ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

PROGRESS REPORT

UNIVERSITY OF MICHIGAN SYNCHROTRON PROJECT

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Project 1922

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ABSTRACT

The report describes the results of experiments on the properties of fast electrons and their interactions with nuclei, and the results of work on the theory and operation of the synchrotron accelerator. In regard to the studies of electrons, four distinct lines of attack are described: (1) the elastic scattering of electrons on heavy nuclei, (2) the inelastic scattering of electrons on light nuclei, (3) the measurement of the gyromagnetic ratio of the free electron, and (4) the measurement of the polarization of electrons through scattering on nuclei. In regard to the studies of the synchrotron itself, all the work reported was directed toward the problem of obtaining higher beam intensity. Specifically, the work included: (1) the redesign and improvement of the injector gun and high-voltage pulse transformer, (2) the measurement of the betatron and synchrotron oscillation frequencies of the beam, (3) measurements of the effects of eddy-current fields, (4) experiments on the relation between the rate of rise of the magnetic field and the efficiency of injection, (5) experiments on the use of brief betatron acceleration at injection, and (6) tests of circuits for slowing the rise of the magnetic field at injection.

OBJECTIVE

Several problems are under investigation under this contract:

1. The elastic scattering of electrons, 30 to 100 Mev, against heavy and medium nuclei. From precise measurements of the angle versus intensity of scattering information bearing upon the radius and distribution of the charge in the nucleus is obtained. This work has been under way for the past 3 years and will be continued in the coming year.

2. Inelastic scattering of 70-Mev electrons by light nuclei. The apparatus for this experiment includes a new 1-meter radius, double-focusing magnetic analyser of 1% energy resolution. Measurements of the energy loss by electrons in scattering will give information on the levels and structure of nuclei.

3. A precision measurement of the gyromagnetic ratio of the electron. The first phase of this experiment, completed in 1953, gave the value of g to ± 1/2% accuracy. The goal in the improved experiment now nearly ready is .001% accuracy. The electron energy is 100 Kev; only auxiliary equipment of the synchrotron is used.

4. An extension of the measurements of electron polarization by scattering to large angles.

5. Machine research and development. Several experiments directed toward obtaining higher intensity in the small-aperture, race-track-type machine are in process. These are studies of the effect of rate of rise of magnetic field and of eddy-current fields upon the efficiency of injection, experiments on methods of slowing the rise of magnetic field at injection, and experiments with brief (100-microsecond) betatron acceleration at the time of injection.

UNIVERSITY OF MICHIGAN SYNCHROTRON PROJECT

During the past year, six lines of research were carried on as follows:

ELASTIC SCATTERING OF HIGH-ENERGY ELECTRONS BY NUCLEI

The principal research program conducted on the synchrotron project in 1954-1955 has been the determination of nuclear "size" by the method of high-energy electron scattering. Nuclear size effects in the electron-scattering cross section are important at the incident electron energies available in the synchrotron. The accessibility of the electron beam at the orbit straight sections makes this type of work possible with the race-track synchrotron. This project and the one at Stanford are the only ones we know to be pursuing this work.

After the discovery of the "small" electromagnetic radius of the nucleus by Lyman, Hanson, and Scott, which was subsequently confirmed by the Michigan and Stanford groups, there has developed a large theoretical interest in radius measurements. The theories have advanced to the point where it has become necessary to improve the experimental precision of radius measurements. There are three experimental approaches to the electromagnetic radius of the nucleus: (1) the optic spectra of mu-mesic atoms, (2) coulomb energy differences between mirror nuclei pairs, and (3) high-energy electron scattering. A good test of theoretical predictions requires that the precision of all three methods be as good as 1%, considerably better than any of the reported results. During the past year a series of electron-nuclear cross sections was measured at Michigan at different electron energies. The results of the measurements are summarized as follows. The nuclear radius, expressed by

$$R = r_o A^{1/3} 10^{-13} \text{ cm},$$

where A is the atomic number, is given by the following values of the coefficient, r_o, for heavy nuclei:

$r_o = 1.14 \pm .15$ measured at 31 Mev
$r_o = 1.19 \pm .09$ measured at 40 Mev
$r_o = 1.21 \pm .18$ measured at 60 Mev

These results are internally consistent, that is, energy independent, and they support the still higher energy measurements performed at Stanford. A report of this work is contained in a publication, "Electron Scattering on Tungsten at 31, 40, and 60 Mev," by R. W. Pidd and C. L. Hammer, Phys. Rev., Sept. 1, 1955 (in press).

