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THE Mc^2 ISOCHRONOUS CYCLOTRON

A Status Report

June 15, 1962

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ABSTRACT

The status of design studies for the Mc^2 Cyclotron, a high-energy proton accelerator, is reviewed. The cyclotron, an isochronous machine with an eight-sector spiral magnet configuration, would provide a maximum beam energy of 900 Mev. An extracted beam of 100 microamperes at an energy of 810 Mev is planned. Three large shielded experiment rooms with a total area of 24,000 ft are arranged so that several experiments can be set up simultaneously; also, multiple beams can be used with a minimum of mutual interference. In separate chapters the report reviews the following: secondary beams; research programs; experimental area; operation of Cyclotron Analogue II, (the electron model of the Mc^2 Cyclotron); cyclotron design and specifications; magnetic field design; accelerating system; residual radioactivity; shielding; building design; and accelerator research and development. The appendices include: site selection; personnel requirements; tentative scope and cost; and a suggested schedule for design and construction.

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The Mc² Isochronous Cyclotron Facility

FOREWORD

The success of the crop of sector-focusing cyclotrons exemplified by the UCLA machine, the Colorado machine, the Berkeley 88-inch, and the Oak Ridge "ORIC" is now so apparent as to fully justify the principles of design and the expense and effort that have been invested in them. The enthusiasm with which the development was being undertaken had been apparent to those who attended the two international conferences that have been devoted to the subject, one at Sea Island, Georgia in February 1959, and one at UCLA in April 1962. This group of machines has been restricted to energies below 100 Mev for protons, but the implications of success are so clear for the energy region of hundreds of Mev that many of the frequency-modulated cyclotrons built in the post-war era must now be regarded as obsolescent. In fact, an illuminating session on "meson factories" formed an important part of the UCLA conference.

In anticipation of this state of affairs, and with the support and encouragement of the Atomic Energy Commission, the Oak Ridge National Laboratory in 1958 undertook to construct an electron model simulating a sector-focused cyclotron that would accelerate protons to a kinetic energy equivalent to about one rest mass. The model, called "Analogue II," performed with complete success, as shown in Figure 5.7 of this proposal, and there is no doubt that protons can be successfully accelerated in unprecedented quantity to rest-mass energies, with modest dee voltages.

The report that follows in these pages is the logical outgrowth of the model work and of the general technical situation. We herein announce our intention to propose next year the construction of an Mc^2 cyclotron with the associated shielding and experimental facilities that experience has shown to be necessary in accelerator projects in order to preclude costly supplementary appropriations after operation has started.

The performance characteristics of meson factories of this kind are so markedly different from those of existing accelerators as to promise the opening of fields of physics, chemistry, and perhaps biology and medicine, that have not yet been explored. In our opinion, respectfully submitted, the United States should consider the construction of two or three accelerators (not necessarily cyclotrons) that can be considered as National centers at which scientists can reach into these fields, to explore the richness and the detail which are to be found when a sufficiently intense particle source provides the point of entry.

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SUMMARY

A research facility for the production and use of intense beams of protons, pions, and muons is described. The accelerator, the Mc² Cyclotron, is an AVF (azimuthally varying field) cyclotron with a maximum energy of 900 Mev. An extracted proton beam of 100 microamperes with an energy of 810 Mev will be available either for direct use or for the production of intense beams of secondary particles.

The proton beam from the cyclotron is directed into a long heavily shielded corridor which contains targets for the production of secondary particles and the deflecting and analyzing magnets which bring beams into the separate experiment rooms. Three heavily shielded experiment rooms have a total usable area of 24,000 ft². A laboratory and office building with a usable floor space of 40,000 ft² is provided.

The new accelerator and associated facilities will permit new and more precise studies of both weak and strong interactions of the elementary particles and will also enable extension of present knowledge of the properties of nuclei and nuclear structure. More refined studies of muonium, mesic atoms, and mesic molecules will be possible. In addition to its use for physics research, the facility will be an important tool for fundamental studies of effects of high-energy radiation on biological systems, including applications in radiation therapy and the problems of space radiation.

The well-known principles on which the accelerator is based have been proved experimentally at ORNL by the successful operation of Cyclotron Analogue II. The Analogue accelerates electrons to an energy of approximately 500 kev, equivalent to 900 Mev for protons in the Mc² Cyclotron. In the Analogue over 2600 orbit turns are achieved in accelerating electrons to full energy; in the proton cyclotron only 900 turns will be required. The analogue has also verified the main features of the expected orbit dynamics.

The Mc^2 Cyclotron will employ the same eight-sector, low-spiral magnet configuration as used in the Analogue. In this fixed-frequency proton machine, two rf cavities between the poles give four accelerations and a total energy gain of 1 Mev per turn; this large rate of energy gain is obtained without use of the expensive gap space required for conventional accelerating structures. The vacuum chamber encloses the whole cyclotron including the magnet, another departure from conventional design. Some pertinent physical characteristics of the machine are as follows:

Beam energy	810 Mev
Mean orbit radius	230 in.
Central magnetic field	4,500 gauss
Maximum magnetic field	18,000 gauss
Magnet diameter	53 ft
Total power (magnet, rf, vacuum)	12 Mw
Vacuum chamber volume	2.6×10^6 liters
Energy gain	1 Mev/turn

Development of the magnet for the Mc^2 Cyclotron is well underway. The first model magnet, a 0.15-scale version of three of the eight sectors, has verified the main features of the design method and yielded estimates of weight and power requirements. Investigations of alternate magnet structures are underway.

Several resonant cavity systems compatible with the magnet configuration are being investigated. Methods were developed to calculate the resonant frequency of cavities of complex shape, to shape the cavities to assure constant gap voltage, and to minimize the rf-power requirements. Models of two cavity types, the TE and the TEM were built and tested. The results verify the design calculations.

1. INTRODUCTION

The New Technology

Recent technological developments have permitted verification of the feasibility of extending the high-intensity characteristic of the fixed-frequency cyclotron to much higher energies. In the race to the very high energies, large areas of physics have been passed over; important fields of research at intermediate energies have received relatively less and less attention. The energy region between the pion and the K-meson thresholds is a case in point. Much important physics remains to be done in this area. The frequency-modulated cyclotrons now operating in this energy range are in full operation, and long waiting periods between runs are the rule. To reinforce research in this field the Oak Ridge National Laboratory is planning to propose the building of a high-intensity cyclotron which will provide a 100-micro-ampere deflected beam of protons at 810 Mev.

High currents in the relativistic region have become feasible with fixed-frequency, azimuthally-varying-field (AVF) accelerators. In these cyclotrons the average magnetic field increases with radius; the axial defocusing thus introduced is overcome by azimuthal hills and valleys in the field. The average magnetic field is shaped to provide isochronism, that is, the particle orbits require the same length of time at all radii, making fixed-frequency acceleration possible. This feature assures at least a 100-fold increase in beam current over that obtained by frequency modulation.

The theory underlying AVF cyclotrons has been known for about 25 years, but it is only recently that accelerator technology has progressed sufficiently to permit the construction of the complex isochronous cyclotrons. At present eight such machines are under construction for operation in the region between 40 and 100 Mev; such machines at Los Angeles, Berkeley, and Oak Ridge have recently begun operating. All the evidence from the operating cyclotrons indicates that AVF machines are indeed capable of high currents, and that the new

cyclotron technology which has grown up with them is capable of extending the energy into the region where the kinetic energy is approximately equivalent to the rest mass of the proton ($E = Mc^2$).

An AVF electron cyclotron constructed at ORNL successfully accelerates electrons to over 500 kev, equivalent to more than 900-Mev protons. From the tests with this model it is concluded that no serious resonances exist in an eight-sector machine which might adversely affect the proton beam before it reaches maximum energy. Most recently, the new isochronous cyclotron (ORIC) at ORNL was successfully test operated with protons to the full radius. Thus, the evidence at ORNL is essentially twofold: (1) The successful operation of ORIC shows that modern cyclotron technology is capable of building the precisely tailored magnetic fields required to assure the acceleration of substantial beams in AVF cyclotrons. (2) The electron model confirms the principle of the isochronous cyclotron in the 800-to 1000-Mev energy range. Many detailed problems still remain, of course, but fundamentally there is every reason to expect that the proposed cyclotron can be built, and that it will perform as expected.

The AVF accelerator, identified hereafter as the Mc^2 Cyclotron because its maximum energy approaches the proton rest mass equivalent, would produce a deflected beam of 100 μ a of protons. This intense beam can be used for the production of secondary particles, pions, muons, neutrons, and neutrinos for a great variety of experiments. The primary protons themselves would also provide an excellent research tool.

Research at Oak Ridge

The Oak Ridge National Laboratory is interested in the Mc^2 Cyclotron for many reasons. It has been clear for some time that a high-intensity accelerator in this energy region should be built, and that it will be a large and complex installation. National laboratories are equipped both for the construction and operation of such a machine. Location at a national laboratory would make the facility available to scientists from

the various universities. ORNL, in particular, has developed considerable competence in cyclotron design, construction and operation, and has, moreover, pioneered in the development of AVF cyclotrons. In addition, the Laboratory has well established groups of research personnel active in the various disciplines required for exploitation of the potentialities of a new research facility of this magnitude.

ORNL has for the past ten years performed extensive work in physics, particularly in nuclear physics. To maintain the physics program of the Laboratory at a high level, a substantial fraction of it should be devoted to the interactions of elementary particles. The Mc^2 Cyclotron suits both the future needs and the present capabilities of the staff. It will extend the range of nuclear physics research to higher energies, where direct processes predominate and are perhaps simpler to understand. It will extend the scope of atomic and molecular research to problems of μ -atoms and molecules, their spectra, and lifetimes. It will provide new fields for research by nuclear chemists, and offer new tools to the biophysicist; in both these fields the Laboratory has established a reputation for research. Beyond that it will extend the research program of the Laboratory into two new areas; various aspects of elementary particle physics, especially some important details of the weak interaction, can be explored with the μ and π beams; and proton-nucleon and pion-nucleon scattering experiments done with great precision, and including polarization effects, will similarly explore the strong interactions.

Graduate Studies at Oak Ridge

The Oak Ridge National Laboratory is currently expanding the program by which its facilities are made available for graduate students at the University of Tennessee and other institutions. It is hoped that in a few years the Laboratory will serve the scientific community by training substantial numbers of graduate students in the sciences. To give the students a balanced choice of research fields,

the addition of the programs made possible by the Mc^2 is most desirable. The cyclotron would add a unique tool for physics and biophysics research, much of which can be usefully conducted in the form of Ph. D. thesis problems in such important fields as weak interactions, nuclear structure, or the interaction of high LET radiation with biological materials. It is envisioned that eventually about 30% of the research will be done in this manner. Also, the Laboratory is placing increased emphasis on temporary post-doctoral appointments. These, too, will be a valuable source of research staff as well as a contribution to the scientific community.

Choice of Energy

The energy of an isochronous cyclotron has an economic upper limit at about 900 Mev; beyond this energy the cost increases rapidly. For example, an increase in energy from 810 Mev to the K production threshold at 1.2 Bev would probably increase the cost of the accelerator by 75 to 100% and make the extraction problem correspondingly more difficult. To this must be added the incremental cost of additional shielding and larger beam handling magnets. The lower limit is set by the nature of the pion production cross section which begins to level off at 450 Mev. We have chosen an eight-sector machine with an extracted beam energy of about 810 Mev for the following reasons: 1) It provides a large yield of secondary particles; pions, muons, and neutrons. 2) It provides these with sufficiently high energies for scattering experiments and with low enough energies for stopped meson experiments. 3) Resonance extraction can be used at this energy in an eight-sector cyclotron. The next lower attractive sector number is six which yields an energy of about 700 Mev, but resonance extraction

may not be as favorable, and the design of a suitable rf system may be more difficult.

Choice of Beam Intensity

In this report the deflected beam intensity is quoted as 100 μ a. This intensity is sufficient to provide well-analyzed beams of mesons, and intense polarized proton beams. It will bring about a hundredfold increase above what is now available, and make many experiments possible which can now be done with the greatest difficulty, if at all. In some cases, most of the mesons must be discarded to achieve highly mono-energetic beams, while in other cases, the full meson intensity will be utilized. Not all experiments will make full use of the 100- μ a beam; for nuclear structure studies 1 μ a is probably sufficient. For short periods in special experiments, on the other hand, beams of 200 μ a may be required and are achievable. The limit of 100 μ a is set primarily by the difficulties involved in handling residual radioactivity in the cyclotron and the beam handling apparatus, magnets, quadrupoles, slits, beam pipes, and beam dumps. For steady beams much in excess of 100 μ a these would require remote handling and maintenance, thus increasing the complexity and cost beyond the limits envisioned for this project. A beam much below 100 μ a would not provide a facility unique and different enough from present accelerators, and would not make sufficient new experiments possible to warrant an enterprise of this magnitude.

Use of Negative Ions

It has been suggested that the acceleration of negative hydrogen ions would provide a beam which could, by stripping to positive ions, be easily removed from the cyclotron. Since the second electron is loosely bound to the atom, there are several mechanisms which might prevent acceleration to high energy. The first of these is breakup of the ion by scattering from the residual gas. It has been demonstrated that with sufficient care the pressure can be held quite low, and this loss mechanism becomes essentially unimportant. The second effect is the breakup

of the ion by the Lorentz force, $V \times B$. Calculations of the penetration of the ion through the potential barrier, taking into account the polarizability of the ion, are pessimistic for the acceleration of these ions to meson-producing energies in the proposed magnetic field. An energy in the Mc^2 range could probably be achieved by reducing the magnetic field and increasing the spiral, but the magnet would become very large. With the proposed magnetic field, however, a beam of H^- ions could be accelerated to intermediate energies. The implications of the available knowledge of H^- stability for high energy cyclotrons are being further investigated.

The Structure of the Report

In subsequent chapters of this report the fields of research made possible by the Mc^2 Cyclotron are outlined, the preliminary development work is summarized, and the status of plans for the facility are reviewed. The production of secondary beams, the proposed experimental programs, and the experimental areas are described in Chapters 2, 3, and 4. Chapter 5 is a brief account of the theory of the AVF Cyclotron, followed by a review of the operation of Cyclotron Analogue II, and some remarks concerning beam extraction. Chapter 6 gives a summary of the design concept of the Mc^2 Cyclotron, while Chapter 7 pertains to the details of magnet design, including recent results from model tests. Chapter 8 discusses several radio-frequency systems for the machine and gives results from experiments with test models. Residual radioactivity and shielding requirements are reviewed in Chapters 9 and 10. Preliminary architectural plans for the facility are presented in Chapter 11. Chapter 12 summarizes the areas of future research and development. Appendices A, B, C, and D describe the proposed site, give preliminary estimate of personnel requirements, outline the scope of the project, and set down a proposed schedule for design and construction. Finally, in Appendix E, the contributors to this report are listed.

2. Mc² CYCLOTRON BEAMS

The cyclotron under consideration is designed to provide an intense extracted beam of 810-Mev protons. The high flux of 810-Mev protons will in turn make it possible to produce secondary beams which will make the machine a most useful tool for nuclear physics research.

