ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Progress Report

# RESEARCH ACTIVITIES IN SYNCHROTRON AND g-FACTOR EXPERIMENTS

Contributors:

| | |
|---|---|
| P. R. Chagnon | D. F. Nelson |
| J. E. Cline | R. W. Pidd |
| H. R. Crane | P. D. Randolph |
| G. M. Edict | A. A. Schupp |

D. A. Naymik

Project 1922

U. S. ATOMIC ENERGY COMMISSION
CHICAGO OPERATIONS OFFICE
LEMONT, ILLINOIS

July 1956

Éngu
UMR
1269

## TABLE OF CONTENTS

## LIST OF FIGURES

Fig. No. Page

# ABSTRACT

Two separate lines of research are being conducted on the University of Michigan synchrotron. One is a program of measuring the nuclear radius by elastic electron scattering. Experiments are conducted at electron energies from 20 mev to 80 mev. In these experiments the circulating beam is used to bombard an internal target. The current program is focused toward an improvement of the experimental precision, to reduce the error from 10% to less than 1%. The other line of research uses the 80-mev x-ray beam to induce short-lived radioactivity in external targets. This work has been inaugurated this year. An elaborate concrete house has been built for collimation of the x-ray beam and for shielding the counter spectrometer. Exploratory measurements which establish the signal-to-background ratio are reported.

Another program of research, not associated with the synchrotron accelerator, is the measurement of the g-factor of the free electron. The polarization and analysis of a 100-kev electron beam is performed by double scattering. The g-factor is measured by magnetic perturbation of the polarized beam. New equipment built for precision g-factor measurements is described. A second experiment which utilizes the same equipment is in progress. This is the experimental measurement of the double-scattering cross section at polar angles of second scattering as large as 170°.

In a third section of the report we discuss the progress on the continuing program of accelerator development. A new injector capable of delivering 2 amperes at 750 kv with an angular divergence of .01 radius is described. The installation of ignitron equipment for control of the guide-field excitation is another major activity in the accelerator development. The new system is designed to increase the beam energy from 80 mev to the 400-mev design limit of the synchrotron.

# I. SYNCHROTRON RESEARCH

# STUDIES OF SHORT-LIVED BETA EMITTERS

J. E. Cline and P. R. Chagnon

## A. INTRODUCTION

In recent years a new method of producing and measuring short-lived activities has been developed and has been in use at the University of Illinois,[1] Iowa State College,[2] The University of Michigan and at laboratories elsewhere. This method consists of the use of time resolution to observe the decay of radioactivity induced in a target by pulsed-beam machines, the observations being carried out between the beam pulses. An experiment now in progress at The University of Michigan utilizes this method to study $\beta^+$-unstable nuclei produced by photonuclear reactions and to measure the ft values for the positron decay from these nuclei. A good measurement of the ft values can provide (1) a needed verification of nuclear models from which theoretical ft values have been calculated, (2) a means for determining the relative strength of the five Lorentz-invariant interactions in $\beta$-decay and (3) a possible means of determining whether the assumption of charge-independent nuclear forces breaks down.

It is this last item that provides the most interesting information and it is planned to investigate this aspect thoroughly.

## B. THEORY

In the formulation of the general Fermi theory of $\beta$-decay,[3] there are five possible Lorentz-invariant interactions: scalar, four-vector, tensor, axial-vector, and pseudoscalar. The pseudoscalar interaction has been shown not to exist alone and consequently does not really belong in a list of interactions giving rise to allowed transitions.

In the early days of $\beta$-decay theory, there were two separate analyses given. The first, by Fermi in 1934,[4] took into account the scalar and four-vector interactions and leads to the Fermi allowed selection rules, $\Delta J = 0$, $\Delta\pi = 0$, $\pi$ being the parity. The second paper, published by Gamow and Teller in 1936,[5] took into account the tensor and axial-vector interactions and resulted in the Gamow-Teller allowed selection rules, $\Delta J = 0, \pm 1$, no $0 \rightarrow 0$; $\Delta\pi = 0$. These separate investigations were later combined into the general theory of $\beta$-decay.

The probability p(E) for emission of an electron of energy E in an energy range dE may be written as

$$p(E)dE =$$

$$\frac{m_0^5\, c^4}{2\pi^3\, h^7}\; F(E,Z)(E^2 - 1)^{1/2}\, E(E_0 - E)dE \left\{ G_F^2 \left|\int 1\right|^2 + G_{GT}^2 \left|\int \vec{\sigma}\right|^2 \right\}. \qquad (1)$$

$G_F$ and $G_{GT}$ are the coupling constants for the Fermi and the Gamow-Teller interactions, respectively. F(E,Z) is the Fermi function which corrects the observed electron energy for the effects of the Coulomb force. This expression may be integrated with respect to E. The result may be written as

$$ft \left\{ G_F^2 \left|\int 1\right|^2 + G_{GT}^2 \left|\int \vec{\sigma}\right|^2 \right\} = \text{constant}, \qquad (2)$$

where t is the half life and f is an integral which corrects the observed half life for the nuclear Coulomb field and the transition energy distribution.

1. <u>(4n + 2) = A nuclei</u>.—Kofoed-Hansen[6] has studied the $0 \rightarrow 0$, $\Delta\pi = 0$ $\beta$-transitions and has noted that they take place between the $T = 1$ states of nuclei of mass number (4n + 2). This being a Fermi type, the only nuclear matrix element which enters in is $\left|\int 1\right|^2$. The matrix element is independent of any nuclear model and is dependent only upon the charge independence of nucleon forces. One finds that for $0 \rightarrow 0$, $\Delta\pi = 0$, $\Delta T = 0$

$$\left|\int 1\right|^2 = T(T + 1) - T_{Z_1}, T_{Z_2} = 2 \qquad (3)$$

for $T = 1$ transitions. So long as T remains a "good quantum number," ft is a constant for these transitions. An experimental investigation of this consistency is an extremely good check on the basic assumption of charge independence. One could find out where T stops being a "good quantum number."

2. <u>Mirror nuclei ($|N - Z| = 1$)</u>.—Wigner,[7] on the basis of a particular nuclear model, his supermultiplet model, calculated the integral square terms in Equation 2 for mirror nuclei. Moskowski[8] used Equation 2 to evaluate the ratios of the G's for such transitions. From existing data, this was calculated to be 0.5. Later, Winther and Kofoed-Hansen[9] plotted the expression

$$B = ft \left\{ (1 - x) \left|\int 1\right|^2 + x \left|\int \vec{\sigma}\right|^2 \right\} \qquad (4)$$

vs x for various experimental ft values. The common intersection of the curves gives the correct values of x and B where $X = G_{GT}^2/G_{GT}^2 + G_F^2$. They obtained a value for x of 0.5 and for B of 2600. The integrals have been evaluated theoretically for superallowed transitions for various nuclear models. If one were to measure ft values which were consistent with values of x and B for some particular nuclear model, then this model would gain some strong experimental support and the values of the G's could be calculated.

It is also supposed at this time that a theory which is similar to that of positron decay from (4n + 2) nuclei could be worked out for positron decay from mirror nuclei, or perhaps any superallowed β-transitions. A theory of this kind, along with the proposed measurements, would indeed define the region of charge independence for the nuclear forces.

## C. EXPERIMENTAL TECHNIQUES AND PROCEDURES

In performing this experiment, we employ the University of Michigan synchrotron. This synchrotron at present accelerates electrons up to an energy of 80 mev. At this point, the electrons strike a high-Z target, producing a high flux of bremsstrahlung. Since the initial electrons are essentially unidirectional, the bremsstrahlung are emitted in a cone containing all energies $\leqq 80$ mev. The solid angle of this cone is given approximately by

$$\Omega = \frac{m_0 c^2}{E_0}, \tag{5}$$

where $\Omega$ is the solid angle and $E_0$ is the energy of the incident electron. This x-ray beam is then allowed to strike a target placed outside the machine itself. The threshold energy for $(\gamma,n)$ reactions is about 12 mev and that of $(\gamma,2n)$ reactions is about 24 mev, so these reactions are certainly possible in our targets.

Since the machine is a pulsed machine operating at 20 cps, there is a certain "dead-time" between bursts of bremsstrahlung. The beam pulse lasts for about 30 μsec, whereas the time between bursts of beam is nearly 50 msec. It is in the utilization of this time between beam pulses for measuring the decay radiation from the target that the ability to measure very short lifetimes of transmuted elements is derived. The technique is applicable to many types of experiments. Targets are prepared at present by evaporating a suspension of the element in amyl acetate on a sheet of 0.5 mg/cm$^2$ Mylar.

After the beam has activated the targets, a photomultiplier tube attached to a scintillation crystal is turned on. The decaying nuclei are observed for about 30 msec and the photocathode is then pulsed off. The output of the photomultiplier is fed through an amplifier into a single-channel pulse height analyzer. The output of the analyzer is fed into a "time analyzer" which divides the pulses among four scalers according to the time at which they occur in the 30 msec during which the counter is on. The block diagram of the system is shown in Fig. 1.

The time-analyzer circuit consists of four cascaded univibrators which operate four gates. The "off" pulse from the last stage then turns off the photocathode flip-flop circuit. The beam-gate pulse is a pulse which occurs 50 μsec before the beam is released from the machine. Each gate is variable from 5 μsec to 10 msec, while the delay pulser is variable from 0 to 40 msec. Since the expected half-lives are much longer than the 50 msec between pulses, it may be necessary to block out the beam periodically and run at, say 5 cps, which would allow 200 msec between beam pulses.

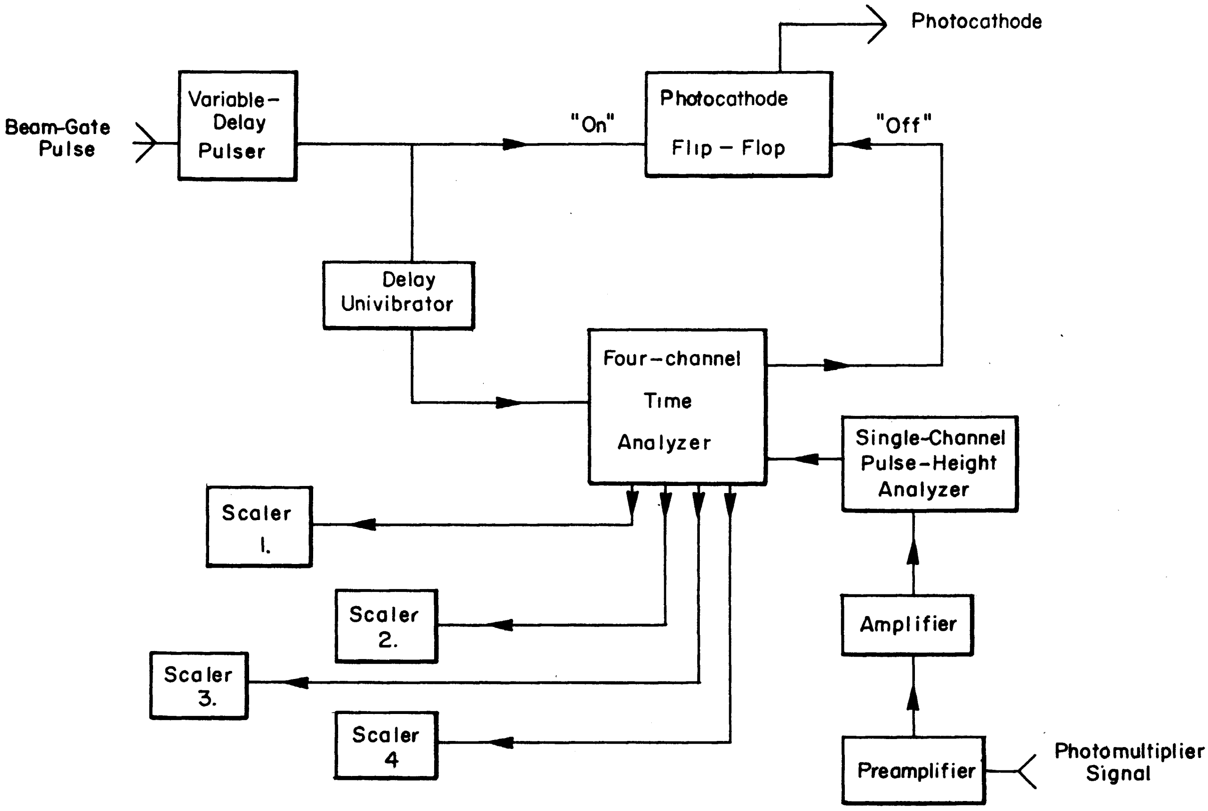

Fig. 1. Block diagram of electronics for study of short-lived beta emitters or isomeric transitions.

D. BACKGROUND AND SHIELDING

When the experiment was initiated, the photomultiplier and crystal were in the same room as the accelerator. The background was so intense as to overshadow completely any decay radiation from any target. Various shielding techniques were employed and none of them proved successful. Even with a great amount of shielding placed around the counter, the background was of such a nature as to prevent any distinction between the situations of "target in" and "no target." A search for the short-lived isomers in thallium,[1] which emit $\gamma$-rays at 720 kev, 480 kev, and 410 kev with respective half-lives of 65 $\mu$sec, 530 $\mu$sec, and 65 $\mu$sec, resulted in no conclusive data. A good example of one of the runs is shown in Fig. 2.