Doctoral theses have been completed in this field by C. L. Hammer and E. C. Raka. Two more theses are in progress, on extensions of the measurements, by D. Naymik and P. D. Randolph. These new measurements should approach the desired 1% precision. One of the experiments will determine the ratio of radii of different nuclei with very high precision. The other experiment should improve the absolute radius measurements through the use of a new large-aperture analyser magnet which is complete and in operation.

INELASTIC SCATTERING OF ELECTRONS BY NUCLEI

New analyser magnets have been put into use for the purpose of resolving and detecting electrons which are scattered with energy loss due to nuclear excitation. High resolution is needed to exclude electrons which have lost energy in collision in other ways, mainly by bremsstrahlung. While no positive results have yet been obtained, the exploration which has been made is of some interest, since it establishes upper limits to the values of the cross sections at 60 Mev. The analysed elastic electron peak provides a reference for cross-section determinations. The background level, well below the elastic peak, determines the upper limit for the inelastic cross section. The elastic cross sections at 55 Mev and a scattering angle of 65° for Z = 4, 6, and 13, respectively, are 1×10^{-28} cm^2, 2.3×10^{-28} cm^2, and 20×10^{-28} cm^2. The upper limits on the inelastic cross sections for the first excited states in the same elements and at the same energy and angle are 3.6×10^{-30} cm^2, 6.9×10^{-30} cm^2, and 9.4×10^{-30} cm^2.

A new analyser system having a resolving power ten times better than the present system (1%) is being assembled for further exploration in this energy range. At the same time, detection apparatus is being tested which can measure directly the target radioactivity induced by electron impacts. The general subject of the study of nuclear properties through high-energy electron collisions is a promising one, and we plan to devote a considerable effort to this problem in the next contract year. One staff member, P. R. Chagnon, and a doctoral student, James Cline, are engaged in a number of exploratory experiments at this time.

EXPERIMENT ON THE GYROMAGNETIC MOMENT OF THE FREE ELECTRON

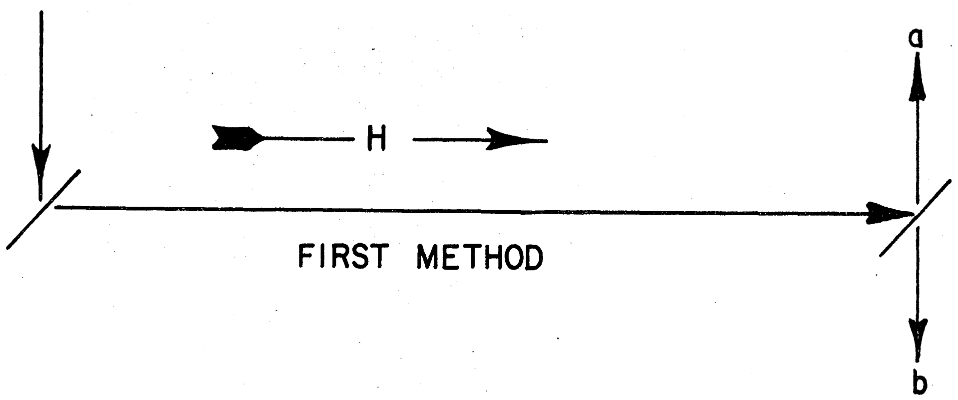
In 1952-53 we performed the first successful experiment on the measurement of the g-factor of the free electron. The apparatus used consisted, with the exception of a long air-core solenoid, of the existing synchrotron equipment. With the proof of the success of the method, and with the desire to push the precision to at least one part in 10,000 (which would put it in the range of significance for modern theory), we separated the experiment from the synchrotron apparatus and began setting it up in improved fashion in a different room. Preparation for the new experiment has been under way for about one year. The following paragraph will describe briefly the original and the new experimental methods, the new experimental setup, the present status of the work, and the plans for the future.

In principal, the method is an extension of the double-scattering experiment, as worked out theoretically by N. F. Mott in 1929. According to the Mott theory, if an electron beam is scattered at large angle, say 90°, by nuclei, the electrons will be slightly sorted as to spin orientation. Those scattered at +90° will have an excess of spins in one direction perpendicular to the plane of scattering and those at -90° will have an excess of spins in the opposite direction. A second 90° scattering of one of these scattered (and polarized) beams will therefore result in an intensity asymmetry. Under the best conditions (about 150 Kev and high atomic-number scatterer), the intensity asymmetry is small—about 10%. Attempts to show this asymmetry failed consistently for many years, but, beginning with the work of Shull, Chase, and Myers in 1943, positive results have been obtained. None of the experiments prior to our own were able to yield any quantitative measure of the g-factor.