Secondary beams should include beams of pi mesons, mu mesons, neutrons, neutrinos, and partially or totally polarized particles. For specific experiments the desired and necessary requirements on the beam may vary considerably, even though the experiments require identical particles at some energies. For example, "good"-geometry as well as "poor"-geometry pion beams are required. The latter is needed, for example, to produce an intense muon beam. To achieve high resolution a sacrifice in intensity may be necessary. Thus, it becomes clear that no single beam-optics arrangement can be used as a permanent set up for all experiments with any given particle. Similarly, the characteristics of a beam cannot be specified, except for general considerations of the capabilities with this cyclotron.

Data for estimating beam characteristics were obtained from reports on the 970-Mev and 660-Mev proton machines at Birmingham and Dubna, respectively, and from other sources.

Proton Beam

The cyclotron will accelerate protons to 810 Mev, with a beam intensity of 100 μ a, extracted; however, the angular divergence and energy spread will be known only after tests with Cyclotron Analogue II are completed. It must be pointed out that not all experiments require the maximum available intensity; in some cases, the high intensity can be detrimental to the experiment--for example, when the background increases more rapidly than the desired counting rate. Thus, provision must be made to produce variable intensities of the primary proton beam. This can be done either at the cyclotron or by accepting only a fraction of the beam produced. The latter alternative may permit simultaneous experiments, or at least testing of equipment and setting up for one experiment while another is in progress.

Pion Beam

The threshold for single- π production by protons on a single nucleon is at 290-Mev proton energy; higher proton energies must be attained, however, before the yield reaches a useful value. Two- π production starts at 600 Mev, and three- π at 935 Mev. For bombardment of heavy nuclei the threshold is lower, due to the Fermi motion of the nucleons inside the nucleus. Although two- π production will be energetically possible for the 810-Mev cyclotron, the yield will be negligible compared with single- π production.

The maximum pion energy possible (with Fermi momentum) is 520 Mev for 810-Mev protons; the shape of the expected yield curve is shown in Fig. 2.1. This shape is not affected by the material of the bombarded target. However, higher yields will be available from higher-Z targets, the dependence being $A^{2/3}$.

Yields of π^+ and π^- mesons obtainable from the beam will differ considerably. According to the isobaric nucleon model one expects the ratio of mesons to be $\pi^+:\pi^0:\pi^- = 11:6:1$ for a target nucleus with equal number of protons and neutrons. In practice, a ratio of $\pi^+:\pi^- = (7\pm 1):1$ is expected from light targets.

A 100- μ a proton beam on a 10-cm thick carbon target is estimated to yield a π^+ flux of $1.0 \times 10^8/\text{s}$ at 45° for a pion energy of 310 ± 2 Mev, into a solid angle of 4.5×10^{-3} steradians. The yield vs energy is shown in Fig. 2.1. The maximum pion intensity does not occur at 45° , however. For example, at 970 Mev the intensity at 20° is about 5 times, and at 10° about 10 times, its value at 45° for the solid angle used above. In addition a pion beam of higher momentum is obtained at the smaller angles. Therefore, it is not unreasonable to expect from the proposed machine a π^+ beam of 150-300 Mev kinetic energy and with $\Delta E = \pm 1$ Mev and an intensity of 10^8 to $10^9 \pi^+/\text{sec}$.

Negative pion beams will be produced in a manner identical to that for the π^+ beam. Since with an external proton beam there is no problem of momentum and charge analysis by the fringing field of the accelerator, one can switch from π^+ to π^- simply by reversing the

Fig. 2.1 Estimated π^+ flux for 810-Mev protons incident on carbon, for a 2-Mev energy spread and a solid angle of 4.5×10^{-3} sr.

polarity of all magnets involved. The expected π^- intensity will be lower by a factor of about seven.

Muon Beam

A muon beam cannot be produced in a target, but must result from the decay of pions. Consequently, muons originate from an extended source, and will form a beam at a small angle to the pion direction. For 400-Mev pions the decay length corresponding to the pion life time is 30 meters; thus, unless the decay path is very long, only a fraction of the pions can contribute to the muon beam.

For monoenergetic pions of momentum p , the lab-system momentum of the muons is distributed almost uniformly over a momentum band from $0.6 p$ to slightly above p . Thus, to obtain a muon beam having a momentum in an arbitrary momentum band within the above limitation, one selects the pion beam with as wide a momentum range as possible just above the momentum band of the desired muons. From a 250-Mev pion beam ($p_\pi = 365 \frac{\text{Mev}}{c}$) with a decay path length of 15 meters one could obtain a muon beam with a momentum of $220 \pm 1 \text{ Mev}/c$ with an intensity of about 0.1% of that of the pion beam.

One must remember that for certain experiments the purity of the muon beam is required to be very high. Thus, for studies of nuclear interactions with μ^- it is desirable to have less than 0.01% pion contamination. Even at this high purity the number of events due to muons and to the contaminant pions will be comparable. With good beam optics and a long additional path length the beam purity can be increased without great loss in muon intensity, since the decay length for 400-Mev muons is close to two miles. Use of counter arrays and absorbers can in some instances increase the effective beam purity by as much as a factor of 1000.

Neutrino Beam

The neutrinos from pion decay can be utilized to study the weak interactions. The maximum intensity is at zero degrees and is independent of the pion momentum (except of course for $p_{\pi} = 0$). For 250-Mev pions roughly half of the neutrinos lie within 20° of the beam direction and have energies greater than 85 Mev. Let us assume for the purpose of a calculation that the neutrinos are parallel to the pion beam and that the pion beam is focused by an 8-in. quadrupole subtending a solid angle of 4.5×10^{-3} radians at the target. For a pion flux of 5×10^8 /sec/2 Mev, and if the quadrupole or system of quadrupoles can focus a pion beam with a 50-Mev energy spread into a beam which will remain parallel over a distance of 30 meters (1 pion decay distance) the neutrino intensity at the target would be about 1.5×10^7 /cm²-sec. It should be recognized that the estimate is extremely optimistic. It indicates, however, that neutrino experiments will probably be feasible with the proposed machine.

Neutron Beam

Neutron beams can be obtained from targets placed in the external proton beam of the cyclotron. A typical set up may consist of a 3-in. thick neutron-producing beryllium target, with the emergent neutron beam defined by concrete and lead collimators and cleaned of charged particles by a magnet placed close to the target. It may be desirable to eliminate charged particles produced in the collimation by a second magnet. A high flux of γ -radiation will, of course, contaminate the beam and must be reduced through the use of lead filters. It may be necessary to deduce the neutron effect from measurements with at least two different filters. (The collision mean free path in lead is 13.8 cm and the radiation length is 0.51 cm.)

A considerable fraction of high-energy neutrons, almost equal in energy to the incident proton energy will come off near zero degrees. The spectrum contains two broad (~ 150 -Mev) maxima superposed on an intense continuum. Energy resolution of such a neutron beam is not possible unless some means of discrimination for either the

neutrons or the neutron-produced particles is provided. For example, for (n,p) elastic scattering measurements a filter can be used in front of the proton detector to accept only the upper end of the neutron spectrum. These methods, however, only ignore part of the beam rather than eliminating it, and, hence, do not reduce the background originating from neutrons of undesired energies.

Polarized Proton Beam

A polarized proton beam could be obtained either by starting with a polarized-proton source prior to acceleration, or by scattering the emerging unpolarized beam. Since most available polarized ion sources are still in the developmental stage, we will consider the second approach only. It has been found that proton polarization by scattering reaches its maximum value at energies and angles corresponding to the diffraction scattering of protons on nuclei. For this kind of scattering the protons are concentrated in a narrow forward cone with an angle of the order of $2\lambda/R$ (λ is the wave length of the incident proton, R is radius of the target nucleus), with a maximum energy close to the incident energy. The maximum polarization of protons produced by diffraction scattering from beryllium is about 60%, and does not change appreciably with energy.

Both quasi-elastic and inelastic scattering will polarize protons; however, the degree of polarization is considerably smaller than for diffraction scattering. The magnitude of proton polarization in quasi-elastic scattering is energy dependent and may become useful at 810 Mev. Since at energies up to 660 Mev diffraction scattering results in 60% polarization and is almost independent of energy, we may assume, however, that this will hold for 810-Mev protons.

3. RESEARCH PROGRAMS

The research programs which will be made possible by the high-intensity 810-Mev cyclotron are rich and varied. New and important data will almost certainly be obtained for both weak and strong interactions of elementary particles. The proposed accelerator should provide an excellent probe for the study of nuclear structure and properties of nuclei. It will also lend itself to fundamental studies of radiation effects on biological systems, including radiation therapy, and problems of space radiation.

The cyclotron will have two principal advantages over existing machines. It will have about 100 times the intensity, and the experimental facilities will be designed to take advantage of this by providing high-quality beams of various particles to well shielded areas. High intensity without a carefully planned and well equipped experimental layout would be wasteful.

In what follows we describe some proposed fields of research which may be performed with the cyclotron. Obviously not all of them can be attacked with equal vigor, and the emphasis they receive will depend largely on the state of science when the machine is completed. One can, however, discern two kinds of research even now: one includes specific experiments of particularly great interest, the other is programmatic research. Some experiments mentioned below which are in the former category may have been done by the time this cyclotron operates, but almost certainly vast areas of research will remain in the latter group. To give an example: the $\mu + p$ weak interaction may be measured sufficiently well in the next five years, but the whole field of π -nucleus interactions should still present ample opportunity for creative and important investigation.

A. Mu-Meson Experiments

The variety of experiments which can be done with mu mesons is very large. The description of the seven fields of study, below, indicates the general areas of research that are promising for a high-intensity cyclotron.

Muon Absorption

Of the three legs of Puppi's weak interaction triangle, muon capture by nuclei is the least well understood at present. Two avenues of progress are discernible. On the one hand, capture in pure hydrogen, deuterium, H-D mixtures, and He^3 promises to reveal the details of the weak capture interaction. As in the history of nuclear beta decay, refinements may be expected to continue to accumulate over the years with increasingly painstaking investigation. High intensity will greatly facilitate the more difficult polarization and angular correlation experiments. On the other hand, once the basic interaction is well pinned down, muon capture in complex nuclei can complement nuclear beta decay in providing information about nuclear structure through nuclear matrix elements, pair correlation functions, etc. The combined theoretical treatment of the nuclear structure effects and the strong interaction renormalization effects on the capture process should continue to propose challenging experiments for years to come.

The current theoretical description of the $\mu + p \rightarrow n + \nu$ reaction is in terms of a Fermi interaction involving four types of coupling, namely, axial vector, vector, pseudoscalar, and "weak magnetism". In contrast with nuclear beta decay the four-momentum transfer q^2 is appreciable. This complicates a test of the universal Fermi interaction (UFI) hypothesis, but on the other hand promises to provide information on the q^2 dependence of the weak interaction form factors, which is not obtainable from beta decay. Among the more interesting questions are: To what extent the universal Fermi interaction hypothesis is confirmed; the nature of the momentum dependence of the form factors; whether predicted virtual pion effects exist, in particular the sign of the pseudoscalar coupling constant (g_P) and the magnitude of the weak magnetism constant (g_M).

Muon capture in hydrogen is the basic reaction for unraveling the μ -capture interaction, similar to the decay of the free neutron for the beta process. Capture in hydrogen is complicated by strong hyperfine effects and by molecule formation. One is now confident that it will be possible to interpret the experiments, since these effects are beginning to be understood. It will be useful to have the results also for capture in pure deuterium, in H-D mixtures, and in He^3 , so as to determine the vector and effective Gamow-Teller coupling constants separately. These will be discussed below under mu-mesic molecules.

For capture rate experiments in hydrogen, the most important feature of the cyclotron facility would be the ability to obtain clean meson beams. The layout of experimental equipment including magnetic analysis, long flight paths, and sufficient shielding are very important. The μ^- beam must be very pure since π^- capture will simulate μ^- capture and neutrons in the beam will simulate neutrons from the capture reaction. The target must be of very carefully controlled isotopic content; either extremely pure H, or D, or of precisely known mixture. The rates of various atomic and molecular processes depend strongly on the mixture. The number of fusions, $p + d \rightarrow \text{He}^3$, can act as a convenient monitor of the deuterium concentration.

Much additional information is to be gained from more difficult experiments such as the following:

(1) The asymmetry of the emitted neutron relative to the polarization of the muon in its K orbit. The induced pseudoscalar interaction should show up strongly. A 40% asymmetry is expected.

(2) The neutron helicity. This gives the neutrino helicity independent of the sign or magnitude of the muon polarization. In view of the possibility of different kinds of neutrinos it is of interest to determine the neutrino helicity independently for each process.

(3) Radiative capture $\mu^- + p \rightarrow n + \nu + \gamma$.

(a) The asymmetry of the γ distribution together with its circular polarization gives the muon polarization just before capture.

(b) The spectrum of the γ ray gives the momentum transfer dependent form factor of the pseudoscalar interaction, by which the induced pseudoscalar can be distinguished from a pseudoscalar bare coupling in the Fermi interaction.

(c) The (n, γ) correlation provides an analogue to the classical recoil-electron correlation in beta decay. It would distinguish between S and V Fermi components and between T and A Gamow-Teller components. While the universality of V-A is expected, it should be confirmed experimentally for μ capture.

(4) (n, n) correlation in $\mu^- + D \rightarrow 2n + \nu$ could give information on the n-n interaction. Unfortunately the simpler measurement of the neutron spectrum is relatively insensitive to the effective range.

Almost all the information on the μ -capture interaction has come, so far, from measurements of partial or total capture rates in complex nuclei. The results have shown that $g_A^{(\mu)}$ is within 30% of $g_A^{(\beta)}$ and that Primakoff's theory of nuclear structure effects is rather good. In addition, a measurement of the asymmetry of the emitted neutron distribution about the initial mu polarization direction has verified the non-conservation of parity and the existence of an effective pseudoscalar coupling with $g_P/g_A > 0$, in agreement with the UFI. Capture in hydrogen, deuterium, and He^3 should pin down the interaction. Experiments in complex nuclei can then be used primarily for information on nuclear structure, much as beta decay is being used since the "clarification" of the interaction.

Pi-mesic hydrogen has not yet been detected because nothing is transparent to the X-rays. With a sufficient intensity of pions one might use a proportional counter containing hydrogen gas. If atomic transitions to the 1S state are not prevented by the Day-Snow-Sucher effect, one would hope to measure the strong π -p interaction through the energy shift and width of the 1S level.

Rare Processes: Intermediate bosons and 2nd order weak processes.

There is considerable interest at present in the possibility that the weak Fermi interaction, which is a contact interaction involving four fermion fields, is not a basic interaction. Instead it is conjectured that, as in the electromagnetic and strong interactions, a boson is exchanged between two pairs of fermions. This idea, which goes back to Yukawa, is very attractive from the standpoint of simplicity and could serve to remove the stumbling block of the non-renormalizability of the weak interactions.