The line at 480 kev, in other data, occurred consistently whether there was a target or not. This is assumed to be due to the thallium in activated NaI crystals. Any $\beta$-decay would be completely masked under these circumstances. The background was determined to be high-energy $\gamma$-rays and both fast

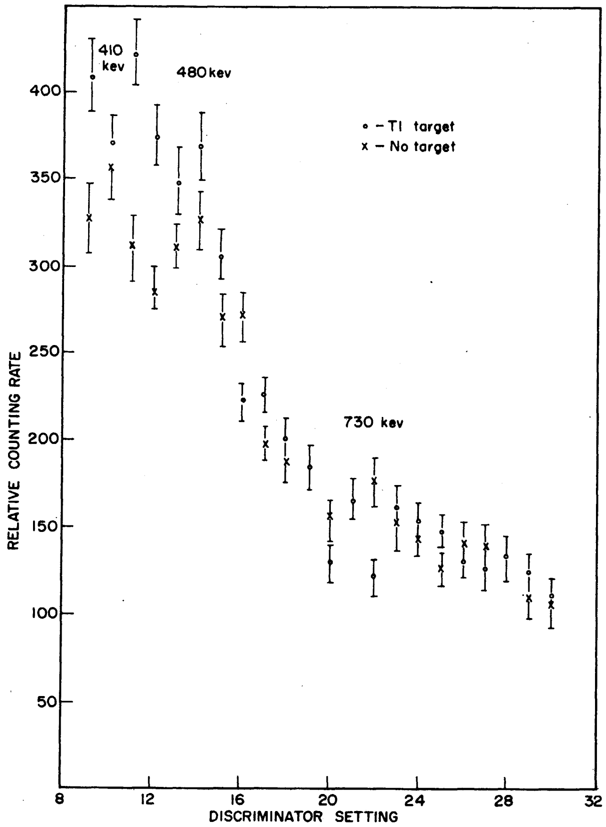

Fig. 2. Pulse-height distribution of radiation from a thallium target, without the concrete shielding.

and thermal neutrons. It was decided to construct a room which would serve the dual purpose of cutting down the background to a reasonable value and of allowing personnel to enter the room in order to change targets without completely turning off the machine. The most efficient (i.e., cheap and effective) material from which to build a wall for such a purpose is concrete. The mean free path of fast neutrons in most common materials is of the order of 25 cm. A flux of 85-mev $\gamma$-rays is reduced to 1/e of its initial intensity in 18 cm in concrete. Taking both of these values into account, the walls were made 1 meter thick. The portion immediately adjacent to the synchrotron was made of a heavy concrete. This concrete has a density of 250 lb/ft$^3$ instead of the normal 150 lb/ft$^3$, the increase in density being obtained by the use of barium-sulfate as an aggregate. This type of concrete was used in the construction of the University of Michigan nuclear reactor.

The "house" itself is constructed of blocks of concrete, each weighing about 3000 lb. Each wall consists of two rows of these blocks, staggered so as to allow no straight path into the room. The ceiling is 7 ft from the floor and is also 1 meter thick and constructed of two overlapping rows of blocks. The room's internal dimensions are 11 ft long by 8 ft wide by 7 ft tall. It was completed in May, 1956.

The bremsstrahlung beam is collimated by 20 in. of lead before being brought into the new experimental room through a port. The beam passes through the room and is brought to rest in 28 in. of water backed by 12 in. of concrete, all of which lie beyond the experimental room. The beam is 1-1/2 in. in diameter at the entrance port to the room, which is about 5-1/2 ft from the synchrotron target. The experimental space is shown in Fig. 3.

With this arrangement, the background with no target has been reduced by a factor of better than 100, and, with a target of thallium, it is now possible to identify the photopeaks, as is witnessed by Fig. 4.

It might be pointed out that the lines in thallium were observed by us almost simultaneously with Vegors.[1] We measured the energy of the longer-lived state to be 480 ± 5 kev instead of 530 kev as had been reported; later remeasurements by the Illinois group yielded a value of 480 kev.

At present, a measurement of the $\beta$-spectra from the four mirror nuclei, $Mg^{23}$, $Si^{27}$, $S^{31}$ and $Ca^{39}$, all produced by $(\gamma,n)$ reactions, and whose energies and life times were measured by Hunt,[10] is being attempted. The purpose of this is to (1) calibrate and check out the equipment and (2) determine and reduce further the background from the target and surroundings. The future program, when this is completed, is to search for $\beta$-decay from elements of $Z > 20$ in the mirror nuclei group or in the $|N - Z| = 2$ group. This region of isotopes is almost completely unexplored and is of considerable theoretical interest, as has been pointed out.

## REFERENCES

[1] S. H. Vegors and P. Axel, Phys. Rev., 100, 1238A (1955).

[2] M. L. Stewart and C. Hammer, Bull. Am. Phys. Soc. II, 1, 206 (1956).

[3] E. J. Konopinski, Rev. Mod. Phys., 15, 209 (1943).

[4] E. Fermi, z. Physik, 88, 161 (1934).

[5] R. Gamow and E. Teller, Phys. Rev., 49, 895 (1936).

[6] O. Kofoed-Hansen, Phys. Rev., 92, 1075L (1953); Phys. Rev., 51, 947 (1937).

[7] E. Wigner, Phys. Rev., 56, 519 (1939).

[8] S. Moskowski, Phys. Rev., 82, 118 (1951).

[9] A. Winther and O. Kofoed-Hansen, Danske Math.-fys. Medd., 27, No. 14 (1953).

[10] W. A. Hunt, Doctoral Dissertation, Iowa State College, 1954.

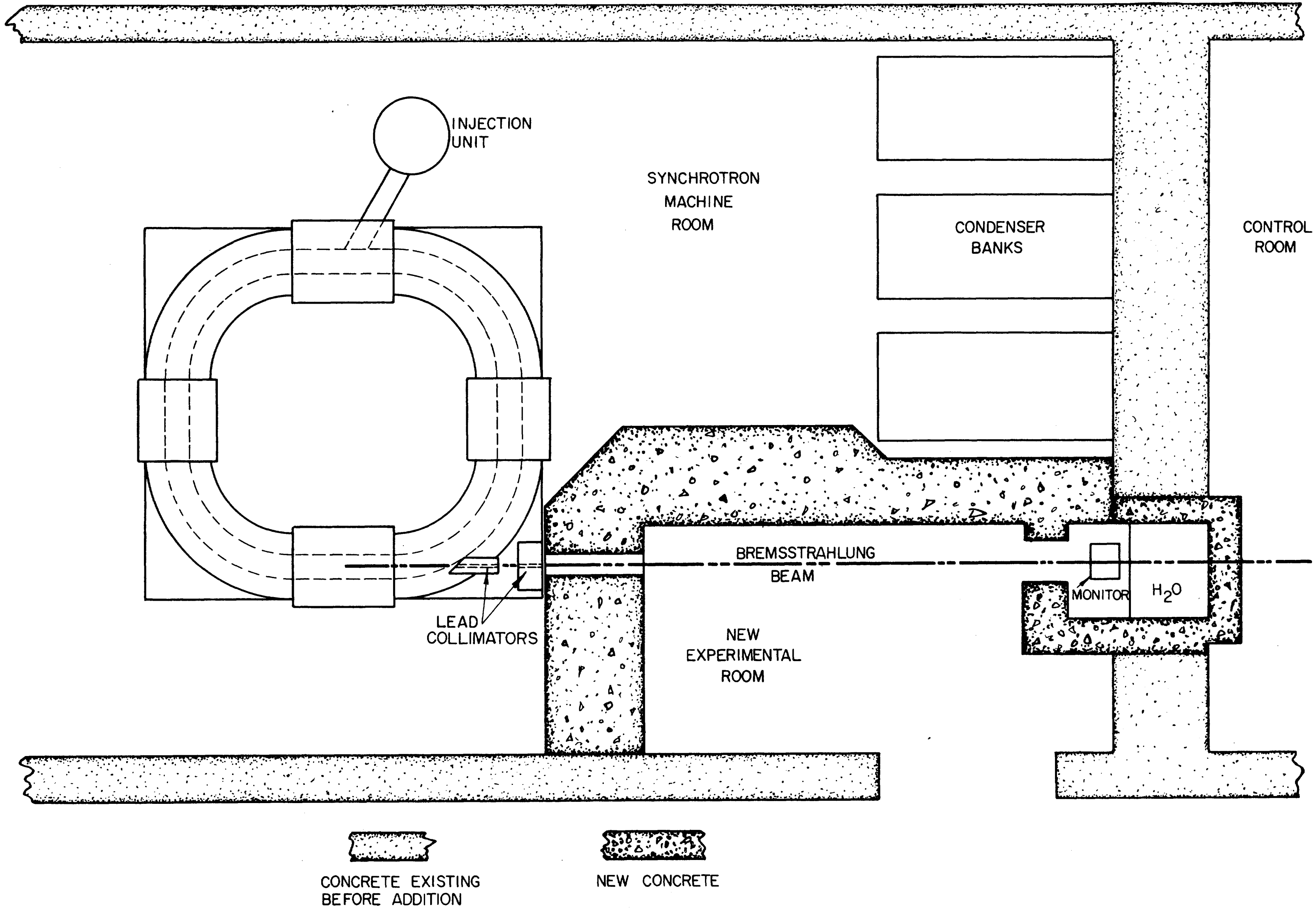

Fig. 3. Plan view of the new shielded experimental room.

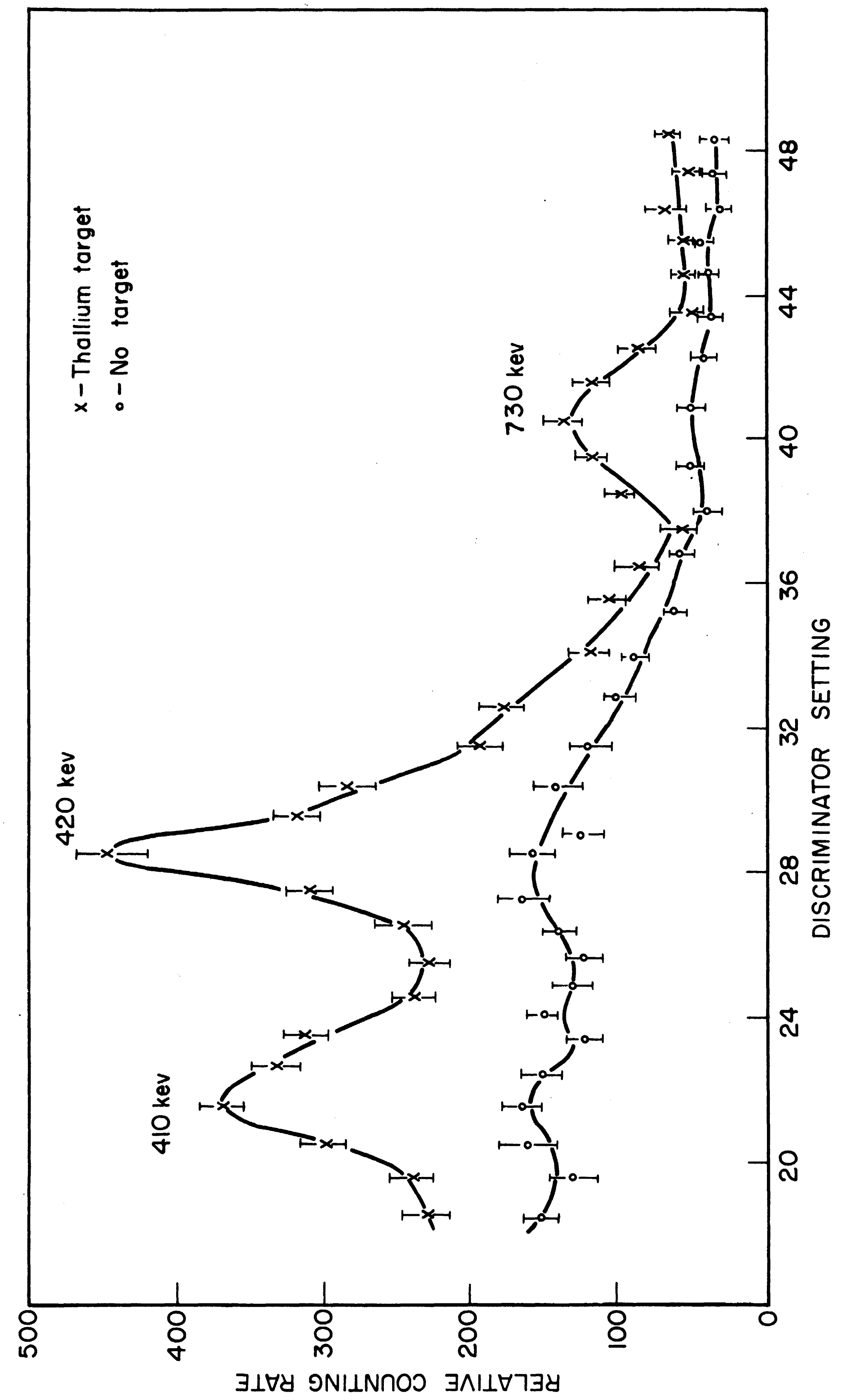

Fig. 4. Pulse-height spectrum of radiation from isomeric states of thallium, taken since the installation of new concrete shielding.