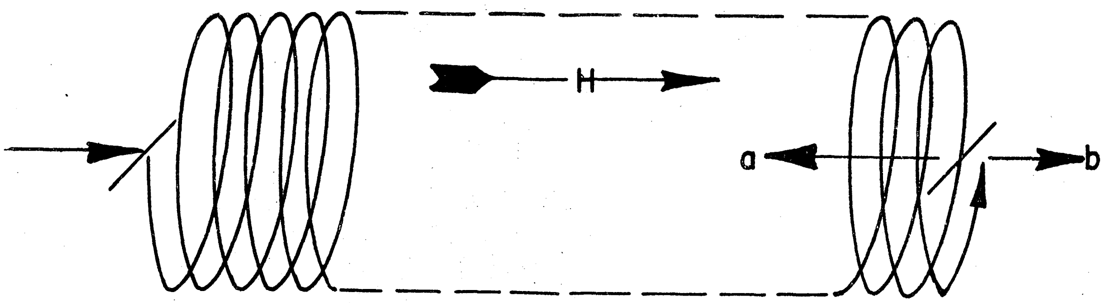
The innovation which we introduced into the double-scattering experiment in 1952 was to insert a longitudinal magnetic field between the first and second scattering points. The effect of the magnetic field is to cause the electron spins to precess and, therefore, to rotate the plane of asymmetry as determined after the second scattering. In our first apparatus, the electrons precessed through as much as 5 revolutions in travelling the 30 ft between scatterers. The g-factor was computed from the amount of rotation of the plane of asymmetry. The accuracy of the result was ± 0.5%.

To obtain greater precision, it is necessary to have the spin precess through a greater number of revolutions, and this means that the electron has to be allowed to stay in the magnetic field for a greater length of time. Simply lengthening the solenoid is not practical (it was 30 ft long in the first experiment). However, it was found feasible to obtain a greatly increased path length by making a radical change in the geometry but without increasing the length of the solenoid. The old and the new arrangements are sketched below.

In the second experiment, the length of time the electron stays in the magnetic field is not limited by the length of the tube. In operation, a short pulse of electrons will be sent against the first target. The magnetic



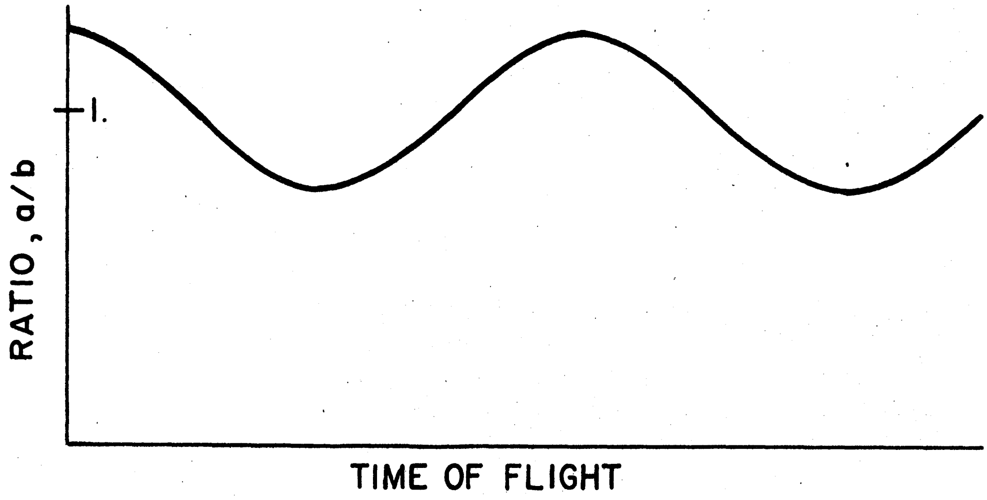
FIRST METHOD



SECOND METHOD

field will then be slightly modified so that the electrons will be trapped in a region between the two scatterers, i.e., so that the helical path will reflect back and forth, never reaching either target. After an interval of some microseconds, the magnetic field will again be modified so as to allow the electrons to strike the second scatterer. The result in which we will be interested will be a plot of the ratio of intensities in the beams labeled a and b against the time interval between the scattering events. It must be recalled here that if the g-factor were exactly 2, as it was believed to be up until a few years ago, the rotation of the spin axis and the orbital motion (around the helix in this case) would be as if we were to mark a small arrow, representing the spin direction, on the rim of a flywheel. In this case, the a/b asymmetry would not change with the time of flight. But, according to recent developments in theory, we expect that the spin-precession frequency and the orbital frequency will differ by about one part in a thousand. If this be true, the asymmetry a/b will change through a complete cycle every thousand revolutions of the orbital motion. The plot of a/b will then appear as shown below.