The hypothesis of bosons mediating the weak interactions implies an increased rate for some of the rarer decay modes. The enhanced rate predicted for the so far unobserved decay $\mu \rightarrow e + \gamma$ would be in conflict with the experimental upper limit. It has been suggested that the intermediate boson hypothesis could be saved, however, if the neutrino ν_μ involved in mu capture and in $\pi \rightarrow \mu + \nu$ were different from the neutrino ν_e involved in beta decay and in $\pi \rightarrow e + \nu$. If $\nu_e \neq \nu_\mu$, then $\mu \rightarrow e + \gamma$ and various other reactions are expected to be non-existent.

All proposed proofs that $\nu_\mu \neq \nu_e$, which seems to be necessary to maintain the intermediate boson hypothesis, depend on the non-existence of various decays or reactions (e.g., neutrino capture reactions). Experimental upper limits on reaction rates are never in themselves conclusive evidence for non-existence. However, direct evidence for intermediate bosons together with a sufficiently low upper limit on a reaction rate would serve almost as well. The upper limit would have to be below the rate to be expected for the decay regarded as a second (or higher) order process in the ordinary Fermi weak interaction. This would require a considerable improvement over present experiments.

Thus, experiments at low energies aiming to elucidate the fundamental nature of the weak interaction will be designed to:

(1) establish whether or not ν_e and ν_μ are the same by lowering upper limits on presently unobserved processes, or

alternatively by observing one such "forbidden" process;

(2) detect effects of intermediate bosons on weak processes;

or

(3) detect second order processes.

A fourth kind of experiment, aiming at direct detection of an intermediate boson, is ruled out for the cyclotron because the mass of the boson has to be greater than that of a K meson; consequently, the meson could not be produced with the available energy. Neutrino-capture experiments are discussed in a later section. Other rare or unusual decay modes and forms of interaction that may be looked for include: $\mu \rightarrow 3e$; $\mu + P \rightarrow e + P$; and $\mu^+ + e^- \rightarrow \mu^- + e^+$. The latter is discussed under the heading of muonium.

The pion decay mode $\pi^+ \rightarrow \pi^0 + e^+ + \nu$ with an expected branching ratio of 10^{-8} is being looked for. One could go on to measure the (π^0, e^+) correlation which would distinguish the V and S couplings. Similarly the (e^+, γ) correlation in the rare mode ($BR \sim 10^{-6}$) $\pi^+ \rightarrow e^+ + \nu + \gamma$ is of interest because of terms dependent on the structure of the vertex. Spark chambers may make such experiments much easier to do.

Basic Properties of the Muon

Increasingly precise values of the basic constants characterizing the muon will be needed as time goes on. The mass and anomalous magnetic moment are important for quantum electrodynamics. The parameters for mu decay have fundamental significance for the theory of weak interactions. These parameters also affect the precision with which other quantities can be obtained. A national laboratory is well suited to pursuing a program of such careful measurements.

In view of the recognized importance and the familiarity of the properties we merely list them: (1) Mass, (2) Magnetic moment anomaly: $(g/2 - 1)$. Present data show agreement with the first radiative correction $(\alpha/2\pi)$; it should be possible to test the α^2 term,

(3) Upper limit on electric dipole moment, (4) Lifetime, (5) Michel's parameter ρ (discussed above), and the asymmetry parameter. Pure and intense beam of muons may enable more precise measurements of all or some of the above quantities.

Muonium

Production of muonium (μ^+e^-) has been detected in dense argon gas by measuring the precession frequency of its magnetic moment in a magnetic field by microwave techniques. A preliminary measurement of the hyperfine structure intervals has been made. If the muon differs slightly from being merely a "heavy electron", the differences in its electromagnetic behavior should show up most easily in the precision measurements that are possible with muonium.

In analogy with $K^0 \rightarrow \bar{K}^0$ transitions, muonium (μ^+e^-) might convert into antimuonium (μ^-e^+). The possibilities are:

1. No direct coupling is present:

- a. If $\nu_e \neq \nu_\mu$, then conversion should not occur.
- b. If $\nu_e = \nu_\mu$, then conversion should occur as a second order process in the mu-decay interaction; however, the rate of conversion would be only 10^{-10} times the rate of the decay of the muon, and so could not be observed.

2. If a direct weak interaction coupling the neutral current of μ^+e^- with the μ^-e^+ exists, the probability that the muon decays as a μ^- is $\approx 2.5 \times 10^{-5}$, assuming that the coupling constant has the "universal" value, $g_V \sim 3 \times 10^{-49}$ erg cm³. No example of any weak interaction involving a neutral current has been observed to date. Such examples have been sought in K^+ and Σ^+ decays.

Once again the lowering of an upper limit on the rate of an unobserved process appears as a likely prospect, one which could still be important in several years. Feinberg and Weinberg have examined environmental effects, concluding that conversion could be observed only in dilute inert gases where muonium cannot be easily formed. The problems involved in producing muonium in a solid and quickly getting it into the gas may resist solution for some time.

Mu-meson Scattering

Mu mesons may be scattered from nucleons or nuclei to obtain form factors for charge and magnetic moment distributions. Although the intensity will be too low to seriously compete with unpolarized electron scattering, such experiments could provide a useful check. Inelastic mu scattering might add something to the information obtained from inelastic scattering of electrons.

The muon beam has the advantage of being polarized. Its intensity and degree of polarization are favorable in comparison with what could be obtained with existing electron beams. Thus, mu scattering may become important for studying phases of amplitudes and spin dependences.

Mesic Molecules

The present interest in mu-mesic molecules is mainly limited to hydrogen and deuterium, in which the detailed molecular properties have a strong influence on the rates of the $p + d$ fusion reaction and of mu-meson capture by P, D, and He^3 .

In isotopically pure hydrogen mu capture occurs both from the atom ($\text{P}\mu^-$) and from the molecular ion ($\text{P}\mu^- \text{P}^+$). One needs to know the relative amounts of ($\text{P}\mu^-$) and ($\text{P}\mu^- \text{P}$), the relative populations of the various hyperfine states, and the magnitude of the muon wave function at the proton in the molecular ion.

The absorption in liquid H_2 gives a measurement primarily of the capture rate in the singlet state (Λ_0). Measurements in the gas would also give only Λ_0 because of the Gerstein-Zeldovitch collisional exchange mechanism, $(\text{P}\mu^-)_{\text{F}=1} + \text{H}_2 \rightarrow (\text{P}\mu^-)_{\text{F}=0} + \text{H}_2$, which becomes more important as the density is increased. Use of the liquid is preferable because of the higher density. It has been suggested that by distinguishing between early and late neutron counts, Λ_0 and Λ_1 may be obtained separately.

In H-D mixtures capture absorption of muons by He^3 atoms present as reaction products seriously complicates interpretation

of data. However, absorption by He^3 is an interesting problem in itself which could be studied.

Mesic Atoms

One can study the capture of the negative muon and pion into atomic orbits, the bound decay rate, depolarization, the mesonic X-rays and Auger electrons, and radiationless transitions of several kinds.

A negative μ behaves essentially as a heavy electron and can be captured by an atom into an orbit characteristic of its greater mass. After capture the μ^- passes by radiative transitions, Auger processes, and in the final stages also possibly by radiationless transitions (with the energy taken up by the nucleus) to its $1s$ orbit, where after a time it may decay or be absorbed by the nucleus. Negative pi mesons will also undergo similar processes, but because of their stronger nuclear interaction will often be absorbed from excited orbits.

Atomic physics is basically determined by the electromagnetic interaction, probably the best understood interaction in physics. By using mesons in place of electrons some effects become enhanced and some new effects occur. Several properties of the muon are primarily responsible for the special possibilities of mesic-atom physics: (1) The incident muon beam is strongly polarized, and consequently polarization measurements at every subsequent stage (decay electrons, X-rays, nuclear γ rays, etc.) provide useful information. (2) The heavy mass of the meson makes the lower orbits lie well inside the electronic K shell, implying (a) that screening of the nuclear charge by the electrons is negligible, so that accurate theoretical calculations can be made, (b) that the meson can perform as a useful probe of the nucleus (for example, above $Z \approx 45$ the K level is actually within the nuclear radius, and (c) that the hyperfine interaction, vacuum polarization, and K-capture interactions are enhanced relative to those of electrons. (3) The muon possesses a decay mechanism.

There are several anomalies in mesic-atom physics which have not been explained. For example, one of these which was revealed by the systematic measurements of Stearns and Stearns on the X-rays from μ and π mesic atoms indicated unexpectedly low yields in the K and L series in the light mesic atoms. Later measurements by several groups give yields which are higher but still are less than expected. Different theoretical assumptions about the relative frequency of capture into initial orbits would alter the expected number of X-rays. A radiationless transition mechanism has also been contemplated. The solution of the "problem of missing X rays" will require further investigation.

Clarification of the problem could come from the direct measurement of the Auger electrons. Their measurement would require very thin sources and coincidence techniques, which in turn would also require a high-intensity meson beam. A group at this laboratory has special skills in this kind of measurement and has interest in the mu-mesic atom application.

The X-ray spectroscopy of mesic atoms has been for a long time of great interest, but many, if not most of the phenomena, that can be studied are limited by the resolution of the apparatus which may be used with the low intensity meson beams available. To quote from a review article by M. B. Stearns, "However, a real boon will be achieved in mesonic spectroscopy when and if the presently proposed high-intensity, high-energy accelerators are built (e.g., FFAG cyclotrons). This could increase the meson beams by a factor of 100 or more. Regular spectroscopic techniques (e.g., crystal spectrometers in the Mev range) could then be applied to the field and effects which are now impossible or difficult to measure could be readily investigated. All effects of vacuum polarization, spin and anomalous magnetic moment of the μ meson, static quadrupole moments, quadrupole moments of excited states of the nucleus should then be in the realm of easy measurability."

B. Strong Interactions

Even after thirty years of extensive study, nucleon-nucleon scattering still continues to furnish valuable new information concerning nuclear forces. Major advances in experimental techniques during the past decade have made possible polarization, triple-scattering, and spin-correlation experiments. These in turn have led to refinements in the phenomenological phase-shift analyses used to fit the energy dependence of the data. The phases thus obtained have been interpreted by theories which can be categorized as phenomenological potentials, meson-theory, or dispersion theory. The first approach has been the most explored to date, but the last holds the highest hope for success.

The threshold for pion production by nucleon-nucleon collisions is about 290 Mev, but the cross section is sufficiently small below about 400 Mev to be neglected in the nucleon-nucleon elastic scattering analysis. At higher energies, interest centers in the ratios of pion production for the various isotopic spin states, because of the direct evidence for charge symmetry and charge independence of nuclear forces.

Analogously to nucleon-nucleon scattering, the corresponding pion-nucleon experiments can give insight into the basic π -p and π -n interactions. For many years measurements of the differential cross sections and polarizations have been made with the aim of obtaining a unique set of phase shifts in the region below the threshold for meson production. Charge independence has been tested at successively higher energies. More recently, isobar models, final-state interactions, the concept of peripheral interactions, and π - π resonances have assumed prominence.

The further development of experimental techniques, e. g. polarized targets and beams, spark chambers, and higher magnetic fields seems promising enough to indicate that the precise systematic measurements characteristic of low energy nucleon-nucleon interaction studies can be extended up to a Bev.

Nucleon-Nucleon Scattering

It is possible to completely describe nucleon-nucleon scattering in terms of a scattering matrix. The initial and final spin-space density matrices each depend upon 16 independent real scalar parameters. This means that in principle 256 experiments could be performed on the nucleon-nucleon system at a single scattering angle for any given energy. Fortunately, the assumptions of invariances under rotations, space-reflection, and time-reversal, provide relationships between the observables which reduce the number of independent experiments to 9 for the p-p system and 11 for the n-p system (9 also if charge independence is assumed). With the unitarity condition for the scattering matrix, integral relationships are obtained that, for elastic scattering, reduce the number of independent angle-dependent functions at each energy to 5 for the p-p system and 6 for the n-p system. At energies where inelastic scattering is possible, the unitarity condition involves additional states, and the last reduction does not hold true.

In general, more than the minimum number of experiments are essential, chiefly because the dependence of phase shifts on S-matrix elements is not linear and consequently multiple solutions easily arise. Additional experiments are also desirable both to check the theoretical assumptions and to detect possible systematic errors in the measurements. The simplest measurements to make are the total and differential cross sections for an unpolarized beam. These have been made, up to several Bev, for the p-p, n-p (p-n), and n-n (n-d) systems.

Next in complexity are the so-called double scattering experiments in which the beam is polarized in the first scattering and analyzed by the asymmetry in the second scattering. The polarization parameter P thus obtained has been measured for the p-p and n-p systems at selected energies up to about 1.7 Bev. However, the precision of the data, particularly for the n-p scattering, could be considerably improved with either a polarized ion source or higher beam intensities.

Triple scattering experiments require a first scattering to polarize the beam and the third scattering to analyze the beam. It is the intermediate scattering involving the Wolfenstein parameters which is of interest. The depolarization parameter D occurs for coplanar scattering, the rotational parameters R and R' are obtained with the second scattering plane perpendicular to the first, and the longitudinal parameters A and A' are studied by precession of the spins in magnetic fields. These five measurements have been made for the p - p system at 90, 140, 210, and 310 Mev. Measurements on the n - p system are in progress at 140 and 210 Mev. This type of data should be extended in energy and precision.

Finally, the spin-correlation parameters involve the simultaneous measurement of the polarizations of both outgoing nucleons. Only the C_{nn} and C_{kp} parameters for the p - p system have thus far been measured (at 310 to 650 Mev), and only in a very small angular range. Spark chambers can greatly increase the detection efficiency, and a polarized target would greatly increase the effective angular range.

The sparcity of data, particularly above 400 Mev, makes clear the importance of further work at higher energies. Higher energy is an experimental advantage, for the slight decrease in efficiency of measuring polarization on the high energy side is overcompensated by the ability to go to larger angles before encountering the rapid fall off on the low energy side. The presence of inelastic scattering leads to the complication of complex phase shifts with a resultant increase in the number of parameters to be determined. Recent calculations indicate, however, that at 660 Mev the phase shifts for $J > 5$ are essentially real. It seems relatively certain that the usefulness of accurate determination of nucleon-nucleon scattering parameters extends throughout the energy range of the cyclotron.

It would be useful to perform complete sets of measurements at several energies at the same laboratory to systematically study the nucleon-nucleon interaction. Experiments thus performed should lead to greater consistency in the data than would be expected from measurements obtained from several locations. Of course, duplicating experiments should be done where possible to check on possible errors.