# HIGH-ENERGY ELASTIC ELECTRON SCATTERING

P. D. Randolph, D. A. Naymik, and R. W. Pidd

## A. REVIEW

A program of electron-nuclear scattering research has been in progress at The University of Michigan since 1950. At the inception of the program, only one set of experiments has been performed, by Lyman, Hanson, and Scott[1] at Illinois, using a 15.7-mev betatron. Their published results indicated a smaller nuclear radius, as determined by electron scattering, than that deduced from nuclear interactions. Their results gave a radius equal to $R = r_0$ $A1/3$ $10^{-13}$ cm, where $r_0 = 1.2 \pm 10\%$. The corresponding nuclear determination gives a value of $r_0$ equal to 1.35 to 1.6, depending on the particular reaction. Our first experiments were conducted at 30 mev and 40 mev,[2] and later at 60 mev,[3] and they confirmed radius measurements at 15.7 mev. These initial results have since been the subject of several theoretical papers. One of the primary consequences has been the revised analysis of the electromagnetic radius of mirror nuclei.[4] With this revision the mirror-nuclei data also yield a value of $r_0$ equal to 1.2, rather than the older value of 1.45. At present it can be said that all the different methods of determining the electromagnetic radius—from electron scattering, from mirror-nuclei $\beta$ end-point energies, and from mu-mesic atomic spectra—are in good agreement. The discrepancy with the radius for nuclear reactions remains.

At the same time that our program was begun, the research group at Stanford University began electron-scattering experiments at much higher energies, using the Stanford linear accelerator. The higher-energy experiments yield intrinsically more detailed information about the nuclear structure,[5] particularly about the structure of the nuclear surface. In regard to the mean nuclear radius, the low- and high-energy experiments are, again, in good agreement.

When the first experimental work was begun, the theoretical analysis available was very fragmentary and in some cases actually misleading. Since then there has been an extensive analysis of the theoretical cross section.[6,7] Generally, these are the features of the electron-scattering cross section: denoting the electron wave number by K and the nuclear radius by R, the scattering of electrons by the nucleus depends on the argument KR. There are three qualitatively different regions defined by the value of KR.

1. $KR \lesssim 0.5$. Low Energy.—The nucleus can be regarded as a point scatterer. For the light elements the Mott-scattering formula is applicable. For heavy elements the Born approximation fails, but the exact analysis is available.

2. $0.5 < KR < 1.5$. Medium Energy.—Diffraction effects are important. Nevertheless, the scattering cross section is independent of the form of the nuclear charge distribution. Different assumed charge distributions, adjusted so that the root-mean-square radii of the distributions are equal, yield identical cross sections. The structural information that can be obtained is definite but limited: the rms radius is determined.

3. $KR > 1.5$. High Energy.—The cross section is influenced by two parameters of the nuclear structure, rather than one as in the medium energy range. The two parameters are associated with the mean radius of the distribution and thickness of the nuclear surface. Inelastic scattering becomes comparable with elastic scattering (inelastic scattering is not observed in the lower energy ranges).

All the Michigan research pertains to case b, the model-independent range in which only the rms radius is measured. Two principal conclusions are drawn from the current experimental and theoretical status of electron-scattering research:

1. There is little more to be learned from further work on medium-energy electron scattering in which the experimental error is 10%. Within this error, all electromagnetic measurements agree. There is no difference from nucleus to nucleus other than the $A^{1/3}$ dependence, and this rule for the size of the nucleus is observed to hold very well for the middle and heavy elements.

2. The information which can be extracted from electromagnetic radius measurements is not complete. If the different approaches to the radius measurement—by mu-mesic atomic spectra, by medium-energy electron scattering, and by high-energy electron scattering—were all improved by a factor of 10 in accuracy, then the knowledge of the parameters of nuclear structure could be substantially improved. For example, mu-mesic atomic spectra and medium-energy electron scattering are determined by different moments of the charge distribution. If these moments were accurately known, a new restriction could be placed on the model of the nucleus. This restriction would pertain particularly to the center of the charge distribution. As another example, if the rms radius obtained from medium-energy scattering were better known, this number could be used in the analysis of high-energy scattering which is most sensitive to the periphery of the nuclear charge distribution. At present the experimental range of parameters is so great that no mutual restriction is placed on the two sets of data.

As a consequence of these conclusions, our old program has been abandoned and we are concentrating all our efforts toward the precision measurement of a few well-studied nuclear species at $KR = 1$.

## B. PROPOSED EXPERIMENTS

Improved precision in scattering measurements is obtained at a high cost. The factor of 10 improvement which is desirable requires a gain of 100 in total counts. Our approach to this problem is in two parts.

1. Analysis of the scattering data requires that the energy spectrum of the scattered electrons be carefully analyzed for the elastic scattering "peak" and for the bremsstrahlung "tail" which always occur. For this purpose we have constructed and used a 180° double-focusing (m = 1/2) analyzer magnet, of necessarily small aperture ($6 \times 10^{-6}$ steradians) for energy analysis. The magnet is shown in Fig. 5. The energy resolution is $\Delta E/E = 1\%$. Examples of an energy spectrum are shown in Figs. 6, 7, and 8. Such distributions have been carefully inspected for inelastic peaks and none were found. Also, the profiles are obtained for different elements and over the whole range of scattering angles. In this way, any variation in the ratio of elastic to inelastic scattering can be found. Once the energy profiles have been found, with an overall statistical precision of 10%, this analysis is set aside. To obtain the $10^6$ counts needed using this magnet would require 400 hours per point.

2. For the large counting rates which are needed for good statistical precision we have constructed a large-aperture ($9 \times 10^{-3}$ steradian) wedge-type magnet of necessarily poor energy resolution ($\Delta E/E = 10\%$). This magnet is shown in Fig. 9. The field of this magnet is centered on the elastic peak and as many as $10^6$ counts can be obtained at every point. A few hours, counting is required at each point. Since these counts will include a certain fraction of inelastically scattered electrons, the observed counting rate must be corrected to give the elastic scattering counts. This small correction is made (a few percent) by using the high-resolution data which exhibit the ratio of elastic to inelastic counting in the energy acceptance range of the large-aperture magnet.

## C. STATUS OF THE EXPERIMENTAL WORK

The high-resolution analysis of the scattered electron spectra is complete. The 180° magnet is in place on one side of the scattering chamber for further use if needed. On the other side of the chamber we have installed the large-aperture magnet. Prior to installation the performance of this magnet was tested, using the hot-wire technique. Fast counting with the large-aperture magnet is scheduled to begin in July of this year.

## REFERENCES

[1] E. M. Lyman, A. O. Hanson, and M. B. Scott, Phys. Rev., 84, 626 (1951).

[2] R. W. Pidd, C. L. Hammer, and E. C. Raka, Phys. Rev., 92, 436 (1953).

[3] R. W. Pidd and C. L. Hammer, Phys. Rev., 99, 1396 (1955).

[4] B. C. Carlson and I. Talmi, Phys. Rev., 96, 436 (1954).

[5] R. Hofstadter, B. Hahn, A. W. Knudsen, and J. A. McIntyre, Phys. Rev., 95, 512 (1954).

[6] A. E. Glassgold, Phys. Rev., 98, 1360 (1955).

[7] D. R. Yennie, D. G. Ravenhall, and R. N. Wilson, Phys. Rev., 95, 500 (1954).

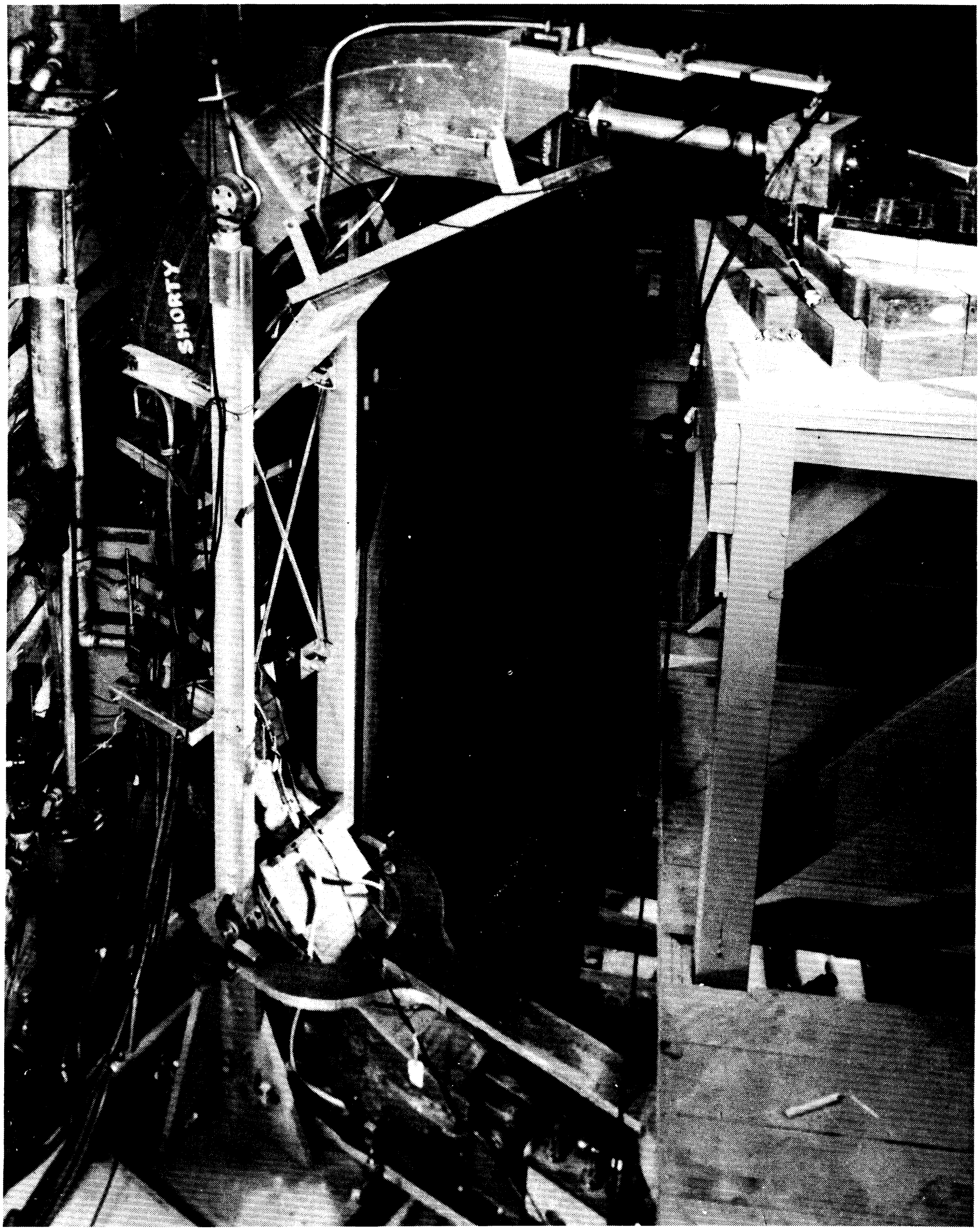

Fig. 5. Photograph of the 180° high-resolution analyzing magnet.

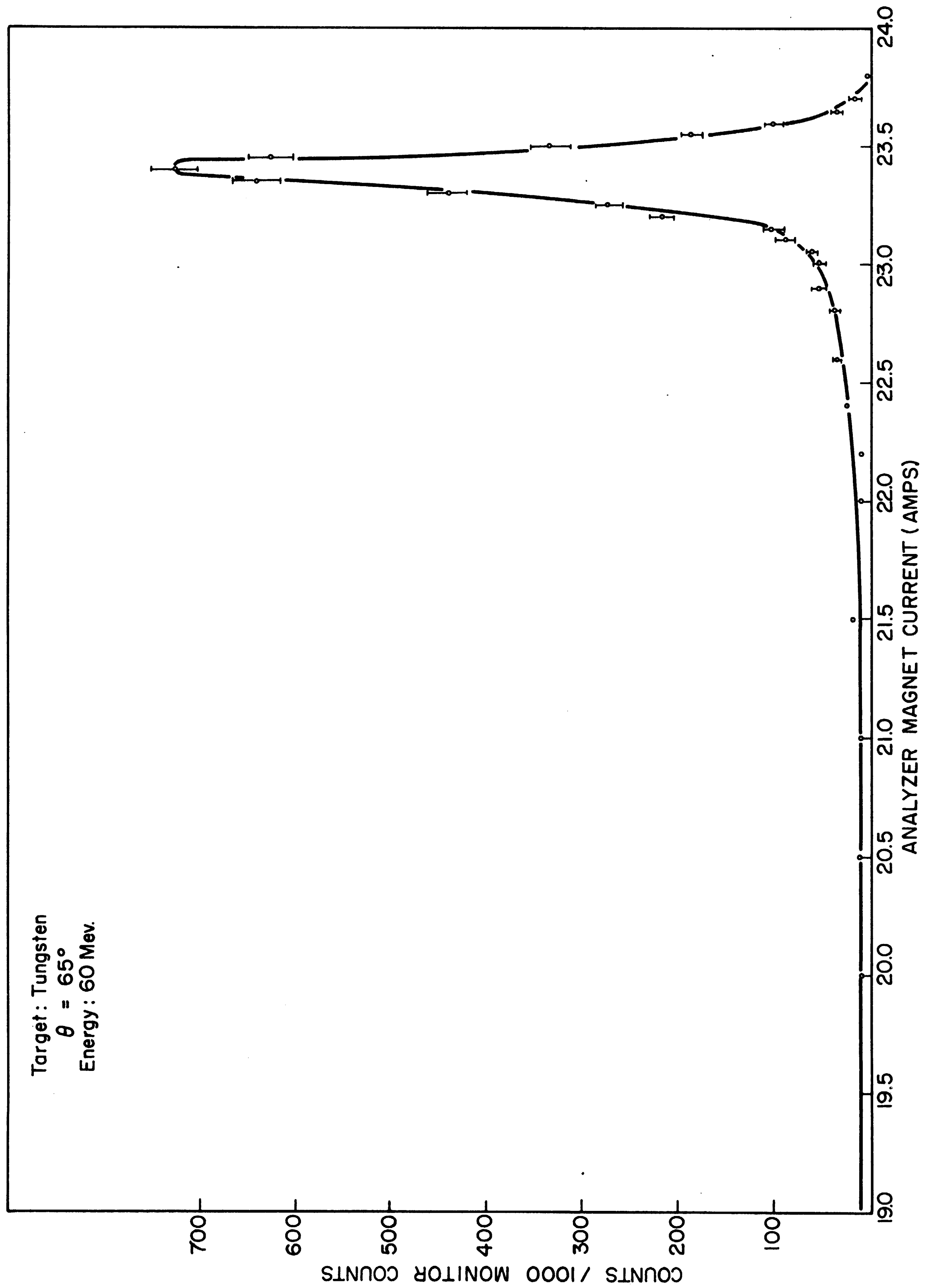

Fig. 6. Momentum spectrum of electrons scattered from a tungsten target at 65°.

