currents

Trapping volts	32	Filament current	0.94 amp
Control plate volts	137	Emission current	0.3 ma
Accelerating plate volts	157	Electron beam	45 μa
Collector plate volts	93		

See Fig. 1 for the reference points involved in the voltage readings.

[5] Bloembergen, Purcell, and Pound, Phys. Rev. **73**, 679 (1948).

The frequency of the nuclear resonance signal was determined by zero beating it in a radio receiver against a known harmonic from a 100-kc standard frequency oscillator. Each cyclotron resonance signal was beat against a known 20-kc marker frequency, and the difference frequency was measured by means of an interpolation oscillator. These three resonant frequencies were measured while the two cyclotron resonance signals displayed on the two oscillograph screens were each held in line with the nuclear resonance signal. After a series of measurements was made the omegatron was removed and the nuclear resonance probe was moved back and forth between its original position and the omegatron position a number of times to determine the nuclear resonance frequency in the same region of the magnetic field in which the cyclotron resonance had occurred.

TABLE II. Proton *vs* hydrogen molecule ion signals for 50 v trapping voltage.

f_1	f_2	f_{Proton} (uncorrected)
3660 kc−5060 cy	7420 kc−1380 cy	21 Mc
3660 −5018	7420 −2200	21
3660 −5300	7420 −1848	21
3660 −5216	7420 −2092	21
Average 3654.852 kc	Average 7418.120 kc	21

Electrode voltages and currents

Trapping volts	50	Filament current	0.95 amp
Control plate volts	137	Emission current	0.35 ma
Accelerating plate volts	157	Electron beam	60 μa
Collector plate volts	93		

See Fig. 1 for the reference points involved in the voltage readings.

The effectiveness of the method in eliminating systematic error due to perturbing radial electric fields depends upon the magnitude of these fields since the linear dependence of E on r assumed above is only approximate. For precision measurements, the trapping voltage and electron beam current density should both be kept as small as possible. Good signals are obtainable with trapping voltages less than one volt and electron beam currents of the order of a microampere. However, even for very large values of these parameters, reasonable precision is obtainable as is illustrated by the data in Tables I, II, and III. For trapping voltages of 32 v and 50 v the computed values of $(f_2-f_1)/f_p$ are 0.179108 ± 0.000011 and 0.179176 ± 0.000016, respectively. Figures following the $\pm$ signs are standard deviations. As was noted in Part II, to the extent that second-order terms in the radial electric fields may be neglected, this yields the difference of the specific charges of the hydrogen molecule and the proton in units of the proton gyromagnetic ratio, $[(e_2/m_2)-(e_1/m_1)]/\gamma$. If these are compared with the value 0.179083 ± 0.000018 computed from Dumond and Cohen constants, a systematic trend toward larger values for higher trapping voltages will be noted. This trend is in the direction and roughly of the order of magnitude that would be expected from the equations of motion. In general, it would be expected that trapping voltages above a few volts would not be necessary. Values of precision measurements made for the lower trapping voltages and smaller beam currents will be published when available.

TABLE III. Nuclear resonance frequency shift when the probe is moved to omegatron position.

Frequency before moving	Frequency shift
21 Mc	3100 cy
21	3112
21	3400
	Average shift 3204
Corrected value of $f_p = 21003.2$ kc	

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Balloon-Borne System for Tracking the Sun

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A balloon-borne system for tracking the sun both in elevation and azimuth is described. The system weighs approximately 125 lb and is capable of "pointing" as much as 20 lb of payload at a predetermined position in the sky. Power requirements are 20 w. An accuracy in pointing of ±15 min of arc has been achieved. At some sacrifice in simplicity, this accuracy could perhaps be improved to ±5 min. Results of two flights, each attaining an altitude in excess of 100 000 ft, are given.

INTRODUCTION

WITH the recent development of large plastic balloons, the region of the atmosphere up to at least 100 000 feet has become accessible to direct investigation by scientific instrumentation. In this article a balloon-borne pointing control for use in tracking the sun will be described and results of two successful balloon flights given. The original experimental model was developed by the University of Denver.[1]

The objective was to design a sun tracker to be carried aloft by balloons which would be capable of correcting for the changes in azimuth and elevation brought about by the balloon's motion due to varying wind velocities in the atmosphere. In addition the tracker had to be relatively light in weight (less than 200 lb) and capable of maintaining a high degree of reliability under the rigors of field use and high altitude flight.

In principle, the tracker consists of two movable platforms (azimuth and elevation) coupled to a "fixed" base, as shown in Fig. 1. Electrical signals are transmitted between the "fixed" base and movable platforms through a suitable slip ring arrangement. By means of optical and electronic systems, a platform can be made to seek the sun and orient itself at a predetermined angle with respect to the sun.

The pointing control in its present form weighs approximately 125 lb and is capable of orienting a 20-lb platform within an accuracy of ±15 min of arc. With some sacrifice of simplicity, accuracies of ±5 min of arc are possible under balloon flight conditions.

During daytime flights, the equipment is protected against the extreme cold of the atmosphere by means of Cellophane or plastic covering which produces a greenhouse effect.

METHOD OF OPERATION

The biaxial pointing control has two modes of operation, one for fine control, the other for coarse control. When the pointer is within 3 degrees of the sun, the fine control is operative. When the sunlight no longer falls on the photocells of the fine control system, the coarse control is operative and the pointer is made to

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[1] Byron E. Cohn, University of Denver, Final Report, Contract AF19(604)-224 with Air Force Cambridge Research Center, Geophysics Research Directorate, L. G. Hanscom Field, Bedford, Massachusetts.