Single Pion Production Experiments in Nucleon-Nucleon Collisions

A number of pion production experiments have already been performed with protons in the energy range from 400 to 900 Mev. The total inelastic cross sections have been measured at several energies for the following reactions:

(1) $p + p \rightarrow \pi^+ + n + p$	(5) $p + n \rightarrow \pi^+ + n + n$
(2) $p + p \rightarrow \pi^0 + p + p$	(6) $p + n \rightarrow \pi^- + p + p$
(3) $p + p \rightarrow \pi^+ + d$	(7) $p + n \rightarrow \pi^0 + d$
(4) $p + n \rightarrow \pi^0 + p + n$	

In addition, the branching ratios (2):(1), (3):(1), and (3)+(5)+(6) : (2)+(4) have been investigated in some detail. It is expected that further experimentation in the next few years will greatly reduce the uncertainties in many of the above cross sections and branching ratios.

Experiments measuring the energy spectra of mesons in the reactions (1), (2), (5), and (6) above have also been undertaken at several energies and pion production angles. Pion energy analysis of reaction (4) has not yet been studied nor has an attempt been made at the energy analysis of the outgoing nucleons.

Angular distributions integrated over energy have been measured for the neutral pion in reactions (2) and (4) at 660 Mev. Some experiments of this type have also been done with the outgoing nucleons and charged pions. However, angular distributions of the outgoing particles at a given energy have not yet been made. Such experiments would require high intensity beams even for p-p experiments, not to mention the n-p experiments.

Polarization of the deuteron in reaction (3) above has been measured at 670 Mev at several angles. Further work of this nature may be expected in the next few years, as it has become increasingly evident that polarization experiments aid in the resolution of certain ambiguities. However, due to their difficulty, slow progress can be expected with the presently available proton beams. Polarization measurements on the outgoing neutron and proton have not yet been attempted. In addition, pion production experiments with polarized nucleon beams are of great theoretical interest. Both the asymmetry of the pion production and the polarization of the outgoing nucleons should be examined.

In general, most of the experimental work on single-pion production agrees with Mandelstam's phenomenological theory. The resolution of some of the existing discrepancies will be aided by further experimentation. Almost all of the above-mentioned experiments would be expedited by a higher intensity beam than now available. In addition, a machine producing beams at several energies would aid in the study of the energy variation of the above experimental quantities.

Pion-Nucleon Scattering

Two complex functions of scattering angle are sufficient to specify the scattering matrix for elastic pion-nucleon scattering below the inelastic threshold. Allowing for an arbitrary overall phase, one concludes that three experiments at any angle completely determine the scattering matrix at that angle and energy. Unitarity implies that only two independent experiments need to be done for all angles. The simplest experiments are the measurement of the differential cross section and final proton polarization.

In the most comprehensive experiment to date, an attempt was made to obtain S, P, and D wave phase shifts at 310 Mev where the inelastic cross section is less than 1% of the elastic. Measurement of the polarization was limited, however, by the analyzing power of carbon to angles such that the proton energy was greater than 90 Mev. As a result four sets of phase shifts are in contention. The ambiguity

could be eliminated by measurement of one of the triple scattering parameters which would be relatively easy with a high-intensity pion beam. Although the ambiguity might also be resolved by improvements in the technique for detecting polarization, it is expected that triple scattering data would have considerable value. Because of the non-linearity of the phase-shift equations, and because of the large uncertainties in the data, it is desirable to over-determine the parameters where possible. In particular, it is noted that in some cases the phase shifts may be more sensitive to a triple-scattering parameter than to $P(\theta)$, especially in regions where $P(\theta)$ is small.

An improved method of phase-shift analysis, incorporating a peripheral interaction treatment of elastic and inelastic processes in the higher angular momentum states gives promise that π -nucleon scattering can be used quantitatively to determine the short range π -nucleon interaction. Since much of the inelastic cross section is expected to come from the peripheral-collision region, it should be useful to measure accurately the elastic scattering well into the π -production energy region.

A great variety of experiments on single-pion production would be made possible with a high-intensity machine. In particular, angular correlations and direction-polarization correlations with energy selection are necessary to go beyond the current interest in phenomenological resonance and isobar models. Careful studies of this process would furnish a quantitative tool for the investigation of strong interactions.

Only the simplest experiments on double-pion production have been done so far, e. g. branching ratios and total cross sections. With a high-intensity beam the difficult correlation measurements, which encompass a wider variety than for single-pion production, could be done. Although such experiments may seem rather far removed from present work, they may be essential for further progress in the mesodynamics of the future. It is to be expected that analysis of the production processes using dispersion relations will eventually reach a high degree of usefulness.

Photon production may proceed through the reactions

Precision measurement of the Panofsky ratio, $R = \frac{\pi^- + p \rightarrow \pi^0 + n}{\pi^- + p \rightarrow \gamma + n}$,

is of continuing interest. Some recent values are 1.53, 1.56, 1.40, and 1.62, with error estimates ranging from 0.05 to 0.2. R can be used in calculations of internal conversion coefficients for reactions (1) and (2), above. These can then be compared to the very accurate values predicted from quantum electrodynamics.

Samios has recently obtained the form factor to first order of the $\pi^0 \rightarrow 2\gamma$ vertex for the virtual π^0 in reaction (1). This was obtained for the differential distribution for the Dalitz pairs in (1). With higher intensity beams more precise data should be obtainable for investigating higher order terms.

C. Nuclear Physics

The beams from the Mc^2 Cyclotron should be very useful for the study of nuclei, their structure, and the basic forces which act in them. High-energy protons even now provide interesting information about low-lying states in light nuclei either by $(p, 2p)$ or (p, d) reactions. Muon elastic scattering can be used for nuclear structure studies in a way similar to the present work with electron scattering. The whole field of π -nucleus interaction has been barely touched because of low intensities and lack of energy homogeneity of π beams. Finally, it may be possible to use μ -capture as a means to measure nuclear moments, transition matrix elements, and other properties of nuclear states.

This section describes a few proposed lines of research in nuclear physics. Some are fairly well understood and their importance can be seen clearly now, while other research possibilities are of necessity still vague. It is worthwhile to note their existence, however, since they may unexpectedly grow into important programs.

The Mc^2 Cyclotron as a Nuclear Structure Probe

Protons from the proposed 810-Mev cyclotron would provide a valuable probe of nuclear shell structure, pair correlations and cluster effects. The advantage of the high energy lies in the fact that the impulse approximation becomes valid. In this approximation the impact of a sufficiently fast particle with a nucleus can be interpreted as a sequence of at most a few collisions with individual nucleons treated as if free. The high-energy protons probe the nucleon bound states by knocking out single nucleons, e. g. $(p, 2p)$ and (p, pn) reactions, or by picking up single neutrons, e. g. (p, d) reactions. Clusters can be investigated by knockout processes; (p, pd) and (p, pa) , for example.

Although the value of high-energy proton nucleus collisions to probe nuclear structure has been recognized for some time and a general description of the reaction mechanisms has been given, experiments up to the present time have been done with poor resolution

and are limited to the lightest elements. At 20 Mev the de Broglie wave length is about the size of an average nucleus. At 810 Mev it is almost 8 times smaller. Thus, the high-energy proton makes a cleaner probe of shell structure. It is less encumbered by complications in the reaction mechanism, i. e., by distortion effects and by the possibility of interacting with more than one nucleon. In fact this last point might make possible the acquisition of new information on some fine details of nuclear structure. For example, in low-energy (p, d) experiments it is not always clear whether some of the less strongly excited states are reached through the reaction mechanism or whether they are inherently connected through nuclear structure with the removal of a neutron. Comparison of high- and low-energy data should shed light on this point. There is, however, no apparent need for a continuously variable energy. Probably sufficient information could be obtained by using the proposed 810-Mev cyclotron for the high-energy data and comparing these results with a few experiments done with other existing machines. It might be said that one well-understood probe is more valuable than several poorly-understood probes, and the high-energy protons should constitute a well-understood probe.

In the study of correlations by knockout of clusters, a high-intensity beam is important, if not essential. In the (p, pd) reaction, for example, the direct knockout of deuterons must be distinguished from reactions in which a proton knocks out a proton and subsequently picks up a neutron. These can be distinguished by the angular correlations. In the direct knockout, the correlation would be that predicted for a mass-one particle scattering from a mass-two particle modified by the momentum distribution of the knocked out deuteron. In the scattering plus pickup case, the correlation would be a pickup angular distribution centered about the correlation angle of the (p, 2p) or (p, pn) reaction. In any of the knockout processes the angular correlation gives information about the momentum distribution of the struck particle. In this work very high resolution equipment must be used; both to produce a narrow energy spread in the incident beam, and to measure the energy of reaction products precisely.

Of particular interest to the Brueckner theory would be a detailed determination of the nucleon-nucleon pair correlation function, to be compared with predictions of, say, the Bethe-Goldstone equation. This function can be obtained as the Fourier transform of the diffraction pattern in the angular distribution of inelastic scattering corresponding to excitations up to a few tens of Mev. For this experiment levels need not be resolved so that heavy nuclei, representative of "nuclear matter", could be studied. High intensity would be useful in the necessary elimination of exactly elastic events by demanding coincidence with gamma rays indicating nuclear excitation. Also one may search for "giant" collective resonances. The high intensity permits $p, p' - \gamma$ correlation and p' polarization experiments yielding more detailed information.

Of theoretical interest would be good elastic scattering differential cross section measurements to be compared with scattering from optical potentials calculated from first principles along the lines of Watson's multiple scattering theory. For simplicity, energetic pions, having no spin, would be the most interesting probe in this case. The higher energy available would improve the validity of the impulse approximation in comparison with Rainwater's earlier work along these lines at 80 Mev.

Nuclear Chemistry with Mesons

A strong program in what is currently called nuclear chemistry can be established with the beams available from the cyclotron. (Nuclear chemistry differs from nuclear physics principally by the fact that the former usually studies the residual nuclei in a reaction, and the latter the scattered particle or energetic light products). Separation and identification of the residual nuclei following a pion interaction can reveal the type of reaction. For example, Te^{123} obtained from an I^{127} target bombarded with π^- can only result from $\text{I}^{127} (\pi^-, 4n) \text{Te}^{123}$. Such information supplements cloud chamber and emulsion data as well as the results of counter experiments in the investigation of nuclear cascade or fragmentation processes.

The bulk of the nuclear chemistry work has been done at the University of Chicago by Turkevich, Sugarman, and collaborators. Relative yields for π^- induced reactions were measured for N, O, Zn, Br, As, and Hg. Large targets, of the order of kilograms, were used to stop all the mesons. Reactions such as (π^-, xn) , (π^-, xp) , and $(\pi^-, xpyn)$ were found. Te^{127} was found in reactions with I^{127} , which may result from a $\pi^- - \pi^0$ charge exchange process.

Very recent work at the Berkeley 184-inch cyclotron is devoted to reactions such as $(\pi^-, \pi^- p)$, which are analogues to proton knock-on processes.

Intense pion beams would make a whole new class of experiments possible. Cross sections could be measured precisely at various energies for a number of interesting reactions, e. g. the charge exchange reaction mentioned above. Differences between π^+ and π^- induced reactions could be investigated. Past experiments with emulsions suggest that (π^+, n) reactions are much less probable than (π^-, n) . In fact π^+ "no prong" events are not seen. These experiments should be repeated with nuclear chemistry techniques since one would expect (π^+, n) events to occur in analogy to (p, n) reactions.

So far, very little work has been done on meson-induced fission, and that all with loaded emulsions. Intense meson beams would make several classes of experiments feasible. The "classical" fission measurements: cross sections, total yields, independent yields, fission spallation competition, could be done. Muon-induced fission, for example, presents some tantalizing possibilities. Although it might be assumed that fission would follow μ^- capture, Zaretsky suggested that nuclear excitation as a result of the $2p - 1s$ μ -mesonic atomic transition can cause fission. This mechanism could be distinguished from the absorption-fission process, since a 5-6 Mev γ -ray would follow μ -capture.

D. Neutrino-Capture Experiments

In view of the special preparations required for neutrino-capture experiments and the greater variety of information to be gained at higher energies, it is reasonable to question whether neutrino experiments should be undertaken with the cyclotron. Unlike muon and pion physics, neutrino physics at cyclotron energies does not, at the present state of the art, lend itself to programmatic research. Nevertheless, the developments of the next few years may indicate that experiments at moderate energy are still of interest. For this reason a discussion of the possibilities, as they appear in 1962, is given.

The local Fermi interaction involves a dimensional constant. Because of this, cross sections grow quadratically with energy, becoming sufficiently large that second order terms need to be included when $E \gtrsim 300$ Bev. However, this increase in strength may be cut off, for example, if the weak interactions are actually mediated by vector mesons (only becoming local in the low-energy limit). Considerations of experiments to determine the nature of the weak interactions in the high-energy region are being made by those engaged in proposals for accelerators in the range of hundreds of Bev.

The experiments at low and ultra-high energies do not exhaust the interest in weak interactions. Many outstanding questions can be answered by experiments in the region of moderate energies. Lee and Yang (1960) have surveyed the theoretical questions of interest, and they and also Pontecorvo (1960) have discussed possible experiments. One is interested in whether or not $\nu_\mu = \nu_e$, whether nucleon form factors appear, and whether a boson mediates the interaction.

M. Schwartz has pointed out that for fixed-proton intensity the reaction rates of ν_μ -induced processes are expected to increase more than linearly with proton energy because as the energy increases (a) the multiplicity of pions increases, (b) the distribution of pions is concentrated more in the forward direction, and (c) the cross sections for ν -capture experiments increase, whereas (d) the only major

disadvantage is a decrease in the fraction of pions decaying before traversing a fixed distance. For a quadratic energy dependence the Mc² Cyclotron will produce as many neutrino interactions, albeit at a lower energy, as a 10-Bev accelerator with a 1- μ a beam.

The experiments can be divided into two classes: (1) those for which the effect sought can show up only at high energies (for example, the production of a massive boson, or the suppression of the growth of cross sections by form factors), and (2) those for which high energy is not essential but has been thought desirable to obtain a large reaction rate. The ORNL cyclotron would have to leave class (1) experiments to higher energy machines. But in view of the larger intensity expected with the cyclotron it is found that experiments of class (2) could be performed advantageously with the lower energy neutrinos ($E_\nu \lesssim 200$ Mev) of the proposed ORNL machine. Pontecorvo has in fact emphasized the possibilities of using such neutrinos with reference to the Dubna synchrocyclotron, which has much less intensity.

Two experiments which might be done using the 850-Mev cyclotron are mentioned below. If $\nu_\mu \neq \nu_e$, then muon antineutrinos ($\bar{\nu}_\mu$) would be obtained primarily from π^- decay, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$, although they are also produced in muon decay: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. The beam of electron antineutrinos would be much less intense since the branching ratio of $\pi^- \rightarrow e^-$ decay is small and one would have to rely on $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. The most promising experiments, therefore, involve incident muon neutrinos or antineutrinos. In such experiments the contamination of the $\bar{\nu}_\mu$ beam by $\bar{\nu}_e$'s can be avoided by sweeping the negative muons out the flight path of the neutrino before they decay.

Pontecorvo's Experiment to Test whether $\nu_\mu = \nu_e$.