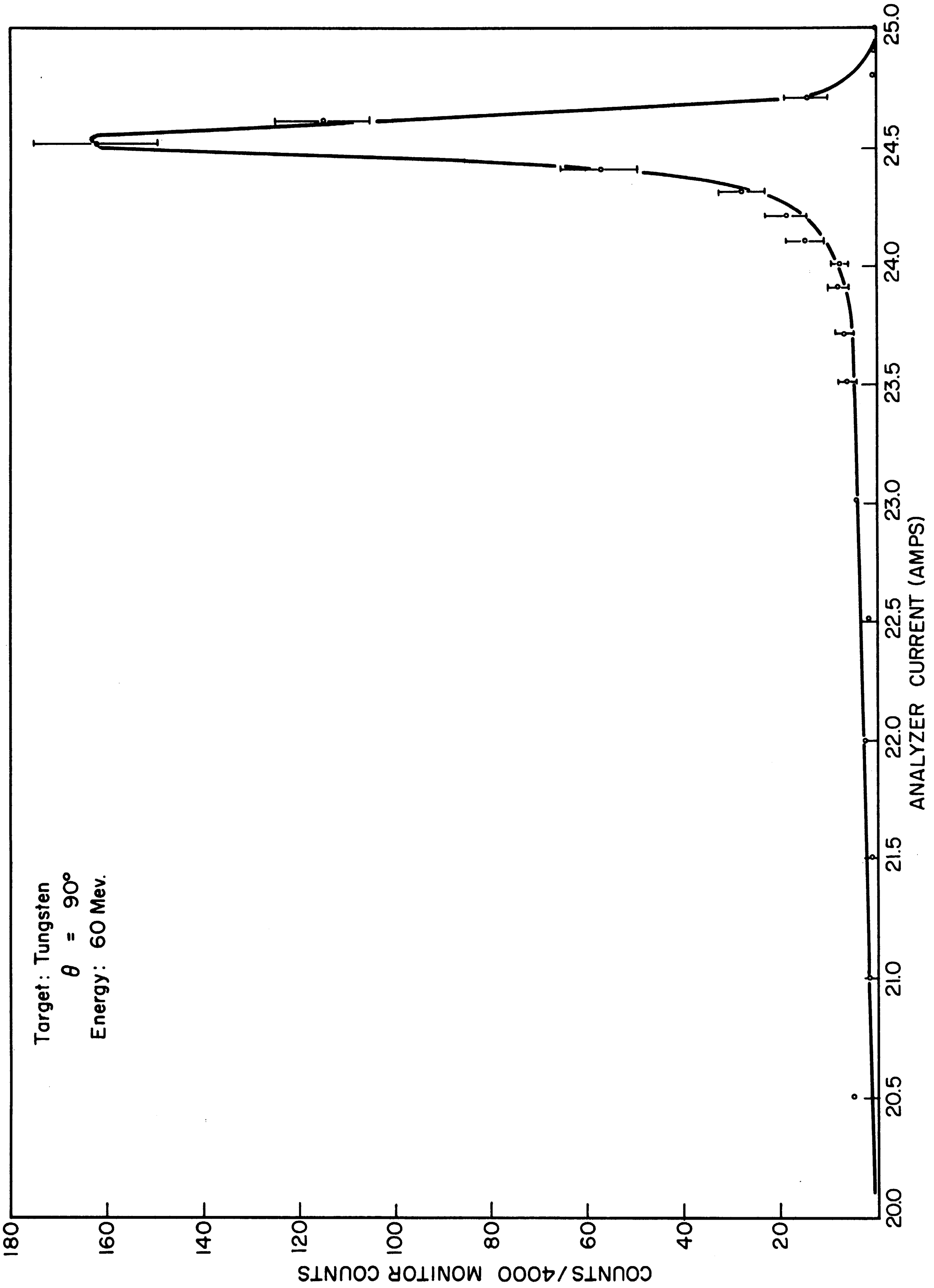

Fig. 7. Momentum spectrum of electrons scattered from tungsten at 90°. Ordinate is relative counting rate.

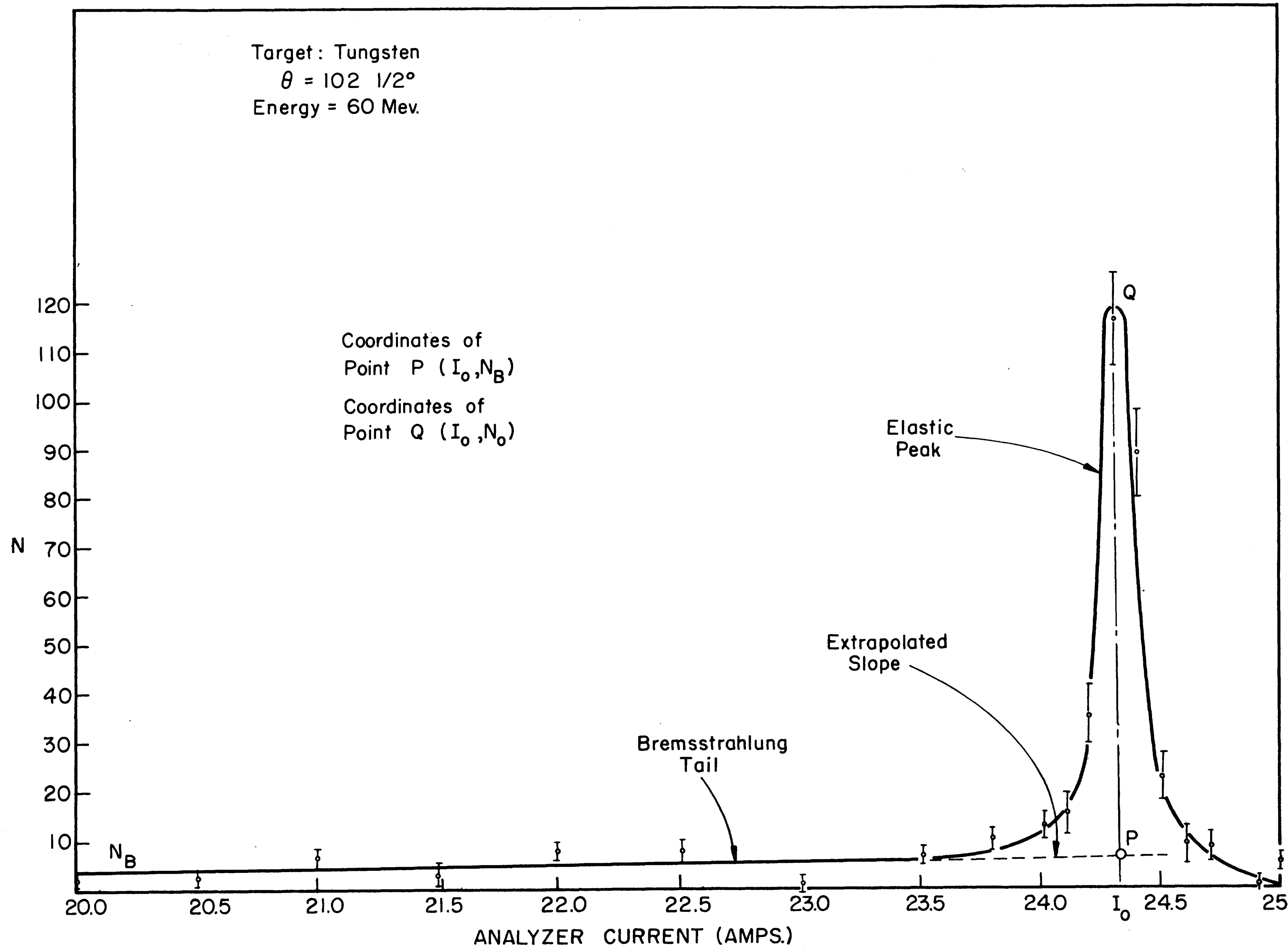

Fig. 8. Momentum spectrum of electrons scattered from a tungsten target at 102.5°. Ordinate is relative counting rate.

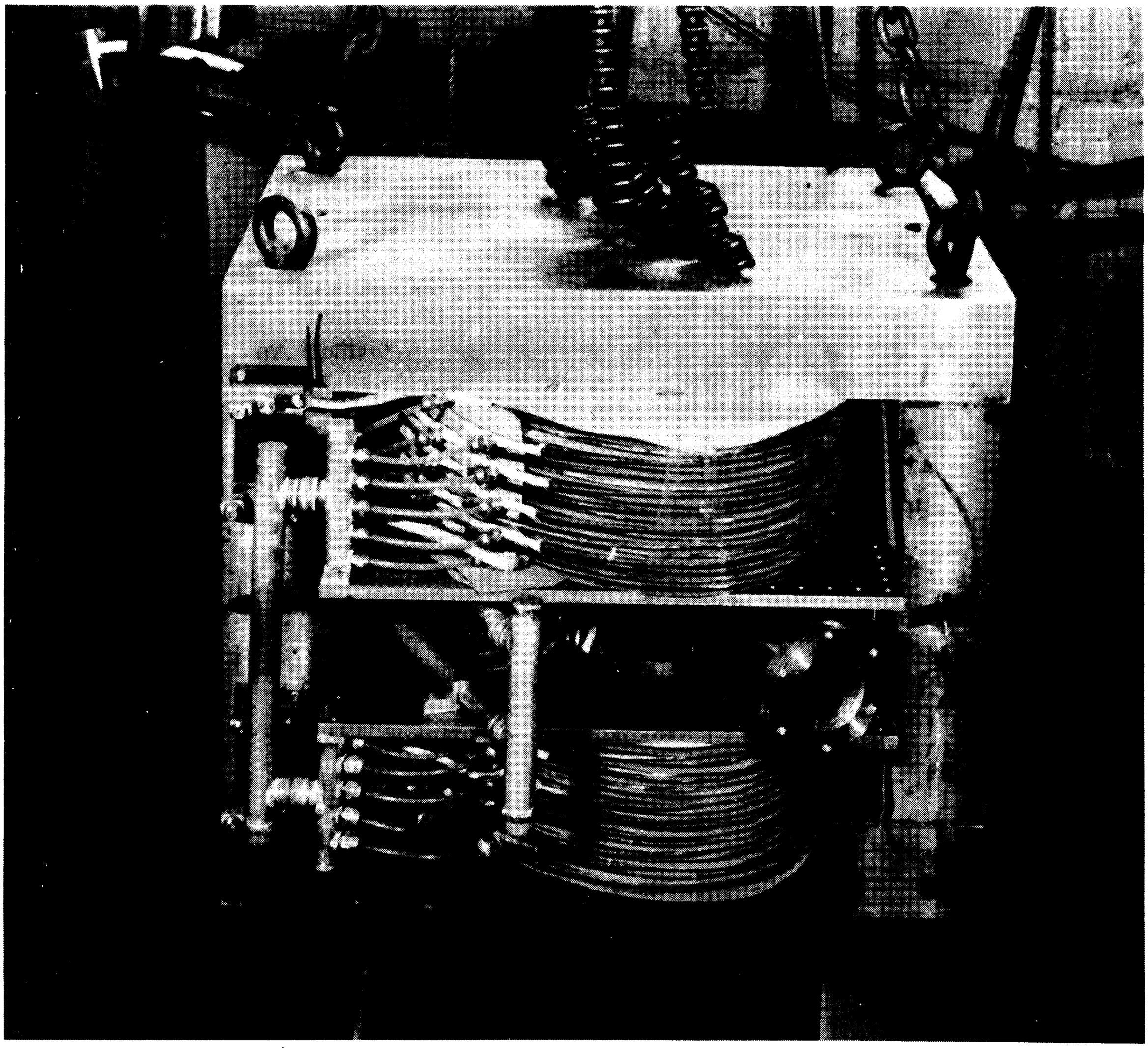

Fig. 9. Photograph of the new large-aperture analyzing magnet.