The time of flight or number of orbital revolutions for each cycle in a/b will give directly the <u>correction term</u> in the value of the g-factor. If the above can be measured to 1%, which seems altogether feasible, the g-factor will have been measured to one part in 10^5.



The apparatus for the new experiment is essentially complete and many preliminary tests of the electron beam in the tube have been made. It was hoped that, before attempting to trap the electrons in the pipe, a measurement could be made by simply allowing the electrons to make 100 or so turns in a helix of uniform pitch, between the first and second scatterers. Some preliminary tests dispelled any such hope. It became clear that the difficulty of producing a uniform enough magnetic field to maintain a constant pitch of about 1 degree over a distance of 12 ft would far surpass the difficulty of trapping the electrons and measuring the time interval. At about midyear, therefore, we gave up what was to be the first phase of the experiment and proceeded toward the final phase. As of the present writing, all the apparatus is in operation except the circuits which are concerned with the pulsing of the beam, measurement of time of flight, and the turning on and removal of the trapping field, which is to say, all the circuits which constitute the difference between phase 1 and phase 2.

The outlook for the future is that actual measurements of the g-factor may be obtained within the coming year. Construction and tests of circuits and components will be finished within one or two months; from that point onward, the progress will depend upon the results of attempts to operate the apparatus as a whole. We have no illusions in regard to the number of "bugs" that will make their appearance. However, any amount of effort and length of time within reason will be justified, inasmuch as this, to our knowledge, is the only experiment which is now under way and which will be capable of a precision measurement of the g-factor of the free electron.

MEASUREMENT OF THE DEGREE OF POLARIZATION OF AN ELECTRON BEAM AS A FUNCTION OF SCATTERING ANGLE

Calculations have been made giving the degree of polarization of an electron beam in the case of 90° scattering, but there are no data, experimental or theoretical, for other angles. A rather simple adaptation of the experimental method used in our first measurement of the g-factor* will give yield data on the degree of polarization as a function of angle and of the other parameters, i.e., the electron energy and the atomic number of the scatterer. A graduate student is making preparations for such an experiment with the intention of developing it into a thesis. This work is being done by Donald F. Nelson.

ACCELERATOR STUDIES

About 20% of the operating hours have been devoted this year to studies of the accelerator itself. These studies are directed toward the intensity problem. The Michigan synchrotron is a "small aperture" machine: it has a guide-field aperture of 5 cm by 5 cm at a radius of 100 cm, supported by only 14 tons of iron. The best intensity obtained to date is 10^8 electrons per pulse, while other synchrotrons and betatrons which develop the same energy produce up to 10^{11} electrons per pulse.

The following observations have been made to determine the factors which limit intensity and the means by which the electron intensity can be improved.

A. Eddy Fields.—The circulating beam has been measured as a function of the rate of rise of the magnetic guide field. These measurements show a greatly improved aperture as the rate of rise is reduced below our present operating point, about 4×10^5 gauss per sec. At the same time, the aperture for beam circulation becomes zero for rates of rise above this value. This limitation appears to stem from the race-track design itself: the field at the magnet end sections which border the straight sections has a large component normal to the iron laminations. Other race-track machines in the country, which operate at much lower field frequencies than the Michigan synchrotron, would probably not show this effect. Circular machines may and do operate at higher field frequencies.

We are approaching this problem in two ways. One is to limit the field rate of rise only during injection where the aperture should be maximum and still retain the same frequency of operation. The second method is to

*"An Experimental Measurement of the Gyromagnetic Ratio of the Free Electron," W. H. Louisell, R. W. Pidd, and H. R. Crane, Phys Rev 94, 7 (1954).

improve the eddy-field corrections which are already employed.

B. Betatron and RF Capture.—The phase aperture for electron capture by the RF immediately at injection is only a few percent. This low percentage capture is demonstrated by beam intensity measurements during injection. We have had some success in accelerating all the circulating beams by means of a short-duration betatron pulse. We plan to employ betatron acceleration for a longer period, 100 microseconds, and to introduce the RF gradually during this period. Experiments on the betatron phase are in progress.

C. Gun.—As one phase of the program for increasing the beam intensity, a new injector is now under construction, the design of which takes into account specifically the problem of maintaining a parallel beam of electrons of such high flux that the space-charge field is of primary importance.