With $\bar{\nu}_\mu$'s with energies less than 100 Mev one searches for

$$\bar{\nu}_\mu + p \rightarrow e^+ + n \quad (*)$$

This reaction is more easily identifiable than the alternative reaction $\nu_\mu + n \rightarrow e^- + p$, although the cross section for the latter is a few times larger. The competing reaction $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ has a threshold of

~ 100 Mev. If the reaction (*) is seen, $\nu_\mu = \nu_e$. If it is not, then one is interested in obtaining an upper limit for the cross section, as in the $\mu \rightarrow e + \gamma$ experiment discussed previously. Even if the reaction is not seen at Dubna or elsewhere, the higher intensity of the 810-Mev cyclotron should enable lowering the upper limit. An estimate of the reaction rate leads to a result, ~ 1 count/hr if $\nu_\mu = \nu_e$, very similar to that of Reines and of Teng for the Argonne 12-Bev ZGS. Whereas the expected cyclotron proton beam of 6×10^{14} protons/sec is 100 times greater, the reaction cross section at the neutrino energy for the cyclotron experiment is $\sim 3 \times 10^{-40} \text{ cm}^2$ or about one twenty-fifth the "saturated" value occurring for $E_\nu \gtrsim 1$ Bev, as predicted by Lee and Yang assuming the same nucleon form factor as occurs for electromagnetic interactions. The validity of this "proportional vector current" hypothesis can be tested by the higher energy experiments.

Using stopped π 's or μ 's one would have a more nearly mono-energetic beam of neutrinos and could obtain an anchor point for the study of the energy dependence of the neutrino capture cross sections. Needless to say a very intense source of pions or muons is needed.

Test for "Self" Term

The production of an $e^- - e^+$ pair by a neutrino in the Coulomb field of a nucleus may be used to test for a "self" term in the weak interactions. The reaction $(\bar{\nu}_e \text{ or } \nu_e) + Z \rightarrow (\bar{\nu}_e \text{ or } \nu_e) + Z + e^+ + e^-$ is of first order in the weak coupling if there is a "self" or "direct" term in the interaction. The existence of such a term is expected on the hypothesis that the weak Lagrangian is of the form $\mathcal{L}_W = \frac{G}{\sqrt{2}} J J^\dagger$, where $J = (e \bar{\nu}_e) + (\mu \bar{\nu}_\mu) + \dots$ is the charged current. If the self terms do not occur then the reaction could still occur, but as a second order process. The reaction

$$(\bar{\nu}_\mu \text{ or } \nu_\mu) + Z \rightarrow (\bar{\nu}_\mu \text{ or } \nu_\mu) + Z + e^+ + e^-$$

would not occur in first order, but is predicted in second order. (The self terms would give $\mu^+ + \mu^-$ instead of $e^+ + e^-$.)

Another type of experiment would give similar information:

$$(\bar{\nu}_e \text{ or } \nu_e) + e^- \rightarrow (\bar{\nu}_e \text{ or } \nu_e) + e^- \quad (\text{elastic})$$

is of first order in the "self" interaction and otherwise of second order, whereas

$$(\bar{\nu}_\mu \text{ or } \nu_\mu) + e^- \rightarrow (\bar{\nu}_\mu + \nu_\mu) + e^- \quad (\text{elastic})$$

is of second order.

Badalyan and Chou have estimated the first order cross section for the pair production process. It grows faster with energy than the elastic scattering ($\sigma_{\text{scat}} \propto E_\nu$, $\sigma_{e^+e^-} \propto E_\nu^2$). For $Z = 80$ and $E_\nu = 100$ Mev, $\sigma_{e^+e^-} \sim 0.7 \times 10^{-41} \text{ cm}^2$, which is larger than the elastic scattering cross section. As a second advantage, it should be easier to detect the pair production than the elastic scattering. If $\nu_\mu = \nu_e$, the self term could be shown to exist by using neutrinos from pion decay in the pair production experiment, but otherwise ν_e or $\bar{\nu}_e$ would have to come from stopped muons for which the ν_e spectrum is soft.

E. Applied Physics

The Mc^2 cyclotron is designed primarily for the study of nuclear matter and the basic interactions of elementary particles. The various beams may prove very useful, however, for other kinds of research, such as the study of shielding in relation to manned space travel. The question whether neutrons could be produced more economically with accelerators than with reactors may bear reinvestigation. This machine will provide the means for such studies.

There are two additional topics which should be mentioned even if they are not developed here in any detail. One is the study of the solid state by means of radiation-induced damage, and the other is the basic problem of ionization losses of relativistic particles in matter. For both these purposes the cyclotron will furnish useful beams. In radiation damage what is wanted is controlled irradiation over a considerable depth of material. Bev protons have a range of hundreds of grams/cm² and a dE/dx which does not vary greatly for considerable energy losses. On the other extreme, if one wants very high damage in a layer deep inside a material, π^- stars would provide an excellent mechanism. High intensity and good energy resolution are of paramount importance.

Ionization losses for various mesons, as well as for protons, in matter constitutes a somewhat unfashionable and worked-over field right now. It may well be of great practical importance and of some theoretical interest when very high resolution meson beams become available, and have to be stopped in thin targets.

Shielding Studies for Space Flight

The existence of radiation belts around the earth, and intense proton radiation from the sun, greatly complicates the problem of manned space flights. The energy of protons in the radiation belts ranges from a few Mev up to 700 Mev, and the maximum intensity is about 4×10^4 protons/cm²-sec. Most solar proton events have a maximum proton energy of 300 Mev, but a few events have been

observed with energies up to 20 Bev. Except for low orbital flights and short excursions into space, considerable shielding will be necessary to protect the astronaut from this lethal radiation. It is imperative that the weight of the required shield be held to a minimum. To accomplish this one must have detailed information describing the space radiations, the penetration of shields by these radiations, and the interaction of the radiation emerging from the shield with the biological system. Information can be gained on the last two items from cyclotron studies, but only shield penetration studies will be discussed here.

Calculations indicate that protons and secondary radiation from them pose the most difficult shielding problem, and it is expected that if the proper proton shielding is employed there will be more than adequate shielding for the electrons.

In thick shields, which are necessary, nuclear interactions give rise to secondary radiation. This becomes the principal source of the dose for protons above a few hundred Mev. No definitive theoretical calculations or experimental measurements have been completed which enable one to calculate the energy spectra, angular distribution, and intensity of the secondary radiation with sufficient accuracy to determine the protection afforded by a thick shield.

The important secondary radiation consists of protons, neutrons, and gamma rays, with the neutrons posing the most severe biological problem. Since the radiation belts around the earth contain protons with energies up to 700 Mev and since some solar emissions have high intensities of protons around 1 Gev, studies of the secondary radiation resulting from the bombardment of a shield by protons at the energy available from the proposed cyclotron would be valuable.

High beam intensity is important for shielding studies because the attenuation of the secondary radiation in thick shields leads to difficulties in obtaining neutron spectra and angular distributions. Besides the gross shielding properties of matter, the cross sections and the angular distributions for certain important reactions should be

measured in detail. A high-intensity accelerator would facilitate these measurements and, in some cases, might make important measurements feasible which are not possible on present machines because of their lower intensity.

It should also be pointed out that these measurements would lead to more exact designs for future accelerator shields through the direct use of the data as well as providing a check on calculations to be used at higher energies. Experimental and theoretical programs which should give much of the desired information are now in progress; however, many studies that can be done on the proposed machine are well beyond the scope of the present programs.

Neutron Production

From time to time there has been considerable interest in developing an economical electronuclear process for large-scale production of neutrons. A high intensity neutron source could, for example, be used to fission depleted uranium. A neutron source plus depleted uranium might in fact, provide a source of power competitive in cost with large reactors.

The two major units of such an electronuclear plant are an accelerator and a target. Both aspects were studied intensively on the MTA Project during the years 1950-1954. At the time the MTA Project ended, the most feasible and economical accelerator concept was believed to be a linear accelerator for accelerating deuterons to 500 Mev. The target problem was not as well developed, although it appeared that the best target configuration was a beryllium primary target, whose stripped neutrons were multiplied in a uranium secondary target through high-energy fission and spallation reactions. Production of Pu^{239} was achieved through neutron capture by U^{238} in the secondary target and in a surrounding subcritical lattice of depleted uranium.

Developments in radio-frequency engineering and electronuclear technology since 1954 indicate that a re-evaluation of accelerator economics might lead to a very favorable case for a cyclotron instead of a linear accelerator. The Thomas-type cyclotron was evaluated

in the early 1950's as a possible MTA accelerator, but was rejected because of uncertainties about resonances which were expected to limit the attainable energy. Now that model tests have shown that it is quite feasible to build a cyclotron for 810-Mev protons, experience with such a machine should prove useful in evaluating the economics of high-energy, high-current cyclotrons of the AVF type.

Possible applications of this process will require new data on the neutron yield. This information is best obtained by direct measurement of the neutrons emitted from typical primary + secondary target configurations (the "external yield") and the number of fission and capture events occurring within the target (the "internal yield"). The external yield can be determined by a manganese bath technique, which does not require a very intense beam of incident particles. On the other hand, the internal yield values must be measured by nuclear chemical methods, and hence require high beams. While the Mc^2 cyclotron is not proposed as a power producer, it would be useful for a study of this whole question, and especially so for the determination of internal yields from complex target assemblies.

F. Biological and Medical Research

Biological Research

A vigorous biology program is necessary in connection with the Mc^2 accelerator. Its principal concern will be the fundamental investigation of the effects of radiation on biological systems, with concurrent programs oriented toward the treatment of cancer in humans and radiation effects of space travel. The fundamental part of this program exists in the Biology Division.

The problem of the RBE of high energy protons (≥ 20 Mev) is essentially solved for single cell organisms. There are negligible data on multicellular organisms. The RBE of protons as a function of energy should be measured for such systems as a problem in fundamental radiobiology as well as on account of the significance this measurement has for space travel. The Mc^2 accelerator, as it is currently conceived, will produce protons at only one energy. However, for low intensities such as are required in biophysics work, lower energies may be achieved by the following method. The full beam is scattered from a hydrogenous target in the corridor, protons scattered through various angles have different energies. These protons then must be magnetically analyzed and piped into one of the shielded rooms. With the addition of absorbers it should be possible to vary the energy from 400 to 800 Mev in at least four 100-Mev steps. Because dE/dx changes slowly with energy the values of RBE may be predicted to be independent of energy at these high energies. The measurements of RBE are laborious but necessary.

High-energy protons have the advantage that dE/dx is practically constant for a small organism such as a mouse, which can thus be exposed to whole-body radiation. In addition to determining the acute effects of such radiation on 30-day survival, and on the blood-forming elements, gonads, and other radiosensitive organs, its effect on life span, tumor incidence, lens of the eye, and aging changes should also be studied. Such a program requires exposure of several hundred mice at varying dose rates from one to 50 rads/min. In addition to mice, other biological systems can be exposed to this radiation. These include groups of cells, simple organisms, plants, and animals.

The π^- beam which will be produced by the Mc^2 cyclotron provides a source of very high LET radiation at the end of the pion range where stars consisting of protons, alpha particles, and recoil nuclei result in very high localized ionization. Three lines of research can be pursued with the pions.

With monoenergetic pions it is possible to deposit a high LET dose in the interior of an animal without excessive damage to the rest of the tissue. The RBE of such radiation can thus be studied for different organs, in a program which is closely related to the use of pions for cancer therapy. Fairly large animals are required for this investigation.

When the range spectrum of the pions exceeds the thickness of the organism, uniform irradiation with high LET particles can be achieved. Here, again, the principal goal is to study the RBE of pion stars, this time in whole-body irradiation.

Finally, π^- stars can be used to destroy selectively organs which are not readily removed by surgery. The destruction of the pituitary in the treatment of certain tumors is an example. However, the method is a powerful one and can be used for other biological or medical investigations as well.

Experimental facilities required by the biology program do not differ significantly from those available for the physics work. It is proposed to include biophysics stations in the three large experimental rooms as the need for them arises. Much preparatory work in dosimetry and in the preparation and characterization of the beam is necessary before any work on biological materials can be done. Close co-operation with the experimental physicists and machine development group will be necessary for this phase of the program. Once this is achieved, the bombardment of mice will require fairly simple setups, and no special facilities. Again, great attention must be paid to the problem of reducing the background, so that the particle under investigation can safely be regarded as contributing the major part of the dose.

Pion Irradiation for Medical Purposes

The study of the medical uses of pion irradiation has as its ultimate aim the possibility of using a beam of negative pions for the treatment of cancer. Although much preliminary experimentation will be needed, involving work with inanimate objects and with experimental animals, it is thought that there is a good possibility of obtaining the desired goal-- to irradiate human tumors more effectively with negative pions than with currently available sources of radiation.

The advantages to be expected depend on the fact that negative pions produce heavy ionization within a few millimeters from the site where the pion stops and the pion-nucleus interaction occurs.

From a radiobiological standpoint, pion irradiation can be discussed under three headings:

Radiation Distribution - density of ionization inside the body. With X-rays or gamma rays the intensity of ionization decreases steadily as the beam of radiation passes through the body tissue, but a very different sort of thing happens with negative pions. If the amount of ionization produced at the surface of the body is given a relative value of one, then for the major part of the pion's range the amount of ionization remains close to one, until, near the end of the range, it rises steeply to a value between five and fifteen. This means that if the end of the track of the negative pion is made to coincide with the depth at which the tumor is located (by selecting negative pions of a certain energy), it is possible to concentrate most of the irradiation in the tumor volume and thereby spare normal tissues.

Relative Biological Efficiency (RBE) - radiosensitivity as related to linear energy transfer. The highly energetic heavy particles and nuclear fragments that form the star at the end of a negative pion's track, have very short ranges; hence, will produce heavy ionization within a distance measurable in microns. This high LET will certainly result in a high RBE per incident particle and should give a high RBE per rad for tumors as compared to normal cells (see the next section). What the RBE of π^- irradiation will be is quite unknown. Theoretical estimates vary so widely

(from 1 to 20) that this very important question can be answered only by experimentation. It is anticipated that the elucidation of this problem will take a great deal of effort, for the reason that several RBE's are likely, depending on the end point used to determine them: i.e., acute mortality for experimental animals, changes in the weight of certain organs, degree of radiation effect on different tissues and tumors, uptake of iron-59 by bone marrow, and other physiological functions. These and other experimental procedures that have been shown to vary proportionally to radiation dose will be investigated. It is expected that a biology research program will be established which will deal with this problem extensively.

Differential Radiosensitivity - radiosensitivity as related to the "oxygen effect." Tumors vary in their sensitivity to radiation, some are more and others less resistant than surrounding normal tissue. Various, and largely unexplored, factors are important here. One of these factors which has been studied and quantitated is the "oxygen effect." Areas of poorly-oxygenated tumor, because of deficient blood supply, are about two to three times less radiosensitive than well-vascularized, well-oxygenated regions of the same tumor, when radiosensitivity is tested with X rays or gamma rays with an RBE of about one. This relationship of oxygen and radiosensitivity has been reported, however, as being of little or no importance with high RBE radiation. It should be expected, therefore, that in the region of star formation in π^- irradiation, the tumor would be relatively more radiosensitive with respect to normal neighboring tissues. If this occurs, it probably would represent a method of overcoming the oxygen effect that is a handicap in gamma-ray therapy in some tumors. This hypothesis can be tested by irradiating tumor-bearing animals with negative pions and gamma rays.