# II. g-FACTOR RESEARCH

# g-FACTOR OF THE FREE ELECTRON, AND ALLIED EXPERIMENTS

A. A. Schupp, D. F. Nelson, and R. W. Pidd

## A. INTRODUCTION

In 1951 an experiment for the measurement of the g-factor of the free electron was contrived by H. R. Crane and R. W. Pidd. Before this time all gyromagnetic ratio measurements were performed on electrically neutral systems. Electrons and protons could be studied through the interpretation of the magnetic behavior of atomic systems. Neutrons, being electrically neutral, have been studied in both the free state and in the atomic state. The basis for the restriction to neutral systems stems from the uncertainty principle, from which it can be demonstrated that particles having an e/m ratio as small as that of the electron cannot be space-separated according to spin states. A Stern-Gerlach-type experiment is therefore impossible for free electrons. The protonic e/m is still smaller than that of the electron, and the proton is therefore covered by the same restriction.

The experiment which was devised by-passes the uncertainty argument. Free electrons are partially spin-polarized and analyzed, but no one-to-one space separation of spin states is involved. The experiment is this: electrons are partially spin-polarized upon single, large-angle scattering in a heavy-nucleus target. This partially-polarized beam is scattered again, and upon second scattering there is an axial asymmetry in the scattering cross section. The amount of polarization and the plane of polarization can be determined by an analysis of this asymmetry. This is the framework of the experimental method. The measurement of the g-factor of the electron requires a magnetic perturbation of the electrons in their course of travel between the two scattering stations.

## B. A REVIEW OF THE FIRST EXPERIMENT

In the first experiment we caused the polarized electron beam to travel along the lines of a uniform magnetic field in the region between the two scattering foils. The plane of polarization was rotated by the Larmor precession of the electrons in the magnetic field. We obtained field strengths such that the electrons could undergo as many as five precession cycles for a maximum rotation of 1800°. The plane of polarization could be determined to an accuracy of about ± 5°. The consequent measurement of the g-factor was accurate to about 1%. In this experiment the primary electron beam was drawn from the synchrotron electron gun. A solenoid was constructed which was 6 in. in diameter and 30 ft long. A power expenditure of 25 kw was required to sustain the maximum magnetic field. Since improving the basic precision of the experiment required either a much greater field, or longer solenoid, or both, the improvement of precision using this apparatus was given up. A complete report of the experiment and the results is contained in an article in the Physical Review, "An Experimental Measurement of the Gyromagnetic Ratio of the Free Electron."[29] A thesis has been published on the same work by W. H. Louisell.[28] In addition to the experimental work, a considerable amount of assistance has been obtained from the theoretical group at The University of Michigan. A theoretical analysis has been performed by K. M. Case and H. Mendlowitz.[30-33]

## C. STATUS OF THE g-FACTOR EXPERIMENT

Since the demonstration of the general method in the first experiment, we have been working along two new lines of work. The principal line is the development of a new geometrical arrangement, based on the established ideas, which would yield a much more precise measurement of the g-factor of the electron. With the new arrangement the theoretical, and, we hope, the practical precision is one part in 10 million. The new experimental approach was analyzed by Case and Mendlowitz, and the analysis culminated in a doctoral thesis[31] by Mendlowitz directed by Professor Case.

The new experiment permits us to obtain an indefinitely large number of precession cycles in a finite apparatus. The primary electron beam travels along the direction of the magnetic field generated by a large (1 ft diameter, 24 ft long) solenoid. The path of the primary beam is displaced from the solenoid axis by 4 in. The beam encounters a thin target and is scattered and polarized. The scattered, or secondary, beam is selected for those electrons which are scattered at about 90° relative to the solenoid axis and also at 90° relative to the radius vector drawn from the solenoid axis to the scattering foil. Actually, angular selection is made for those electrons which have a slight forward component of momentum in the direction of the primary beam. Thus the secondary beam is a small-pitch helix concentric with the solenoid axis progressing with the sense of the primary beam. The secondary beam encounters an analyzer target and is scattered again, into two detectors placed on the solenoid axis. The pair of counters detects the plane of polarization of the secondary beam. Gun, foils, and detectors are all within the nearly uniform field of the solenoid.

If the secondary beam executes only a few revolutions between the two scatterers, the cyclotron motion and precession of the electrons remain nearly in phase. If $g = 2$, then the cyclotron and Larmor frequencies are identical. In this case, the original polarization of the beam is preserved, and more electrons are scattered toward the first detector—toward the gun— rather than toward the second detector. A correction to the g-factor value of 2 would cause the rate of spin precession to advance or lag relative to the cyclotron motion. A correction of one part in 1000 is predicted by theory and has been measured with high precision by other means. This correction would lead to the following phenomenon in our experiment. After 500 revolutions the scattering asymmetry detected by the counters for a few revolutions would be reversed. After 1000 revolutions the original asymmetry is restored. After 1500 revolutions, reversal again, and so on. We measure specifically the difference frequency between the cyclotron motion and spin precession, and this difference frequency is a direct measure of the correction to the g-factor of the electron. We hope to follow 1000 periods of asymmetry reversal.

The large and controlled number of beam revolutions is obtained through the use of an auxiliary technique. The primary beam is pulsed on for $10^{-7}$ seconds. The beam scatters and forms a spiral. This $10^{-7}$ seconds corresponds to the time for about 50 revolutions. When the spiral beam is at the center of the solenoid, small coils placed on the geometric axis are pulsed on. The radial magnetic field created by these coils acts as a barrier on either side of the beam. The spiraling beam reflects from the barrier fields and drifts back and forth along the solenoid. It cannot reach either foil. At a later time the barrier stationed just before the second scattering is turned off and the beam drifts onto the target.

The construction of the apparatus for this experiment, the gun, solenoid, vacuum system, and circuitry, was completed during this contract year. A photograph of the apparatus is shown in Fig. 10. At present we are conducting tests of the equipment. A circulating beam has been detected and we are engaged with the trapping technique. We should have reliable data at the end of this year. The problem of developing the apparatus and obtaining the first experimental results has been assigned to Arthur A. Schupp as a thesis problem. Schupp has been associated with this work since its inception. K. M. Case pointed out that the new experimental arrangement required further analysis, particularly with regard to the effect on the polarization due to the slight magnetic field inhomogeneity needed for focusing. The summary of their work is published in the thesis of Mendlowitz.[31]

## D. DOUBLE SCATTERING OF ELECTRONS

Double scattering of electrons first gained prominence when Mott[1,2] in 1929 published an exact calculation of the double-scattering cross section of electrons (described by the Dirac wave equation) scattered by the Coulomb field of the nucleus. This theory predicts that the electron beam scattered from the first target (the "polarizer") will be axially symmetric in intensity but will have a partial spin polarization depending on the angle of scattering. If a portion of this scattered beam is allowed to strike a second target (the "analyzer"), the resulting doubly scattered beam will have an axial asymmetry in intensity. The double-scattering cross section has the functional form $\sigma = \sigma(\theta_1, Z_1, E)\sigma(\theta_2, Z_2, E)[1 + S(\theta_1, Z_1, E)S(\theta_2, Z_2, E)\cos \phi_2]$, where $\theta$ and $\phi$ are spherical angles, $Z$ is the nuclear charge number, and $E$ the electron energy. The subscripts refer to the first and second targets. The "asymmetry factor" $\delta$, where

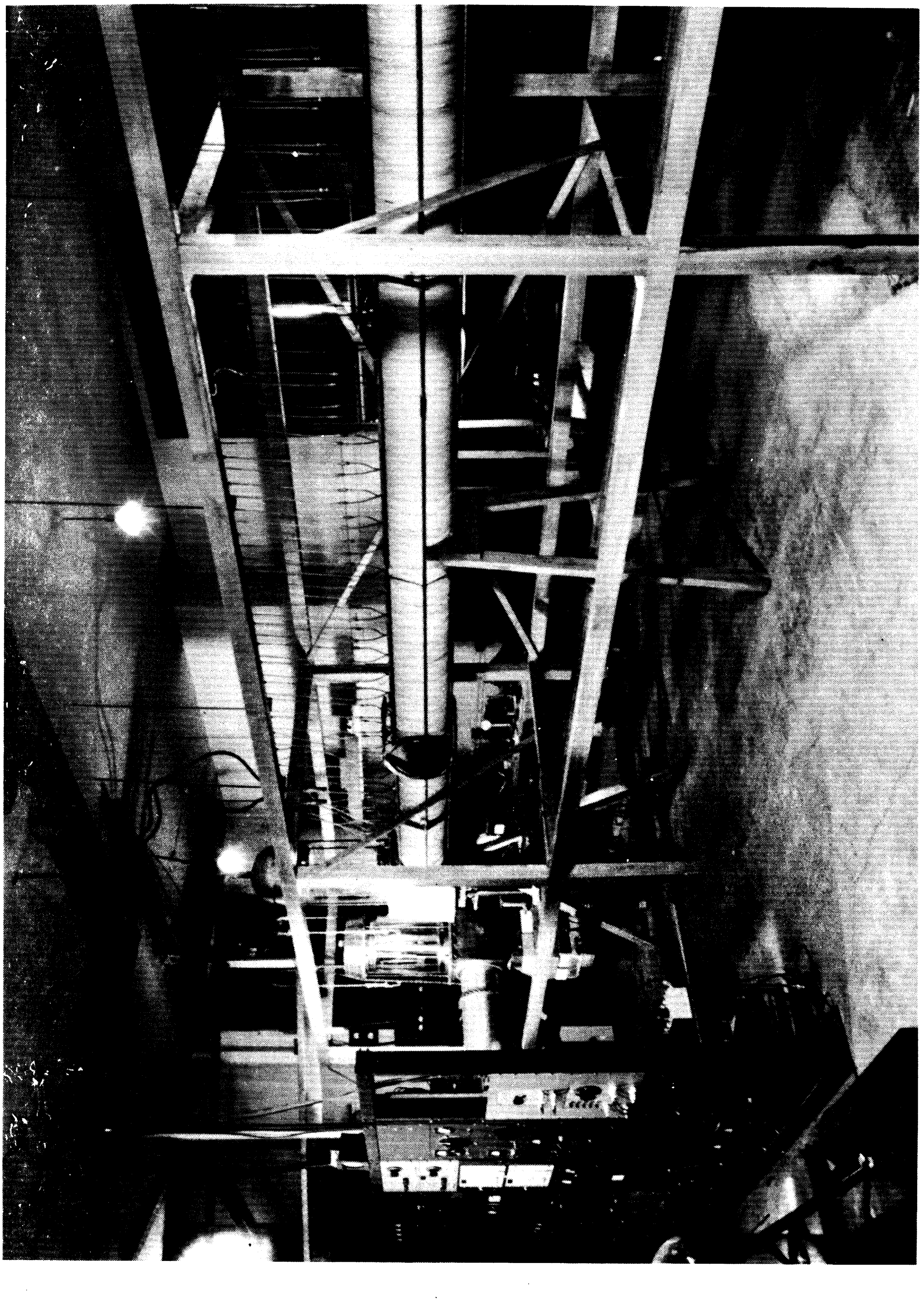

Fig. 10. Photograph of the g-factor experimental apparatus.

$$\delta \equiv S(\theta_1, Z_1, E)\, S(\theta_2, Z_2, E) \quad ,$$

is the quantity of major importance for it embodies the effects of spin-orbit coupling in two scattering events. For $Z_1$ and $Z_2$ large, $\theta_1$ and $\theta_2$ around 135° and E between 100 kev and 500 kev $\delta$ will be about 0.15.

Recently, at our suggestion, Sherman,[3,4] working under AEC contract No. W-7405-eng-48, has calculated $\delta$ for a variety of parameter values on the Livermore Univac. A number of attempts at evaluating $\delta$ when electron screening of the nuclear Coulomb field is included have been attempted.[5-7]

In the decade or so following Mott's publication several attempts[8-18] were made to verify experimentally the Mott theory. All these yielded negative or inconclusive results. Errors in experimental procedure were later recognized in all these experiments. This led to one successful, though very limited in scope, experiment[19] which obtained a value of $\delta$ agreeing with theory to within experimental error. However, only one such value was checked—that for $\theta_1 = \theta_2 = 90°$, $Z_1 = Z_2 = 79$, E = 400 kev. A more recent attempt[20-25] at measuring $\delta$ for several other parameter values of this five-parameter function was considerably less successful. Thus today, twenty-seven years after publication, the Mott theory is still largely unverified. Consequently there is a considerable interest in electron double-scattering experiments. This was brought out a number of times at the recent International Conference on Quantum Interactions of the Free Electron at the University of Maryland (April 23-25, 1956).

Not only does the double-scattering experiment have intrinsic interest of its own, but it has taken on further importance as an essential component of the first experiment for the measurement of the g-factor of the free electron.[26-29] This experiment was conceived by Crane and Pidd and carried out by Louisell on this AEC project. A refinement of this experiment which also utilizes double scattering is now being carried out on this project by Arthur A. Schupp. A theoretical extension of the Mott theory to include magnetic fields intervening between the polarizer and analyzer targets has been carried out by Mendlowitz and Case[30-33] in conjunction with this project.

For these reasons an experimental study of double scattering was undertaken as a thesis problem by Donald Nelson on this project. It is now in the advanced stages. The experimental asymmetry will be found for gold (Z = 79) and cadmium (Z = 48) at E = 121 kev and 75 kev from $\theta$ = 70° to $\theta$ = 170° (the asymmetry below $\theta$ = 70° is negligibly small). Sherman[34] has calculated $\delta$ for these parameter values especially for us. Gold at 121 kev and 75 kev was chosen since the Mohr and Tassie[7] calculation of $\delta$ considering electron screening was carried out for these cases. The experimental procedure is such as to allow dividing out of the data spurious asymmetries such as apparatus asymmetries, finite aperture asymmetry, and apparent asymmetries due to time variations in beam intensity. A magnetic field parallel to the beam between scatterers is being employed to avoid inverse-square loss in beam intensity. At the same time, the background is reduced by moving the counters far from the electron source. Mendlowitz and Case have shown that the effect of the field is only to rotate the asymmetry. Following their method a calculation of the depolarization effects of this field is being carried out by Nelson. Experimental conditions have been chosen to minimize other possible depolarization events such as multiple scattering and plural scattering in the gold foils and scattering from gas, target holders, and beam-defining slits.