In a parallel electron beam of uniform density, the potential has the form $Z^{4/3}$, Z being measured in the direction of flow. In order to produce a parallel space-charge-limited beam of finite extent, the electron gun must be so designed that the potential in the charge-free region adjacent to the beam also has the same form. One method of obtaining such a field is to construct a system of two or three electrodes, the shapes of which are empirically determined so as to achieve the desired field. The difficulty with this system is that the electrodes must, as is usual in such cases, have lateral dimensions which are large compared to the spacing between them. In designing a gun to be operated at 750 Kev, one finds that the spacing must be of the order of 20 cm so that the cathode will operate in a space-charge-limited fashion; this then would require electrodes several feet in breadth, which is felt to be prohibitively large.

An alternative way of obtaining approximately the desired field is the use of several closely-spaced plane electrodes, the potentials of which are programmed in such a way as to approximate, stepwise, the desired field. The lateral dimensions of the gun may then be reduced in proportion to the number of additional electrodes while the overall length evidently remains the same.

As a further refinement, the electrode at cathode potential may be shaped as in the two-electrode gun, so as to provide more nearly the correct field in the immediate vicinity of the cathode, where the electron beam is most sensitive to the exact form of the field.

In order to test whether these considerations would indeed lead to the design of a successful gun in practice, a small low-energy gun was assembled from available parts, and operated at 50 kv, d.c. This gun did produce a collimated beam of approximately the calculated current. In accordance with this experience, a ten-electrode electron gun has been designed and is now under construction, having the following specifications:

Operating Voltage	750,000 volts, derived from pulse transformer
Current Density	5 amp/cm^2 approx.
Beam Diameter	1 cm, approx.
Beam Current	3 amps, approx.
Cathode Type	Philips Dispenser, planar
Overall Length	7.5 in.
Electrode Diam.	5.5 in.
Ang. Divergence	less than 0.01 rdn.

The outer edges of the electrodes project from the vacuum system into a water cylinder which is to serve as a potential divider. The center of each electrode is depressed, the depressions being programmed in such a way as to convert the uniform field in the water to the desired steadily increasing field in the vacuum.

The space-charge divergence of the beam after it leaves the injector can be expected to increase the beam diameter to approximately 2 cm after a one-quarter turn in the synchrotron. It is estimated that the present injected beam fills the entire "doughnut" after a one-quarter turn.

D. Radial Oscillations in the Synchrotron.—A measurement of the guide-field fall-off index which was performed last year has led us to a better understanding of the electron orbits in the synchrotron. The radial oscillations of the electrons were caused to build up and explode the beam with resonant excitations. It was expected that a single resonant frequency would be found which would give the radial oscillation frequency and that from this result, in turn, the fall-off index could be computed. Instead, it was observed that not one but a band of equally spaced frequencies could knock out the beam. The source of this effect was identified with the breathing motion imposed on the electron orbits by the phase oscillations. The significance of these results, as they affect synchrotron design, are given in a recent publication: "Betatron Oscillations in the Synchrotron," C. L. Hammer, R. W. Pidd, and K. M. Terwilliger, Rev Sci Inst 26 (1955), pp. 555-56.

SCIENTIFIC PERSONNEL

R. W. Pidd (Associate Professor, Project Director)
H. R. Crane (Professor)
P. R. Chagnon (Instructor)
D. M. Dennison (Professor)
K. M. Case (Associate Professor)

Graduate Students:

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STUDENT HELPERS

Part-time student helpers are not listed by name. They are used in the work to the extent of about four at any given time.

THESES PRESENTED DURING YEAR

None.

THESES IN PREPARATION

"Elastic Scattering of Electrons on Heavy Nuclei," D. A. Naymic.

"Elastic Scattering of Electrons on Light Nuclei," P. D. Randolph.

"Inelastic Scattering of Electrons on Light Nuclei," J. Cline.

"A Precision Measurement of the Gyromagnetic Ratio of the Free Electron," A. A. Schupp.

"The Polarization of Electrons in Nuclear Scattering," D. A. Nelson.

PAPERS AND ABSTRACTS PUBLISHED

"Betatron Oscillations in the Synchrotron," C. L. Hammer, R. W. Pidd, and K. M. Terwilliger, Rev Sci Inst, 26 (1955), p. 555.

PAPERS IN PREPARATION

"Electron Scattering on Tungsten at 31, 40, and 60 Mev," R. W. Pidd, and C. L. Hammer, Phys Rev Sept. 1, 1955 (in press).