Even though the use of negative pions in the treatment of cancer seems promising, it is to be realized that many questions will need to be investigated before an attempt may be made to start a clinical trial. In the course of these studies insight should be gained on the biological effects of this novel tool of irradiation. The program would proceed in three

main stages which in chronological order are: Stage I. Studies of beam characteristics, dosimetry, and radiation protection. Stage II. Biological experimentation to determine relative biological efficiency and differential radiosensitivity. Stage III. Clinical trials.

Beam Intensity and Dosimetry - It is estimated that useful dose rates for biological and clinical experiments could be obtained with a flux of about $5 \times 10^6 \pi^- / \text{cm}^2\text{-sec}$. This flux would deliver about 20 rad/min at the end of the particle range. (This figure is very tentative; present theoretical estimates vary by a factor of 5, and this matter should be among the first ones to be studied.) High pion fluxes are not available anywhere at the present; for some time to come the Mc^2 cyclotron will be the only machine with which negative-pion irradiation can be studied.

Negative pions of 100 Mev have a range of about 30 cm in tissue; since no patient or biological system thicker than 30 cm is likely to be irradiated, 100 Mev is the maximum energy that will be required. For ranges of 1 to 2 cm in tissue, pions of very low energy are required. They will be obtained by attenuating more energetic negative pions through an absorber.

It may be necessary to vary the range of negative pions in tissue during irradiation. Heavy ionization occurs in a slice of tissue, the thickness of which is determined essentially by the energy spread of the π^- beam and the extent of the ionization region of the star. Beams with little energy spread deposit most of their energy in a layer of tissue less than 1 cm thick. Although it may be highly desirable in some type of experiments to be able to concentrate most of the irradiation within such close limits, in considering irradiation of human tumors that may measure several centimeters in thickness, this effect would prevent uniform irradiation of the tumor. It will, therefore, be necessary to vary rapidly and continuously the range of the negative pions either by sweeping their energy or by interposing variable thicknesses of an absorber.

In the irradiation of tumors the cross section of the beam should closely correspond to the cross section of the object to be irradiated.

Although there will be a practical limitation to the maximum cross-section area that can be obtained, it is anticipated that cross-section areas of about 300 cm^2 could be achieved with little sacrifice of flux. Careful control and study of the beam will be required to ensure that it is reasonably uniform over its cross section.

Radiation protection. - Because the primary proton beam and the target where negative pions are being produced would be outside the treatment room, protection from them and their associated radiation will be provided by adequate shielding. The matter of protection inside the treatment room is, however, of great concern to its users, experimenters, and possibly to patients. From the decay of negative pions and their interaction with absorbers and the object being irradiated, gamma rays, muons, and fast neutrons will be produced. This may constitute an annoying problem or a hazard, depending on their quantity and the protective measures instituted. Initial study indicates that the patients will not receive an excessive amount of total-body irradiation, but this will need to be carefully studied during the early stages of the program.

Clinical Trials. - After the problems of beam calibration, ranges in tissues, and other physical aspects of this project have been solved, and the preliminary biological experiments described in previous sections have been completed, π^- irradiation will be tried on human patients. Techniques should not be difficult to master; the main problem probably would be the ever-recurring one in radiation therapy: tumor localization, which depends not on machines, but on human limitations.

Single fields should probably be adequate and ideal for treating small lesions. For large tumors, however, it may be necessary to use two or more fields. The reason is that if the lesion is thick, the energy spread of the π^- beam will need to be considerable; it may well be that under these circumstances the ratio between tumor dose and entrance dose is less than 1. Hence the tumor would have to be cross-fired from two or more portals of entry, as is done with X-ray and gamma teletherapy. If

multiple fields are used, provision will be required to carefully align tumor and beam for each position, whether by rotating the patient or by bending the π^- beam.

The Mc^2 isochronous cyclotron being a large and complicated installation might have an unfavorable impact on patients. Aside from the psychological harm this might do, there is the practical consideration that a scared patient that moves, and a patient that moves during treatment is the curse of radiotherapy. Rather than devising ingenious and draconian restraining devices, it seems more humane and practical to set up the treatment room in such a way that it does not look threatening to a sick and bewildered person: painted walls, as little noise as possible, and most of the machine out of sight, if this can be arranged.

In the early stages of clinical trials, only patients with incurable cancers will be treated, because it would not be right to experiment with a patient who might have a lesser but certainly better known chance of being cured by some other means. During this time it should be possible to treat some patients with multiple areas of malignancy with both gamma rays and negative pions to compare the effects of each type of radiation therapy. Patients with very advanced malignant diseases would not be treated with negative pions; because it is difficult to appraise what one has done with this group of patients.

As soon as the usefulness of π^- irradiation has been confirmed, potentially curable patients may be treated in a controlled clinical study. There is no better way of convincing oneself or others that something is curative, than curing with it.

4. EXPERIMENTAL AREA

The experimental area consists of three heavily shielded rooms arranged along a corridor, Fig. 4.1 and a medical facility placed at the end. The experimental areas are large, well shielded, and generously provided with analyzing and steering magnets. Every effort is made to keep the background of unwanted particles in the experimental rooms low, and to separate areas of high radiation hazard from those normally occupied by the experimentalists.

The cyclotron beam is steered down a long corridor which serves two functions: (a) Secondary particles are produced and energy analyzed in the corridor and deflected into the experimental rooms. (b) The corridor provides a flight path of 250 ft for the decay of pions, resulting in a fairly clean muon beam. In general, the proton beam is stopped in the corridor, keeping the source of background as well as intense residual radiation out of the experimental areas.

In designing this area it was realized that extensive and well shielded experimental facilities are necessary if one is to take full advantage of the intense beams made available by the accelerator.

Primary and Secondary Beams

Secondary beams of pions, muons, and neutrons are produced in the corridor. For purposes of this discussion we include the production of polarized protons by elastic scattering from carbon as a secondary beam.

For the production of muons it is proposed that pions be produced at position A, Fig. 4.1 and decay in-flight down the corridor; the resulting muons are deflected by a 90° magnet into the last shielded room. In such an arrangement it is important not to analyze the pion beam since a spectrum of muon energies is obtained from the pion decay. Strong focusing lenses, including a strong focusing deflecting magnet, must be provided from point A essentially all the way to the experiment. The proton beam travels down the beam

Fig. 4.1 Plan view of cyclotron vault and experimental area; thin-walled sections of shielding are backed with earth.

pipe with the mesons, but is not deflected very much by the magnet, and can be dumped some distance beyond it. Additional pion cleaning can be obtained with absorbers in the beam.

For pion experiments, position B is used as the point of production. Pions are then bent and analyzed by a magnet, and steered into the middle experimental area. Strong focusing must be provided from the point of production to the experiment. Forward pions are shown in Fig. 4.1; pions at 90° from the target can enter the room directly, while low-energy pions from the backward direction can be obtained by inverting the magnet. The proton beam is stopped some distance beyond the magnet.

The middle area is also envisioned as the place for neutron experiments. Neutrons are produced in the corridor, position C, and enter the middle room through a hole in the shield wall. Position C is also the location at which polarized protons are produced by scattering from a carbon target. The polarized protons are bent slightly by a small magnet into the large 90° magnet, which directs them into the first experimental area. Good energy analysis for these protons is obtained in this way. The primary proton beam for both neutron and polarized proton production is dumped beyond the large bending magnet.

Neutral pions must be used at the point of production; experiments with them are planned for the first experimental room.

The primary proton beam, unpolarized, will be used in the first experimental room, which is the most heavily shielded. A separate beam-dumping vault is located at the end of this room; it is designed to minimize background when an intense proton beam is used for an experiment.

Good energy analysis for the various beams is provided by the bending magnets in the corridor; additional analysis can be obtained from the switching magnets in each experimental room. Monoenergetic beams are necessary for work with thin targets, which in turn are required in many cases to exploit the full advantages of precise measurements offered by an intense beam.

Shielded Experimental Rooms

The principal shielded experimental rooms are identified as proton, pion, and muon areas. These names simply indicate their primary function as now envisioned, and are not meant to imply an exclusive use for any area. All three rooms are quite similar, about 80 x 100 ft, with a 40-ton bridge crane to service each area. Personnel and small equipment access is provided by mazes, six-feet wide. Large equipment is brought in through plugged doors. Each room has a switching magnet which distributes the incident particle beam to different experiments. It is anticipated that experimental setups will not have to be torn down between runs; long and painful alignment procedures can thus be held to a minimum.

A portion of the floor of each room is excavated to form a pit, which is covered with removable concrete slabs. Radioactive pieces of apparatus, targets, beam monitors, magnet slits, etc. will be stored there. The shield wall between the corridor and each room contains a slot about 6 feet high, running the whole length of the wall. This will be filled with concrete blocks, except for holes through which the beam can pass. Flexibility for future experimental requirements is the purpose of this arrangement. The 6-ft height is to allow easy access and room for large quadrupoles or small magnets which may be buried in the wall. If the shielding in the wall proves insufficient, blocks of heavier material may be substituted for the concrete. Some penetrations will also be included in the walls between the experimental areas, and between the cyclotron and the proton room, for, as yet, unforeseen experimental purposes.

It is anticipated that additional shielding for the counters will be required in each room. Perhaps concrete igloos may be constructed. For this purpose each room will be stocked with a number of shielding blocks, and additional shielding can be procured for an experiment, as needed.

The pion and muon rooms are less well shielded, since it is not planned to bring the primary beam into them. The proton room, on the other hand, has sufficient shielding to accept the whole deflected proton beam. This room is also provided with a beam-dumping vault, which is shielded both from the outside, for health reasons, and from the proton room to keep the background there to a minimum.

The basic advantage of three rooms is that experiments can be in progress in one while people are working in the others. To this end the corridor also has a concrete plug in it, so that adjustments at the far end can be made, while the beam is used in the proton room. Two conditions make the cyclotron inoperable: if work in the upper corridor is in progress, or if the shield wall separating the proton room from the corridor is not intact. Such periods may be utilized for low-beam bombardments ($1 \mu\text{a}$) in the cyclotron vault itself, e. g., for nuclear chemistry irradiations.

The 30-ft wide corridor is provided with two 50-ton cranes, one for each end and two blocked entrances for large equipment access. The corridor will contain magnets, quadrupoles, and beam stops, as well as additional concrete blocks for auxiliary shielding.

Targets and Beam Stops

Targets used for secondary beam production will probably vary from 1 cm to 10 cm in thickness and, depending on the material, will dissipate from 1 to 15 kw of power. This requires water cooling, but otherwise presents no serious heat transfer problem. These targets will become radioactive, of the order of kilocuries for thick targets at equilibrium, and will have to be handled remotely and dropped into lead containers. Thin targets, or targets of suitable material such as carbon or beryllium, will be much less radioactive and easier to handle.

A serious problem is the disposal of the primary beam, only a small portion of which is used to make secondary particles. Beam stops will have to be placed in the corridor to absorb the power and

deal effectively with the radioactivity problem. Current ideas on the subject envision a 3-m long water tank in which the beam will be stopped. The entrance may be through a graphite diaphragm, and the tank itself constructed of pure aluminum to minimize the radiation level. Slow neutron activation in these materials yields no long-lived activity. The water from the beam stops can be drained and circulated through ion exchange columns to extract the radioactivity due to impurities, or Be^7 spallation product from $\text{O}^{16} + \text{p}$. The aluminum shell would contain significant amounts of Na^{24} and Na^{22} , but it can be made cheaply enough to be disposable.

The beam stop in the proton room would similarly be a tank of water with a long graphite entrance slit to admit proton beams from anywhere in the room. The stop itself is in a vault behind a 15-ft concrete-equivalent wall with a narrow slit for beam entrance. The vault has a removable ceiling; crane access is provided for alteration and removal of the tank.

Electronic Wiring and Counting Rooms

It is expected that a very large number of cables, with various impedances and characteristics, will be required for experiments. Fast coincidence circuits will also be necessary. The cables leave the experimental rooms through false floors or walls of the maze. They then enter the principal counting area which is adjacent to the cyclotron control room and close to the area where the power supplies and the regulators for magnets and quadrupoles are located.

Limited amounts of wiring will be installed between the main counting area and individual laboratories for equipment which is either being checked out or requires special care and cannot be moved.

Medical Facility

The medical research and treatment facility is designed for use with negative pions. Since the useful pion energies will be between 30 and 100 Mev, it is important that the irradiation be performed as close to the source of pions as possible, to minimize loss of pions by decay in flight. The pions are made in position D and taken off in the backward direction where low energies are more plentiful. The wall separating the corridor from this medical facility must be as thin as possible and should be made of steel. The pions are bent and enter the lower floor of the facility. Absorbers and analyzing magnets are located on the lower floor while the patient is on the upper floor. The facility is designed so that patients may be irradiated lying down. The medical facility requires other rooms in the same area; the proposed layout is shown in Fig. 4.2.

Fig. 4.2 Section view of suggested layout for a medical facility.

5. CYCLOTRON ANALOGUE II

Cyclotron Analogue II, Fig. 5.1, which achieved first operation in August 1961, was conceived as an experiment to demonstrate the feasibility of isochronous acceleration of particles to kinetic energies approaching the rest mass equivalent energy and to reveal any unexpected phenomena which might prevent the use of the isochronous acceleration for a high-energy, high-current cyclotron. Also, the Analogue will be used for an experimental study of resonant beam extraction.

The performance of the Analogue is almost exactly as calculated. A beam can be obtained at 445 kev in the Analogue with an energy gain per turn of only 170 ev indicating that 2600 turns are achieved. The coupling resonances of the radial and axial motion of the electrons have been clearly identified and shown to cause little attenuation. Measurements of the attenuation of the beam with radius show no beam loss to a radius of 10 in. and a gradual decrease beyond that point. The cause of the attenuation and possible means for its elimination are now being studied.

Theory

In the classical cyclotron, the magnetic field must decrease with radius to provide focusing of the ions toward the median plane. Otherwise, the ions are lost to the dees or the walls of the vacuum chamber after only a few revolutions. The classical cyclotron is not isochronous; the radially decreasing magnetic field necessary for axial focusing produces an undesirable decrease of orbit frequency with radius. Ions initially in phase with the radio frequency gradually get out of step and cease to be accelerated when the phase shift reaches 90° . The mass increase with velocity produces a similar effect and in the classical cyclotron cannot be compensated because of the axial focusing requirements. These two aspects limit the ordinary cyclotron to low energies, typically 20 Mev for protons, and stimulated the development of the frequency-modulated cyclotron, or synchrocyclotron. These machines, however, are limited to low intensities. In recent years there has been much interest in a new class of cyclotrons which are truly isochronous and achieve

Fig. 5.1 Cyclotron Analogue II.

axial focusing by new methods which circumvent the limitations of the classical cyclotron.