The experiments of Nelson and Schupp use a large amount of equipment in common and the two programs are kept in close contact to minimize interference between them. Equipment used in common includes the 150-kv accelerating supply, electron-gun filament and grid supplies, the solenoid for producing the magnetic field used between scatterers, the vacuum system and control circuits, the regulating circuits, and scaling circuits. Thus a double use of the equipment is being obtained even though the two experiments do not utilize all these pieces of apparatus in the same way. For instance, in the double-scattering experiment only the solenoidal field along its axis is used, but this axial field is used even beyond the solenoid ends. In the g-factor experiment only the off-axis field is used and only in the central portion of the solenoid. Also, this apparatus is in a sufficiently versatile form so that further experiments using polarized beams of electrons are possible.

The equipment for the double-scattering experiment is completed. Single scattering has been accomplished and the beam has been focused at the second scattering station. The initial results confirm our expectations of an excellent counting rate after double scattering (as high as 1000 counts per second) and a high signal-to-background ratio (10:1).

## E. FUTURE EXPERIMENTS

Aside from the intrinsic value of both experiments, the g-factor experiment and the double-scattering experiment have a practical interrelationship. We hope, by studying the polarization of electrons at angles larger than 90°, to find an optimum scattering angle for the g-factor experiment. As the scattering angles are made larger, more polarization is obtained but the scattering intensity is reduced. The selection of scattering angles other than the present 90°-90° may improve the intrinsic accuracy of the g-factor experiment.

We have begun studies of other means of preparing a polarized electron beam. There are several untried suggestions in the literature. One of these which we want to try is the photoelectric liberation of polarized electrons from a magnetized metal. We would accelerate these electrons to an energy suitable for the scattering analysis of polarization.

Other studies relate to a modification of the g-factor experiment in basic concept. Since we have a trapped beam of polarized electrons, it appears possible to couple radio-frequency energy into the beam for depolarization. The resonance frequency for depolarization would provide a direct measure of the g-factor of the electron.

Almost all our effort during the next contract year will be concentrated on the conduct of research already begun. It will be possible at best only to explore the feasibility of these new suggestions. They are discussed here principally to suggest, as it appears to us, the new research which may emerge from our present studies.

## REFERENCES

[1] N. F. Mott, Proc. Roy. Soc., A124, 425 (1929).

[2] N. F. Mott, Proc. Roy. Soc., A135, 429 (1932).

[3] N. Sherman, Bull. Am. Phys. Soc. II, 1, 1, 37 (1956).

[4] N. Sherman, UCRL 4664 (unpublished).

[5] J. H. Bartlett, Jr. and T. O. Welton, Phys. Rev., 59, 281 (1941).

[6] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc., A177, 341 (1941).

[7] C. B. O. Mohr and L. J. Tassie, Proc. Phys. Soc. (London), 67, 711 (1954).

[8] R. T. Cox, C. G. McIlwraith, and B. Kurrelmeyer, Proc. Nat. Acad. Sci., 14, 544 (1928).

[9] C. T. Chase, Phys. Rev., 34, 1069 (1929).

[10] C. T. Chase, Phys. Rev., 36, 1060 (1930).

[11] E. G. Dymond, Nature, 128, 149 (1931).

[12] E. G. Dymond, Proc. Roy. Soc., A136, 638 (1932).

[13] E. Rupp, Phys. Z., 33, 937 (1932).

[14] E. Rupp, Z. f. Physik, 88, 242 (1934).

[15] G. P. Thomson, Phil. Mag., 17, 1058 (1934).

[16] E. G. Dymond, Proc. Roy. Soc., A145, 657 (1934).

[17]H. Richter, Ann. d. Physik, 28, 533 (1937).

[18]K. Kikuchi, Proc. Phys. Math. Soc. Japan, 22, 805 (1940).

[19]C. C. Shull, C. T. Chase, and F. E. Myers, Phys. Rev., 63, 29 (1943).

[20]K. Shinohara and N. Ryu, Phys. Soc. Japan, 5, 119 (1950).

[21]N. Ryu, Phys. Soc. Japan, 5, 423 (1950).

[22]N. Ryu, Phys. Soc. Japan, 7, 125 (1952).

[23]N. Ryu, Phys. Soc. Japan, 7, 130 (1952).

[24]N. Ryu, K. Hashimoto, and I. Nonaka, Phys. Soc. Japan, 8, 575 (1953).

[25]N. Ryu, Phys. Soc. Japan, 8, 804 (1953).

[26]H. R. Crane, R. W. Pidd, and W. H. Louisell, Phys. Rev., 91, 475 (1953).

[27]W. H. Louisell, R. W. Pidd, and H. R. Crane, Phys. Rev., 91, 475 (1953).

[28]W. H. Louisell, Thesis, Univ. of Mich., 1953 (unpublished).

[29]W. H. Louisell, R. W. Pidd, and H. R. Crane, Phys. Rev., 94, 7 (1954).

[30]K. M. Case and H. Mendlowitz, Phys. Rev., 91, 475 (1953).

[31]H. Mendlowitz, Thesis, Univ. of Mich., 1953 (unpublished).

[32]H. Mendlowitz and K. M. Case, Phys. Rev., 97, 33 (1955).

[33]H. Mendlowitz and K. M. Case, Phys. Rev., 100, 1551 (1955).

[34]N. Sherman (private communication).

# III. ACCELERATOR DEVELOPMENT

# THE Mk. V INJECTOR

P. R. Chagnon and J. E. Cline

## A. INTRODUCTION

One of the principal factors limiting the usefulness of the Michigan electron synchrotron for certain types of experiments, particularly inelastic electron scattering and experiments in the bremsstrahlung beam, is the intensity of the electron or x-ray beam available. At its present stage, the synchrotron accelerates $10^8$ electrons per pulse, or slightly more. This compares rather unfavorably with the figures of $10^{11}$ or $10^{12}$ which are said to be typical for betatrons and some synchrotrons. This low intensity is attributed to three principal causes: (1) a large fraction of the injected beam is driven into the walls of the vacuum chamber when phase bunching occurs at the beginning of the r-f acceleration cycle; (2) the number of electrons injected is relatively small; (3) the angular divergence of the injection beam is excessive. The first of these difficulties might be alleviated by the use of betatron-type acceleration during the initial period of acceleration, before the r-f is turned on. A preliminary effort has been made in this direction but this project has not yet been carried to its culmination.

The present paper concerns itself with an attempt to remedy the next two difficulties, which are attributed to the injector proper, and describes an entriely new injector, hereinafter called the Mk. V, which has been constructed for use with the Michigan synchrotron. The Annual Report for 1954-55 contained some preliminary remarks on this subject; at present it is possible for a more complete account to be given.

## B. OUTLINE OF THE DESIGN CONSIDERATIONS

A few general remarks are in order before the actual design of the injector optics is discussed. What is desired is to produce a perfectly parallel beam of electrons, the current density of which is to be limited only by space charge. But this is precisely the type of electron beam existing in an infinite planar diode, familiar to all students of elementary electronics. Hence, the electric field <u>within</u> the electron beam must have the planar-diode form:

$$\left.\begin{aligned} E_r &= E_\theta = 0 \ , \\ -E_z &= (\text{const.})\ j^{2/3}\ z^{1/3} \end{aligned}\right\} \quad 0 \leq r \leq a \ , \qquad (1)$$

where z is measured from the cathode (or virtual cathode) in the direction of the electron beam, j is the current density, and $E_r$, $E_\theta$, $E_z$ are the components of electric-field intensity along cylindrical coördinates. In order to generate a planar-diode beam of finite extent, it is necessary that the above field distribution exist everywhere within the beam, and hence the boundary conditions determine the electric field outside the beam region. For a cylindrical beam of radius a, this means that, for r > a,

$$\left.\begin{array}{l} E_\theta = 0 \ , \\ E_z \longrightarrow -(\text{const.})\ j^{2/3}\ z^{1/3} \text{ as } r \rightarrow a \text{ from above} \ , \\ E_r \text{ is determined by } \operatorname{div}(\vec{E}) = 0 \end{array}\right\} \ r > a \ . \qquad (2)$$

These requirements are met in the Pierce electron gun,[1] which consists basically of two electrodes semiempirically designed to achieve the desired external field. The Pierce design does not seem suitable for the present application by reason of its size. The spacing between the electrodes (see design parameters, below) should be about 20 cm, so that in order to preserve a reasonable aspect ratio, i. e., the ratio of radius to spacing, the electrodes would have to be several meters in diameter.

The optical system of the Mk. V injector constitutes an attempt to approximate the ideal field distribution by using a series of plane electrodes, maintained at uniform potential differences, but whose spacings are programmed in such a way as to approximate in a stepwise fashion the desired field. Figure 11 shows the approximate value of $E_z(a)$ in the Mk. V injector as compared to the ideal field distribution. One conical electrode, that surrounding the cathode, is used, since in this region the uniform-field approximation would be very bad. This design permits the overall diameter of the optical system to be made about equal to its length.

An equivalent way of interpreting the action of the optics is to say that, in each gap, electrons are accelerated in a uniform field, with attendant space-charge defocusing, but that, at each electrode, the increase in gradient acts as a positive lens to refocus the beam by an appropriate amount. Evidently some of the beam is lost at each electrode; this is what must be sacrificed for compactness.

## C. DESIGN PARAMETERS

In applying the above considerations to the design of a specific electron gun, one must begin with those parameters which are fixed by the requirements of the synchrotron. In order to reduce the effect of stray magnetic

---

[1] J. R. Pierce. The Theory and Design of Electron Beams. New York: D. Van Nostrand Co., Inc., 1954.

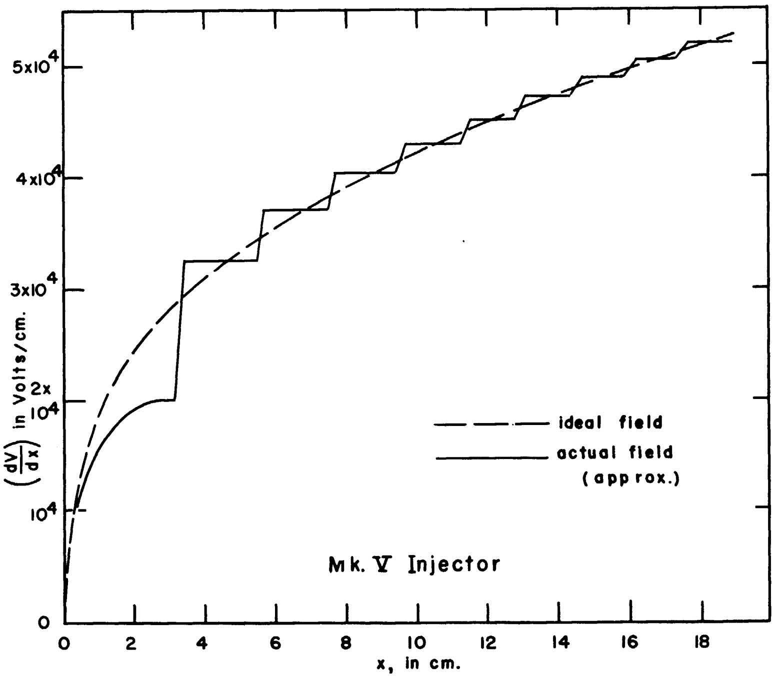

Fig. 11. Ideal and actual graphs of the z-component of electric-field intensity at the edge of the electron beam.

fields and to limit the extent of the frequency modulation required in the accelerating system, a value of 750 kev has been chosen as a desirable injection energy. The physical aperture of the electrostatic inflector is about 1 cm and the vertical acceptance aperture is estimated to be also about 1 cm, so the Mk. V injector is designed to give a circular beam 1 cm in diameter.

If a perfectly parallel beam of high current density is formed, the beam will rapidly spread out, due to the electrostatic repulsion of the electrons for each other. If the electron speed is high, this effect is partially canceled by the mutual magnetic forces among the electrons, but the cancellation is incomplete for speeds appreciably less than the speed of light. Since the space-charge spreading means that the beam becomes divergent as well as enlarged, there is a practical limit to the usable current density of the injected beam. In this case, the current density which leads to a doubling of the beam diameter in 1 meter of travel is about 5 amp/cm$^2$; this therefore was chosen as the current density to be achieved with the new injector. This amounts to a current of over 3 amp peak, or about 1.5 x $10^{13}$ electrons injected during the synchrotron's acceptance time, which is about 1 $\mu$sec. By comparison, the present or Mk. III injector delivers about $10^{12}$ electrons in a rather poorly collimated beam.

To summarize, the Mk. V injector is to deliver electrons at a peak current of some 3 amp at a peak energy of 750,000 volts in a beam 1 cm in diameter.