In 1938, L. H. Thomas showed that the inclusion of azimuthal variation in the magnetic field of a cyclotron would provide axial focusing forces of sufficient magnitude to free the field shape from the limitation of a negative radial gradient. Briefly, the focusing arises from the non-circular orbit shape introduced by the magnetic field variation with azimuth; the radial velocity component and the azimuthal component of magnetic field produce a force toward the median plane.

In 1956, D. W. Kerst showed that large additional axial focusing forces are produced if the azimuthal variation in the magnetic field is made to spiral. This is an alternating gradient force which derives from the interaction of the angular velocity of the ion with the alternating radial gradient of the spiral magnetic field. It is the spiral focusing that has made cyclotrons in the energy region 400-900 Mev practical. The required magnitude of the azimuthal variation in magnetic field is impractically large for a machine with pure Thomas focusing (straight poles).

In an AVF cyclotron, the magnetic field on the median plane, specialized to a sinusoidal variation with N periods (sectors), may be expressed as

$$B_z(r, \theta) = \langle B(r) \rangle \left\{ 1 + f(r) \cos N[\theta - \zeta(r)] \right\} \quad (1)$$

The term $\langle B(r) \rangle$ is the average of the magnetic field at radius r , $f(r)$ is the amplitude of the azimuthal variation, and $\zeta(r)$ describes the spiral of the magnetic field with radius.

The focusing of the particles is ordinarily expressed in terms of the frequency, ν_z and ν_r . These frequencies* are given approximately by

$$\nu_z^2 = - \frac{R}{\langle B \rangle} \frac{d\langle B \rangle}{dR} + \frac{N^2 + 1}{N^2} F^2 \left\{ 1 + \frac{2N^2 + 1}{N^2 + 1} \tan^2 \gamma + \right. \\ \left. \frac{1}{N^2} \left[\frac{R^2}{F^2} \frac{dF^2}{dR} - \frac{N^2}{N^2 + 1} \left(\frac{R}{F} \frac{dF}{dR} + \frac{R^2}{F} \frac{d^2 F}{dR^2} \right) \right] \right\}$$

*These equations are derived from those of L. Smith and A. A. Garren, UCRL 8598.

$$v_r^2 = 1 + \frac{R}{\langle B \rangle} \frac{d\langle B \rangle}{dR} + \frac{N^2}{(N^2 - 1)(N^2 - 4)} F^2 \left\{ 3 (1 + \tan^2 \gamma) + \right. \\ \left. \frac{5N^2 - 8}{N^2} \frac{R}{F} \frac{dF}{dR} + \frac{N^2 - 1}{N^2} \frac{R^2}{F^2} \left(\frac{dF}{dR} \right)^2 + \frac{N^2 - 4}{N^2} \frac{R^2}{F} \frac{d^2 F}{dR^2} \right\}$$

where: $F^2 = \frac{1}{2} f^2$ and $\tan \gamma = R \frac{d\zeta}{dR}$.

For many purposes, particularly for machines with a large number of sectors, the following equations are adequate:

$$v_z^2 = - \frac{R}{\langle B \rangle} \frac{d\langle B \rangle}{dR} + F^2 (1 + 2 \tan^2 \gamma), \quad (4)$$

$$\text{and } v_r^2 = 1 + \frac{R}{\langle B \rangle} \frac{d\langle B \rangle}{dR}. \quad (5)$$

It can be shown that v_r (in the approximation of Eq. 5, which is independent of sector number) is given by $(1 - \beta^2)^{-1/2}$ and, hence, is numerically equal to the total energy of the particle expressed in units of rest energy. This means, of course, that $v_r = 1$ at the center of the cyclotron and increases monotonically with energy; $v_r = 2$ occurs at a kinetic energy equivalent to the rest energy, which is 938 Mev for protons or 511 kev for electrons. In a machine with a finite number of sectors, however, $v_r = 2$ occurs at a lower energy, for example, at about 815 Mev in an eight-sector cyclotron with moderate spiral. During acceleration the radial focusing frequency will pass through 1/4 integral, 1/3 integral, 1/2 integral, and integral values. For a particular cyclotron, depending on the pole number, these may be regions of instability in the radial motion of the particles. The situation may be briefly categorized by consideration of an equation of the form

$$a v_r + b v_z = n \quad (6)$$

where a , b , and n are zero or integers. Where $n = N$ the number of sectors in the machine, the resonances are called "essential resonances." Otherwise, the resonances are called "imperfection resonances." A resonance with $b = 0$, $a \neq 0$ is a radial resonance; $a = 0$, $b \neq 0$ is an axial resonance. Where neither a nor b are zero, a coupling resonance is described. In a properly designed magnetic field the axial resonances cause no difficulty since ν_z is kept in the range 0.2 to 0.3 away from the imperfection resonance $\nu_z = 1/2$.

The reason for the choice of eight sectors for the Mc^2 Cyclotron can be stated briefly. In a three-sector cyclotron the essential half-integral radial resonance, $2 \nu_r = 3$, causes serious instability. Likewise in a four-sector cyclotron the essential resonance $3 \nu_r = 4$ causes substantial beam loss. Six- and eight-sector machines are free from strong essential resonances; $\nu_r = 3/2$ and $\nu_r = 4/3$ are imperfection resonances; but if the strength of the imperfection harmonics, the third and fourth, are low, no difficulty is anticipated if the ions are started at the center of the cyclotron with low radial amplitude. Eight sectors are preferred for the Mc^2 Cyclotron because the energy at $\nu_r = 2$ is somewhat higher than for six sectors; also, the symmetry easily permits four accelerating gaps per revolution, a situation well suited to rf cavities.

Beam Extraction

The extraction system planned for the Mc^2 Cyclotron is a modification of the Tuck, Teng, LeCouteur scheme. It was developed by M. M. Gordon and T. A. Welton at ORNL. The results of Gordon's studies are summarized in a paper in the proceedings at the 1959 Sector-Focused Cyclotron Conference, Nuclear Science Series Report No. 26. Basically the method depends upon the highly nonlinear (cubic) property of the essential $8/4$ resonance which causes radial oscillations once started to rapidly increase in amplitude. Another property of the resonance is that it is quite weak for small amplitudes so that some perturbation must be introduced in the magnetic field near the extraction radius to develop large coherent radial oscillations. For extraction at

$\nu_r = 2$, a suitable amplitude driving force is introduced by a small second harmonic ($\cos 2\theta$) perturbation in the magnetic field which will drive the 2/1 imperfection resonance and develop sufficient radial amplitude that the non-linear resonance acts strongly.

The study was made using the same basic field parameters, spiral, and flutter of Cyclotron Analogue II and proposed for the Mc^2 Cyclotron. He showed that with a $\cos 2\theta$ field bump of the order of 10^{-3} of the mean field that the rapid growth of organized radial oscillation was achieved. The dynamics were essentially as expected; the radial amplitude gain per turn increased as the third power of the number of turns, and a turn separation of nearly 4 cm was developed before axial instability set in (the radial gain for 1 Mev/turn is about 0.08 cm). The process cannot be allowed to continue indefinitely because the axial oscillation frequency increases with radial amplitude, eventually reaching the value $\nu_z = 1$ where axial stability is lost as a result of the coupling resonance $\nu_r = 2 \nu_z$.

Gordon's studies, although taking into account a reasonable radial amplitude, assumed perfect correlation of energy with turn number. Additional theoretical studies are required to take into account the effects of phase shift of the ions due to an imperfect magnetic field, noise in the accelerating voltage, space charge, and similar effects which affect the energy-turn correlation. Also, the possibility of minimizing the rise in axial focusing frequency with radial amplitude by shaping the magnetic field in the extraction region needs to be investigated. Analogue II will be an invaluable tool for experimental evaluation of beam extraction.

Description of the Electron Cyclotron

The Analogue is an eight-sector, spiral-pole cyclotron with the same basic field parameters, spiral law, flutter, etc. as the Mc^2 Cyclotron; these are listed in the following table.

Table 5.1. Analogue II specifications

Cyclotron unit (c/ω)	16.000 in.
Central field (B_0)	41.926 gauss
Orbit frequency	117.399 Mc/sec
Axial focusing frequency, ν_z	~ 0.2
Energy for $\nu_r = 8/4$	445 kev
Energy for $\nu_z = 0$	530 kev

Electrons are accelerated to, and beyond, the integral resonance, $\nu_r = 2$, which occurs at a kinetic energy of 443 kev ($\nu/c = 0.84$). Axial focusing and an isochronous mean field are provided to an energy of 530 kev. The magnet, a completely iron-free system, shown in exploded view in Fig. 5.2, consists of three principal parts: 8 pairs of sector coils, which produce the proper azimuthal variation and spiral in the magnetic field for axial focusing; five pairs of large circular coils, which, together with the sector coils, produce the average magnetic field required for isochronous orbits; and finally, 32 pairs of trimming coils, which are used for fine adjustment of the average magnetic field to within a few parts in 10^4 of the isochronous requirement. The coil system is mounted on a massive support casting, which serves to maintain precise alignment. A magnet half with the trimming coils removed is shown in Fig. 5.3.

The accelerating system consists of a quarter-wave strip-line resonator driven by a modified commercial communications transmitter operating at a frequency of 117.4 Mc/sec. A feedback loop around the transmitter, with the screen voltage of the final amplifier as the control parameter, stabilizes the output to a few tenths of a percent.

A two-region vacuum system eliminates atmospheric loading from the coil structure and organic materials from the high vacuum beam space. The beam space, separated from the coil system by two thin

Fig. 5.2 In this view of the Analogue, the lower half of the coil system is expanded to show the relation of the various components.

Fig. 5.3 Eight sector coils mounted on the support casting.
The main average field coils are visible between the coils.

aluminum diaphragms, is maintained at a pressure of 10^{-6} torr by a 6-in. mercury diffusion pump, with a liquid nitrogen baffle. The region containing the coil system and its support structure is maintained at about 10 microns by a mechanical pump.

The periphery of high vacuum space is provided with several large ports for the installation of either viewing windows or experimental apparatus. The rear of the vacuum tank has a single large port which permits removal of the dee system without disturbing the precise alignment of the magnet coils.

Power supplies for the Analogue field coils are of two types. Fifteen trimming coils which contribute less than 1% of the central magnetic field are energized from a single 100-volt regulated source, with individual adjustable resistance networks for precise adjustment of the current. Transistor-regulated power supplies with ~ 1 part in 10^4 stability are used for coils which contribute more than 1% to the magnetic field. Several sizes are used; each matches the particular requirements of the load. The largest unit provides 530 amp at 10 volts for the sector coils.

Threshold Voltage

The minimum threshold dee voltage measured for acceleration of electrons to an energy of 443 kev ($v_r = 2$) is 60 volts rms, which indicates a maximum energy gain of 170 ev/turn. The threshold is practically independent of radius. At 70 kev the threshold is 50 volts rms, a decrease of less than 20%; thus the threshold seems to be limited by conditions at the center, phase-slip or otherwise, rather than by field errors throughout the machine. The 170-ev threshold for electrons is equivalent to 310 kev/turn for 810 Mev in the Mc^2 Cyclotron, for which a 1 Mev/turn energy gain is planned.

Resonances

As was reported at the Brookhaven International Accelerator Conference in September 1961, acceleration of electrons to full radius was achieved with only small deviations from the currents calculated for the several coils. The early operation of the machine was without benefit of special coils to cancel the horizontal component of the

geomagnetic field; nevertheless, a beam was easily obtained at full radius, but a substantial loss in intensity was observed at a radius of 10.3 in., at which point ν_r , the radial focusing frequency, is about 1.3. This was originally thought to be the $\nu_r = 4/3$ resonance but has since been shown to be the difference coupling resonance $\nu_r - \nu_z = 1$. The loss in beam at the difference resonance is completely eliminated by cancelling the horizontal component of the earth's magnetic field. The original misidentification of the resonance was caused by an error in sector-coil current sufficient to change ν_z in the region in question from ~ 0.2 to ~ 0.3 .

Also observed in early operation was a change in the axial height of the beam at a radius of 12.65 in., which is near the proper location for the sum coupling resonance, $\nu_r + \nu_z = 2$. Further experiments have confirmed that assignment. In the Analogue, small changes in sector-coil current produce large changes in ν_z with practically no change in ν_r ; thus the shift in location of resonances can be used for positive identification. A series of observations were made at 97%, 98.5%, 100%, 102.5%, and 105% of the standard sector-coil current (533.32 amperes), with a different set of computed circular coil currents used to maintain an isochronous mean field in each case. The results, Fig. 5.4, demonstrate that the shift of the locations of the resonances with changing ν_z is consistent with the assignments $\nu_r - \nu_z = 1$ and $\nu_r + \nu_z = 2$. The bars extend from the point at which axial growth was observed to the point at which maximum amplitude occurred. The different width of the bars illustrates qualitatively the difference between slow and rapid crossing of a resonance. It was observed that the attenuation is larger when a resonance is crossed slowly.

Fig. 5.5, a time exposure photograph of a phosphor-coated probe withdrawn at constant rate, illustrates the axial envelope of the beam. The photograph was made with a slight horizontal magnetic field purposely remaining so that a slight effect at the difference resonance in the region $\nu_r = 1.3$ is visible and also the sum coupling resonance near $\nu_r = 1.7$.

Fig. 5.4 Location of resonances at various sector coil currents.

5.13

Fig. 5.5 Time exposure photograph of phosphor-coated probe withdrawn radially from the cyclotron.

Attenuation

The attenuation of the beam with radius was measured with an insulated probe and microammeter. The results, Fig. 5.6, illustrate clearly that cancellation of the horizontal component of the geomagnetic field, approximately 200 milligauss, eliminates attenuation at the difference coupling resonance. The cancellation has little effect on the attenuation beyond $v_r = 1.4$. It is not known whether the observed decrease in current is real or merely a defect of the measurement caused by high-energy electrons scattered from the probe tip.

At the sum coupling resonance no appreciable attenuation occurs. Although the axial dimension of the beam increases from 3/16 in. to 3/8 in., it is easily accommodated in the 5/8 in. available aperture. A magnetic field imperfection that would drive the sum coupling resonance has not been discovered. The possibility that the resonance is being driven by the accelerating system is being investigated.

An observed tendency for the beam to rise away from the mid-plane at outer radii indicates a nonplanar magnetic median surface. The beam can be centered in the gap by unbalancing the currents in the upper and lower of either of the outer two average field coil pairs, or in the sector coils, but the attenuation is little affected.

The electron source used in these observations is a filament which can be moved radially over a small range in the center of the accelerating gap to optimize the location for a given dee voltage. No accelerating electrode, or slit, to define the beam is used; unquestionably, many electrons with large radial amplitude are accelerated. A new electron source, almost ready for testing, will inject a narrowly defined beam at an energy of 2.5 kev. With this apparatus both the energy and angle of injection may be varied to permit a study of the radial amplitude dependence of attenuation and resonance effects.

Energy Measurements

A series of electron energy measurements to verify the computed values were made at several radii by analysis of the energy spectra of the bremsstrahlung emitted from the tip of an aluminum probe. A

Fig. 5.6 Attenuation of the beam in Cyclotron Analogue II.