## D. DESCRIPTION OF THE INJECTOR

1. The Pulse Transformer.—The high-voltage supply for this injector consists of a high-voltage pulse transformer in general similar to that presently in use. It is an air-core transformer wound of flat aluminum ribbon and acetate insulation. There are four turns on the primary and two hundred on the secondary, giving an open-circuit voltage ratio of 50:1. The coupling between the windings is not very tight, however, and this, together with losses in the primary circuit, results in a overall voltage ratio of about 33:1. In operation, a 0.1 μf condenser is charged to 20,000 volts or more and discharged into the primary of the pulse transformer through a triggered spark gap. The secondary voltage waveform is approximately a damped sinusoid having a period of some 15 μsec and a Q of about 5 under load. The useful portion is the peak of the first cycle, where the voltage remains relatively constant for the required 1 μsec. Indications are that it is practicable to draw peak currents of 100 amp or more from this transformer.

Actually, there are two primary windings in parallel, and two secondary windings side by side (P in Fig. 12). The secondaries are connected to each other at both ends by large condensers, so that they are effectively in parallel for the high-voltage pulse. The purpose of the double windings is to permit the power required to heat the cathode to be carried to the high-voltage terminal, which is the inner tubing. There is thus about 110 volts a-c between the secondaries, with stepdown transformers (Q in Fig. 12) located in the high-voltage tube to supply the appropriate heater voltage. A movable grounded plate (R) is adjusted so that the transformer will arc to it, rather than across its windings, should the dielectric strength of the gas (see below) prove insufficient. A metal sleeve connects the pulse transformer to the electron gun proper.

2. The Electron-Optical System.—Figure 13 shows the major components of the beam-forming system, or optics. Electrons are emitted from the dispenser cathode (A) located in the high-voltage head (C). This head also contains the conical copper electrode operated at cathode potential which greatly improves the field distribution near the cathode, as discussed above. The electrons pass through the central holes in the electrodes (G) which are separated by Nonex glass insulators[2] (H). The electrodes are in the form of flat soup plates and their outer edges project into a column of water contained in the jacket (F). This provides a uniform voltage distribution for the electrodes. Each electrode is "dished in" by a different amount, so that the electric field at the center is not uniform but has the form discussed in Section B, above, and shown in Fig. 11. Because of the importance of the field very close to the cathode, an adjustable ring (D) has been provided. This ring screws onto the head (C) and is driven by a nylon gear (E) on a lucite shaft which passes through the water column to an external motor drive. Motion of ring (D) varies

---

[2] These insulators are supplied by the High Voltage Engineering Co., Cambridge, Mass., and used in the ion tubes of that company's Van de Graaff machines.

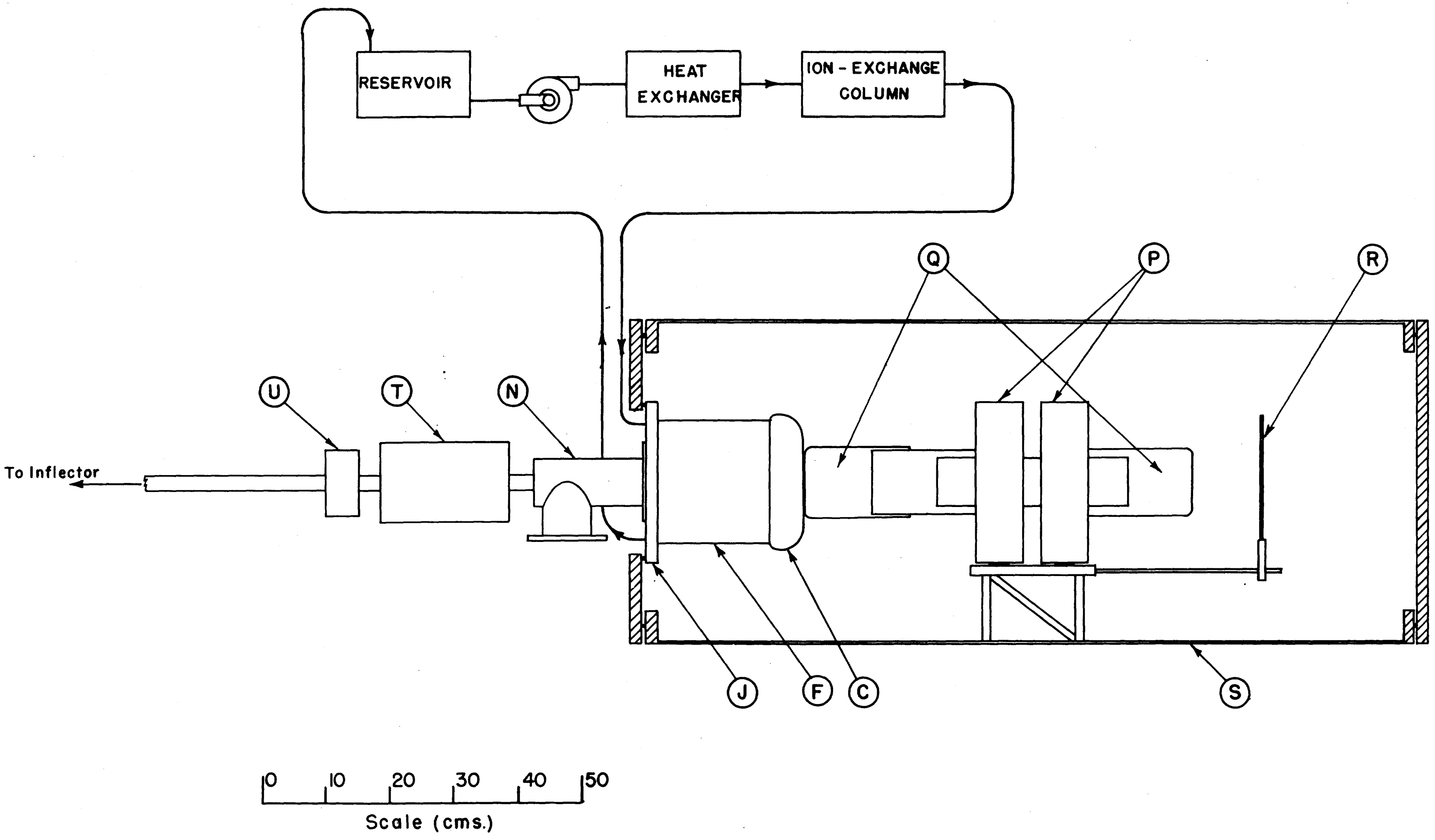

Fig. 12. The Mk. V Injector, assembled, with schematic diagram of water circulating system. (C, F, J, N) as in Fig. 13. (P), pulse-transformer windings: (Q), spaces for filament transformers: (R), grounded plate: (S), iron tank: (T), refocusing magnet: (U), deflection coils.

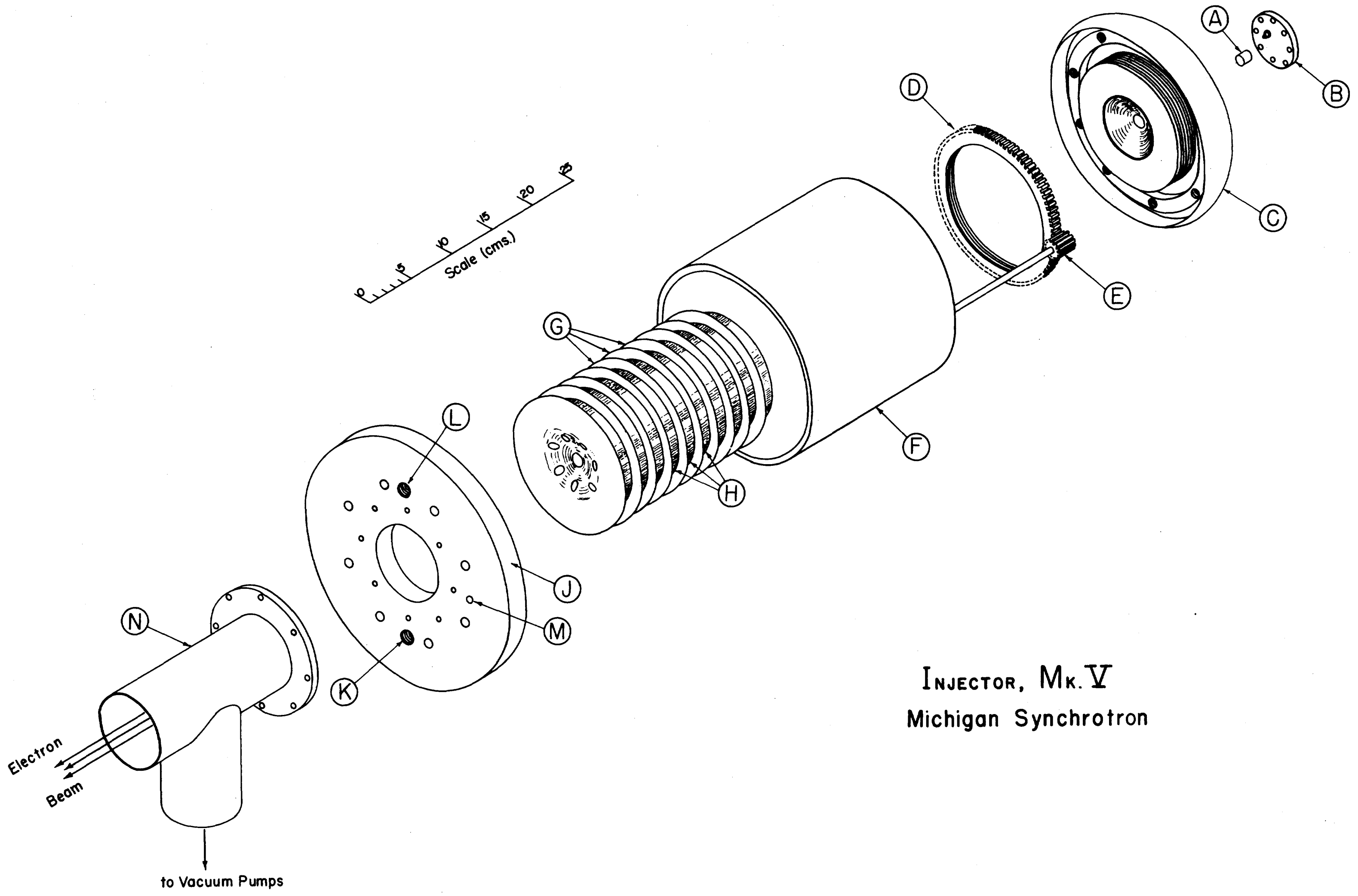

Fig. 13. Exploded view of the electron-optical system. (A), cathode: (B), cathode mounting plate: (C), high-voltage head: (D), focusing ring: (E), focusing drive gear: (F), pyrex jar: (G), electrodes: (H), insulating spacers: (J), base plate: (K), water inlet: (L), water outlet: (M), bushing for focusing shaft: (N), coupling to external vacuum system. Details such as bolts and gaskets have been omitted.

the amount of water between (C) and the first of the rings (G) and so controls the potential difference from the cathode to the first anode so that focusing of the beam may be optimized.

Rings (G) are spun aluminum and contain staggered pumping holes. The rings and insulators were assembled with Vinylseal cement in a jig to insure alignment. The assembly was put under approximately 1800 lb compression and baked at 110°C for twenty-four hours. This forms a single solid unit which has shown no sign whatsoever of vacuum leaks after about six months' immersion in the water jacket.

3. The Cathode Assembly.—The injector requires a flat-disc cathode which will emit 5 amp/cm$^2$ at moderate temperature and will not be destroyed by arcing or minor vacuum leaks. The Philips dispenser cathode[3] meets these requirements very satisfactorily. It consists of a tungsten surface impregnated with oxides of barium and strontium which are driven to the surface when the cathode is heated. The cathode and its helical tungsten heater are assembled on cathode plate (B) with tungsten and tantalum leads (not shown) so that the entire assembly may be removed when it becomes necessary to change a heater. The power for heating required in this geometry is of the order of 200 watts, and one of the major problems left unsolved is that of constructing a heater that will neither burn out nor short to the cathode. Since changing the heater is a rather lengthy operation, it is felt that this problem must be solved before the injector can be installed as part of the synchrotron.

4. Refocusing and Deflection Coils.—When the electron beam emerges from the last, or ground-potential, electrode, the electric field about it suddenly drops from about 50,000 volts/cm to zero. This constitutes a negative lens, and is in fact the only negative lens in the system. In order to compensate for this effect, the refocusing magnet (T, Fig. 12) has been provided. The optimal adjustment of (T) overcompensates for the defocusing and produces a slightly convergent beam, in order to allow for space-charge spreading. The minimum diameter and complete parallelism of the beam therefore occur some distance beyond (T). It is not possible to compensate entirely for space-charge spreading, since a more convergent beam tends to diverge more rapidly. This lens is really two thin magnetic lenses with their magnetic fields opposed, to minimize distortion. The magnetization required is of the order of 3000 amp turns.

The deflection coils (U) are simply a standard television deflection yoke mounted on the beam tube. Currents through the coils are adjustable to allow the beam direction to be varied slightly.

5. The Gas System.—In the past, the injector systems used in this laboratory have been operated in insulating oil. Since the oil must be thoroughly outgassed before each use to prevent the formation of bubbles, opening

---

[3] Cathodes designed especially for the Mk. V injector are supplied by the Philips Laboratories, Irvington, N. Y.

the injector for servicing and reassembling it is an extensive operation. Instead, the Mk. V injector uses a tank containing dielectric gases under pressure, in the manner of Van de Graaff machines. Although the dielectric strengths of materials are generally different for short pulses than for steady voltages, the usual mixture of sulphur hexafluoride and nitrogen has been used as a starting point. Various combinations of $SF_6$, nitrogen, Freon-12, and $CO_2$ have been tried at various pressures. No specific conclusions have been drawn, but it seems clear that there will be no particular difficulty in finding a suitable mixture for work at 750,000 volts.

In addition to the tank (S), an auxiliary storage tank is in use, the gas being transferred from one to the other by means of a refrigerator compressor. Less than 10% of the gas is lost in each complete transfer.

6. The Water Circulating System.—As mentioned above, the bleeder resistor which performs the voltage distribution in the injector optical system is the column of water filling the space between the accelerator stack (G,H) and the pyrex jacket (F). The water serves the additional important function of cooling the cathode head (C). Water is a nonlinear conductor, and one finds that its effective resistivity for these high-voltage pulses is lower than the small-current value by a factor of ten or more. In order to limit the current in the water column to a reasonable value, it is necessary to use highly purified water whose small-current resistivity is at least $10^5$ ohm-cm. Water which has been distilled and then passed through an ion-exchange column is found to be satisfactory for this purpose. The water is allowed to degas for several weeks before use. The complete water circulating system is depicted schematically in Fig. 12. A small ion-exchange column has been incorporated into the circuit in order to counteract the poisoning effect of the metal parts. The heat exchanger cools the circulating water, the temperature rise in the injector itself being some 10°C. The water entering the jacket is first led to the high-voltage end in a Saran tube to cool the cathode head and flows back to the low-voltage end and finally back to its reservoir.

Peak currents in the water column range from 10 to 50 amp. Loading of the pulse transformer, as estimated by the damping of its oscillations, does not seem to be serious even at the latter value.

7. Mechanical Assembly.—Under operating conditions, the accelerator assembly is held together by the pressure of the gases in the main tank. It is sometimes desirable to evacuate the main tank without evacuating both the vacuum system and the water jacket. To provide for this, eight lucite bolts are used to fasten the injector assembly. These bolts, not shown in the figures, screw into the cathode head and pass through the water jacket, through the base plate (J), and are fastened on the outside with cap nuts fitted with watertight gaskets.

Those parts of the vacuum system nominally grounded, namely, parts (J), (N), and the beam tube, are insulated from each other and connected to ground through small resistors so that current measurements can be made. At present, the beam is stopped in a Faraday cup about 1 meter beyond the exit port and current measurements can also be made of the beam reaching this cup.

## E. PRELIMINARY TESTS

Principally because of the remaining problem of finding suitable heaters for the dispenser cathodes, extensive tests of the complete injector have not yet been carried out. Most of the testing has been between 350,000 and 400,000 volts, or about one-half of the anticipated operating voltage. The principal results may be briefly summarized:

1. the electron beam can indeed be focused to a spot less than 2 cm in diameter at 1 meter from the exit port, which is what one has reason to expect;

2. the optimal setting of the focusing ring is near the middle of its range, which indicates that the field near the cathode is approximately correct;

3. the peak beam current at various energies follows the three-halves power law of the planar diode and is roughly 1 amp at half of final voltage, which extrapolates to 3 amp at final voltage;

4. the beam current 1 meter from the exit port is not appreciably less than that at the exit port, which indicates that the beam is a parallel one, within .01 radian.

## F. FUTURE MODIFICATIONS AND INSTALLATION

In view of the results listed above, there appears to be no need for any basic modification in Mk. V. If it should ever be desired to operate at higher current densities, lower energies, or both, all that would be necessary would be to remove or short circuit some of the electrodes, starting from the ground end, until the desired had been reached.

No definite plans have been made as yet for installation of the injector as a part of the Michigan synchrotron. At the present time, the machine is in use continually, and some of the experiments in progress would not benefit from the increased intensity. Because of space limitations, the new injector cannot be placed at the location of the present one, but rather an additional electrostatic deflector would be required to allow the Mk. V to be placed in a suitable location.

Thus at the moment it seems inadvisable to interrupt the operation of the synchrotron. On the other hand, it is expected that the synchrotron will be moved, in about two years, to larger quarters on the North Campus of the University. In this case there would be ample room for the injector to be installed without requiring a crooked beam path, and there would be no additional time lost beyond that required to move the synchrotron.

Nevertheless, if the need for greater intensity becomes any more urgent than it is now, the Mk. V injector will undoubtedly be installed on the machine in its present location.

# IGNITRON SYSTEM FOR EXCITATION OF THE GUIDE FIELD

Glenn Edict

## A. IGNITRON MAGNET-PULSER CONTROL

Since February, 1956, a portion of the synchrotron group effort has been assigned to the task of installing the ignitron magnet-pulser control furnished by Westinghouse. This ignitron control will overcome limitations on maximum energy now imposed partly by the presently used 20-cycle oscillator.

At present the synchrotron magnets and capacitors are connected in parallel to make a system resonant at 20 cycles (Fig. 14). For higher magnetic fields than are possible at present, two ignitrons will be connected between the magnets and capacitors as shown in Fig. 15. The magnets can then be pulsed, each current pulse describing a single complete 20-cycle sine wave. The pulse repetition rate will be variable from 4 per sec at 400 mev to 20 per sec at about 100 mev. The increased repetition rate at lower energies permits maximum use of the machine at these energies.

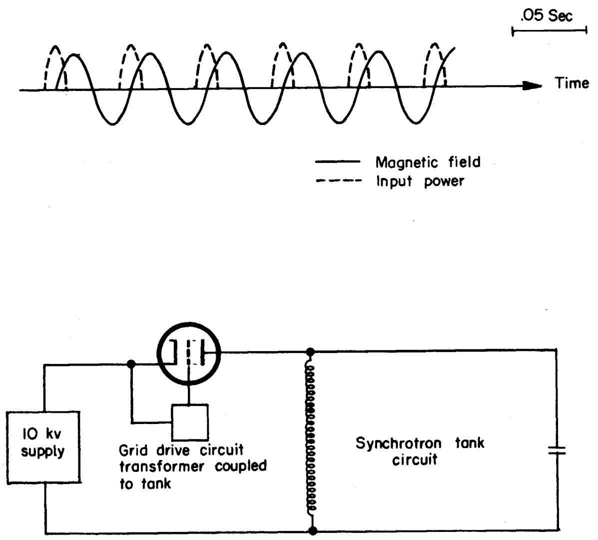

Fig. 14. Synchrotron tank circuit operated at 20 cycles by charging tube connected as an oscillator.

Provisions were made by the manufacturer for the adjustment of certain critical components on the control, and these adjustments have been made. However, circuits involving the operation of auxiliary anodes and firing grids were still not operating correctly, and gross changes in the values of several

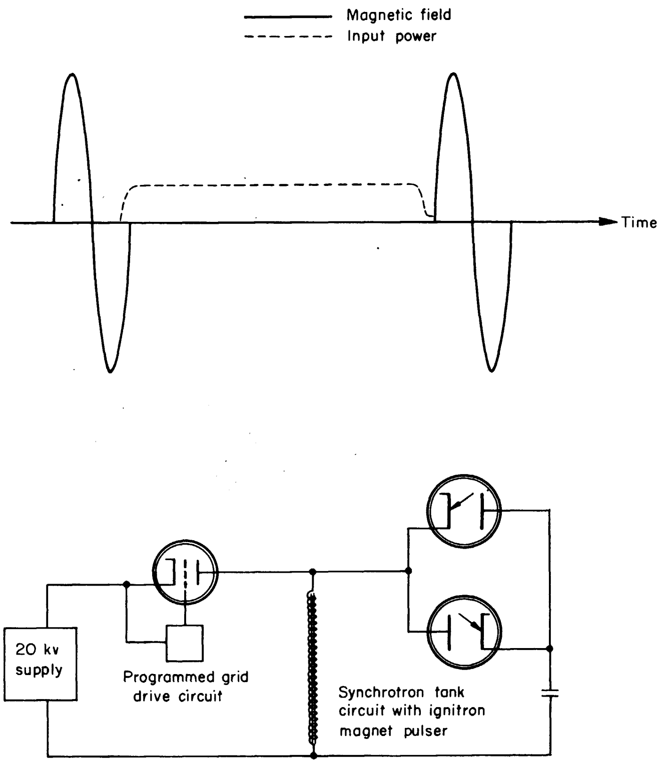

Fig. 15. Ignitrons for operation of synchrotron on 20-cycle pulses.

circuit components used by the manufacturer were required to correct this difficulty. The heat exchanger required for correct operation of the ignitrons, together with auxiliary heaters for satisfying minimum operating temperature requirements on the ignitrons, have been installed, and temperature-limiting and water-flow switches have been adjusted.

## B. CHARGING SYSTEM

Work is nearly complete on the design and construction of circuits which must be used in connection with the ignitron magnet-pulser control for recharging the main synchrotron capacitors between successive pulses. At present a transmitter-type vacuum tube connected as an oscillator, its grid self-biased and transformer-coupled to the 20-cycle synchrotron tank circuit, supplies necessary energy to the tank circuit from a d-c power supply (Fig. 14). This power supply is a conventional 3-phase, full-wave supply, and for economy has been filtered only for the elimination of rectifier switching transients. The oscillator tube may be considered simply a device by which energy is added 20 times a second to the tank circuit, the significant fact being that the resulting peak power demand made on the d-c power equipment is several times greater than the average power demand. While this economical arrangement has proved entirely satisfactory at our present energy of operation, it will prove feasible at higher levels, where the magnets will be pulsed at low repetition rates, only if the peak charging rate with respect to the increased average charging rate is made more nearly unity.

One purpose of the new charging circuit, while still employing a charging tube, will be to obtain a more even charging rate at high magnet energy levels. The charging tube will no longer be connected as an oscillator, but its grid will be driven by a special driving circuit with programmed operation determined by the repetition rate, the maximum permissible charging current, and the peak voltage desired on the main tank capacitors. Advantage will be taken of the fact that at 400-mev operation the magnet current, while still describing a 20-cycle sine wave, will be interrupted by the ignitrons so that four complete pulses will occur per second. The limitation in the repetition rate is imposed by the ignitrons; the magnets conduct current only 20% of the time. The drive circuits of the charging tube will function to insure uniform charging during at least the remainder, or 80%, of the time (Fig. 12). Thus the d-c power supply at 400-mev operation must be designed to furnish peak power only 100/80 times the average power. At lower energies a higher repetition rate will be used and the power demand will again become pulsating in character, an acceptable situation because of the reduced average demand.

A second function of the new charging circuit will be the accurate controlling or regulating of the tank capacitor voltages and peak magnet current. It is expected that this will permit more accurate results in several classes of experiments. The circuits which control the charging tube and the peak tank capacitor voltage may be described briefly as follows. A sample voltage is obtained from the tank capacitors and compared to a carefully regulated reference voltage. The correction is amplified, and chopped at 50 kc, and this latter signal is delivered through a gating circuit, across an air-core isolation transformer to the charging tube grid-drive circuits, where it results, after rectification and appropriate amplification, in a positive signal being applied to the grid of the charge tube. The grid of the charge tube is normally biased at cut-off.

The 50-kc signal will appear at the grid-drive circuits and will result in conduction across the charge tube unless: (1) the tank voltage has increased to the correct operating value—in this situation the 50-kc control signal will automatically be reduced by the regulator circuit to hold the tank voltage at the correct level; (2) the voltage difference between the plate and cathode of the charging tube has exceeded some preset value—this prevents charging during a magnet pulse when the voltage on the tank circuit has reversed as in normal operation, or because of an ignitron fault, and in general insures that charging will take place only when the plate-cathode voltage is such that charging can take place with reasonable efficiency.

## C. AUXILIARY CIRCUITS

Work has been completed on a system of circuits for firing the ignitrons in the ignitron magnet-pulser control. These include:

1. Pulse-shaping circuits for delivering signals of the correct voltage and amplitude to the trigger input of the control. These trigger signals have been specified by the manufacturer of the control.

2. Gating circuits, some of which operate simultaneously, or have overlapping functions to provide maximum protection against:

   a. Firing an ignitron before the other has recovered.

   b. Firing an ignitron when an inverse voltage exists across it.

   c. Firing an ignitron before the charging circuit has returned the tank capacitors to the correct operating voltage.

3. A gating circuit to prevent the operation of the charging circuit immediately following the firing of the first ignitron. This circuit is necessary because, on a magnet pulse, the regulator circuit would normally operate to attempt to keep the tank voltage constant until the charging-tube plate-cathode voltage became sufficiently great to close the charging signal gate. Provision is made to remove or by-pass the gate which prevents charging immediately after the firing of the first ignitron in the event that at high repetition rates it becomes desirable to charge without a time delay on both sides of one of the zero values of the magnet-current sine wave, as is done at present with the oscillator-connected charging tube.

4. A system of interlocks to remove the main power in the event of failure of any of several critical power supplies, such as the charging tube fixed-bias supply.

All circuits have been designed wherever possible with "fail safe" features, the failure of a component, power supply, or tube resulting only in the stopping of necessary equipment with no spuriously generated pulses or signals at the instant of failure. In the few instances where intrinsic "fail safe" techniques could not be used, critical tubes or components have been paralleled, or external interlocks used.

## D. SUMMARY

Water heating and cooling equipment for the ignitrons in the ignitron magnet-pulser control have been installed. Auxiliary circuits and interlocks for firing this control have been completed. Circuits required for recharging the main tank capacitors on pulse operation are now being completed and tested. These circuits will permit essentially uniform demand on the power rectifiers and primary power equipment and will eliminate the need for more costly filtering of the supply or the use of power equipment capable of supplying markedly peaked loads; they will also permit accurately controlled peak magnet currents. The combined effort will permit the magnets to be operated at higher, and more accurately controlled, energies than possible at present.