3 x 3-in. sodium iodide crystal with associated photo-multiplier mounted in a lead collimator and a 256-channel pulse-height analyzer were used to obtain the spectra. The results, Fig. 5.7 show good agreement with the calculated energy to the $\nu_r = 2$ resonance at 440 kev, beyond which a deviation toward lower energies is observed. This result suggests, as was expected, that beyond the resonance the beam consists of a portion which reaches the probe tip by rapid radial amplitude growth and a portion of initially small radial amplitude which accelerates through the resonance.

Summary

Analogue II clearly demonstrates that isochronous acceleration of protons to 900 Mev is possible. The operation of this machine is predictable and reliable; a fact which demonstrates not only the principle but the practicality of such an accelerator and removes any concern of instability caused by unknown phenomenon or combination of phenomenon.

The observed beam characteristics of the Analogue are in good agreement with the computed orbit properties. It has been shown that at least 2,600 turns are achieved in accelerating electrons to full energy whereas only 800 will be required in the Mc^2 Cyclotron.

The future work will be aimed at obtaining a high ion transmission efficiency, further elucidating the resonance behavior and beam extraction using a second harmonic field perturbation.

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Fig. 5.7 Computed (solid curve) and measured (points) energy as a function of radius.

6. CYCLOTRON DESIGN AND SPECIFICATIONS

In this section the arrangement of the eight 600-ton spiral magnet sectors, the interleaving radio-frequency cavities, and the 92,000-ft³ vacuum chamber are shown in relation to each other, as presently visualized. The preliminary design specifications are summarized in Table 6.1.

Cyclotron Design

Closely following the proven configuration of Cyclotron Analogue II, the magnet is designed with eight sectors. The steel sectors for the magnet poles are rectangular in cross section, and are spiraled outward from the center. Spiraling the sectors reduces the flutter required and results in a smaller machine for the desired energy. To achieve sufficient flutter and to reduce the power requirements, the magnet gap must be small. A gap of 8 in. is chosen; this leaves a clear gap of 4 in. between the pole-face windings. With this gap the required tolerance for alignment of the pole face of each sector with the median plane is ± 0.004 in. The final shaping of the magnetic field will be obtained by the distribution of currents in the pole-face windings, as illustrated in the chapter on Magnet Field, below.

Since the gap is small, a system of accelerating with cavities placed perpendicular to the median plane is adopted. The cavities will be inserted vertically in the 16-in. wide spaces between adjacent sectors, Fig. 6.1. The various types of cavities under study are described in the radio-frequency section, (Sec 8) below.

The magnet is supported at the outer edge and near the center by large columns braced with ring girders to form a rigid structure. The steel columns that pass through the bottom of the vacuum chamber are sealed in such a manner as to allow relative movement between the vacuum chamber and columns.

The entire magnet and the accelerating cavities are completely contained within a cylindrical vacuum chamber which has a removable head. This feature greatly facilitates the installation, alignment,

Table 6.1. Preliminary design specifications.

Proton energy, max (internal beam)	900 Mev
Proton energy, extracted beam	810 Mev
Mean orbit radius, extracted beam	230 in.
Number of sectors	8
Spiral of sectors	$\theta = (r\omega/c)^2$
$\tan \gamma$, at extraction	1.41
Central magnetic field	4500 gauss
Maximum magnetic field	18,000 gauss
Orbit frequency	6.86 Mc/sec
Beam space	4 in.
Magnet gap	8 in.
Magnet power	10.0 Mw
Magnet weight, steel	4800 tons
Magnet weight, copper	120 tons
Accelerating system	2 cavities, 4 gaps
Frequency of accel. voltage*	13.72 or 20.58 Mc/sec
Energy gain, max	1 Mev/turn
Radio-frequency power	500 to 800 kw
Extraction system	cos 2 θ magnetic bump at $\nu_r = 2$, with magnetic channel.
Extracted current	100 microamperes
Vacuum volume	2.6×10^6 liters.

* Several cavity system are being evaluated; they will operate on either the 2nd or the 3rd harmonic of the orbit frequency, depending on the system chosen.

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Fig. 6.1 Plan view and section of Mc² cyclotron.

and maintenance of these components. There is also the additional advantage of removing all vacuum loading from the magnet. The vacuum tank will be 60 ft in dia and 50 ft high, Fig. 6.2. Preliminary investigation shows that by using 30-in. T beams for ring girders and 6-in. longitudinal T beams spaced 3° apart, 0.5-in. plate stock will be adequate for the tank wall. The dished heads will also have a thickness of 0.5 in.

The components of this machine are large and heavy and must be designed with the problems of assembly, alignment, and maintenance in radiation fields taken into consideration. The magnet coils will be sealed in special stainless steel tanks and then attached to the pole tips. This prevents the electrical insulation being exposed to the vacuum.

A 150-ton crane will be used to assemble the machine. Each pole tip is supported and positioned in the magnet by a yoke. The lower yokes and pole tips are first lowered onto the support platform and aligned. Due to a large voltage gain per turn and the consequent large orbit separation near the center, it will be possible to use stanchions in the magnet gap at the inner ends of the sectors to help prevent deflection and to maintain the critical gap tolerance. The upper yokes and poles are lowered onto the stanchions and outer yoke alignment block. When fully assembled the overall height of iron will be about 14 ft. Upon completion of the magnet assembly, the cavities will be installed and aligned with the median plane.

Vacuum Pumping System

The very large vacuum volume, 2.6×10^6 liters, does not pose a particularly serious problem. The free-air volume of a tank affects the pump-down time, but the type of material and the total surface area affect the ultimate pressure. Studies will be made to determine the best compromise between materials and cost for the fabrication of the tank. For the lowest outgassing rate stainless steel clad, mild steel, or aluminum could be used.

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Fig. 6.2 Vertical section of Mc² cyclotron.

For rough pumping a series and/or parallel arrangement employing Roots blowers and mechanical pumps could evacuate the tank in a reasonable length of time. Approximately 30 of the new five-stage 32-in. oil diffusion pumps equipped with anti-backstreaming baffles would rapidly reduce the pressure to 1×10^{-6} torr.

A thorough study will be made to determine the best vacuum system design and components. One phase of this study will include an investigation of the operation of oil diffusion pumps in a radiation field. The rough pumping system will be located outside of the radiation field.

7. MAGNETIC FIELD DESIGN

A 0.15-scale model magnet, with 3 sectors of the 8-sector design (Fig. 7.1) was fabricated and tested to determine the feasibility of constructing an Mc^2 magnet with characteristics similar to Analogue II but using the general techniques developed for and used in the construction of the ORIC magnet. This procedure has lead to the design of a magnet that is readily calculated, and the measurements made with the model have demonstrated the reliability of the calculations.

In principle, the magnetic field of Cyclotron Analogue II (Fig. 7.2) could be scaled up to accelerate protons to the same ratio of kinetic energy to rest energy that is obtained for the electrons. The values of the average field and flutter would be correct for the heavier particles, and would, in fact, have to be achieved within a rather small tolerance. A closer examination of the Analogue field suggests, however, that such a magnetic field shape would be difficult to obtain with pole tips of rectangular cross section. It could be obtained with pole sectors of a complicated shape, but this would increase the cost considerably. A geometry with pole tips of simple rectangular cross section can be found that gives the correct average field and flutter. Since the azimuthal field variation is more nearly a square wave, a cyclotron with this pole geometry will for the same peak field be smaller in diameter than one scaled up from the Analogue field.

A trapezodial approximation for the field shape was used to determine the pole geometry of the 0.15-scale model magnet. When the field goes to zero between sectors, as it does at large radii, the flutter depends only on the relative width of hills and valleys; this ratio can be readily determined for a required value of flutter. The maximum field on the hill can be determined from the required average field and flutter. At smaller radii, where the field does not go to zero, the solution for hill width and peak field is more complex, but obtainable.

Fig. 7.1 Three-sector model of eight-sector magnet with steel pole pieces, 0.15 scale.

Fig. 7.2 Magnetic field of Analogue II, with scale for Mc^2 proton cyclotron.

For a chosen pole spiral angle, axial focusing requirements establish the flutter and hence the ratio of the peak field to mean field at any radius. The choice of the peak field, then, establishes the size of the magnet. The present design study was made for 18 kgauss at a radius of 0.9 cyclotron units, the maximum pole radius; this gives a cyclotron unit of 274 in. The average beam radius is 233 in. for 810 Mev. An 8-in. gap between the iron poles provides 4 in. for the beam and 2 in. for pole-face windings on each pole.

There is sufficient iron in the yoke to keep the flux density in the yoke under 20 kgauss. The yoke overhangs the pole sectors so that the yokes for the 8 sectors form a solid plate except for a 16 in. wide slot in each valley for the rf cavities. This geometry minimizes the total volume of iron for this type of magnet. All dimensions are, of course, subject to change as the design progresses and more information is obtained from model and theoretical studies. In fact, the very preliminary data on the 0.15-scale model suggest changes that should be made, but, since the changes have not been checked, this report will cover only the system that has been studied.

The magnetic field vs azimuth in the model (Fig. 7.3) closely approximates a trapezoid and indicates that saturation is not excessive. A plot of the measured peak field vs radius (Fig. 7.4) and the average field vs radius (Fig. 7.5) agree with the calculated field within the experimental error of the data. The flutter (Fig. 7.6) is larger than required at all radii, but is very similar in shape over the outside 50% of the machine, where most of the beam orbits are made. At smaller radii the azimuthal gradient was larger than anticipated; the field in the valley approached zero at smaller radii than originally estimated. The flutter in the model was, therefore, larger than expected. This discrepancy can easily be corrected by widening the hill and reducing the peak field on the hill to maintain the correct average field. The flutter at the 16-in. model radius can be decreased about 50% by increasing the hill width 5 degrees.

Fig. 7.3 Magnetic field vs azimuth in 0.15 scale model.

Fig. 7.4 Peak field vs radius.

Fig. 7.5 Average field vs radius.

Fig 7.6 Flutter vs radius.

The model has demonstrated the power requirements for such a magnet. A summary of the characteristics of the 0.15-scale model and the full-scale magnet are listed in Table 7.1. If the same coil construction were used for the full-scale magnet, 16.5 Mw would be required to produce the magnet field. By eliminating the extra leads required on the model to obtain the desired ampere-turn distribution and by more efficiently using the available volume for conductors, it is estimated that the power requirements for the large magnet can be held under 10 Mw.

The model program will now be directed primarily toward the question of cost since the practicality of an iron-core magnet with radial-gradient coils is well established. Other magnet designs will be investigated to determine if a more economical magnet can be built that will still be compatible with the rf system necessary for accelerating protons to 810 Mev. For example, a magnet with an increased spiral angle will be studied because the flutter for such a magnet will be less; this will permit a stronger valley field which in turn gives a larger average field at a given radius. The increased average field reduces the radius, and thus the cost of a machine for a given energy.

Table 7.1 Some characteristics of the 0.15-scale
model and full-scale Mc^2 Cyclotron magnets

	<u>Model Magnet 0.15-Scale</u>	<u>Mc^2 Magnet Full-Scale</u>
Cyclotron unit	41.1 in.	274 in.
Magnet diameter	96 in.	53 ft
Pole radius	37 in.	20.5 ft
Beam radius	35 in.	19.4 ft
Height	25 in.	14 ft
Gap between pole tips	1.2 in.	8 in.
Gap between radial-gradient coils	0.6 in.	4 in.
Steel, per sector	4,000 lbs	600 tons
Steel, total.	12,000 lbs (3 sectors)	4,800 tons
Copper, total	450 lbs (3 sectors)	100 to 150 tons
Power	600 kw	7 to 10 Mw
Spiral	$\theta = r^2$	$\theta = r^2$

The large sector coils across the hills to establish the steep radial gradient are the main consumers of power in the present magnet design. Other methods of establishing the radial gradient are being studied. One large main coil around all the sectors would establish the necessary field with a substantial reduction in the power required to energize the magnet, but before this approach can be pursued very far a suitable rf system must be conceived.

Many of the techniques, and some of the equipment for measuring magnet fields for ORIC are being used directly in the detailed measurements of the 0.15-scale model of Mc^2 . A temperature compensated and controlled Hall generator is again used as the sensing element, and all of the electronic data-recording equipment from ORIC will be used. The 30-in. precision gear from the ORIC 1/4-scale model was adapted for positioning the probe in a polar coordinate grid in the Mc^2 model. Because of the size of the full-scale magnet (41-ft and 4-in clear gap) and the number of points that must be measured to produce a single field map (perhaps 100,000), it is evident that the problems of positioning a probe to a high degree of accuracy and recording the field in the finite time are not trivial. Schemes using a single probe and positioning it to all points on the measurement grid (as in ORIC) are being examined. This method would be most time consuming. Another possibility is to use multiple probes; however, this would require calibration and compensation for each probe. In either system a fast automatic data-recording system will be required.

One of the problems associated with the magnet construction will be the selection of a steel analysis and casting technique that will give homogeneous pole tips with good magnetic properties. In fabricating ORIC the pole tips were forged from selected sections of large ingots that had been ultrasonically examined so that areas containing imperfections could be avoided. A different technique may be necessary for the Mc^2 Cyclotron because of the large size of the spiral pole pieces.

Future model studies will include the construction of an 8-sector model of the central region and a very accurate model on which measurements suitable for orbit calculations can be made. From these measurements the details of the pole tips and coils will be determined prior to construction of the full-scale machine.

8. ACCELERATING SYSTEM

A unique feature of the Mc^2 Cyclotron is that it will employ accelerating cavities instead of a conventional dee system. Cavity resonators fitted between the magnet sectors occupy no magnet gap space and require considerably less rf power than a dee system. Two basic types of cavities have been investigated and working models of each type have been constructed.

Harmonic Acceleration in an 8-Sector Cyclotron

In the Mc^2 Cyclotron it would be possible to accelerate particles eight times in one revolution since there will be eight slots in the magnet which could contain accelerating cavities. Other possibilities would be four and two accelerations per turn. For the case of two accelerations the accelerating voltage may be applied in slots A-E (Fig. 8.1a), for example. Then the frequency of the accelerating voltage must be 1, 3, 5, etc., times the cyclotron frequency, f_c . This, of course, corresponds to the ordinary dee system in which ions are accelerated every 180° in azimuth. For the case of four accelerations per turn there are several combinations of cavity location, frequency, and phase which will produce maximum energy gain per turn for a given gap voltage.

Consider, first, cavities placed in slots A, C, E, and G; and define the accelerating field to be positive in the counter-clockwise direction. Then for phasing such that E_A (electric field in slot A) is positive, E_C negative, E_E positive, and E_G negative the particles gain maximum energy if the frequency of the accelerating voltage is $2 f_c$, $6 f_c$, etc. This accelerating field could be obtained by the use of two 90° cavities operating "in-phase." One cavity would occupy slots A-C and the other cavity slots E-G. There exists also the possibility of electrically phasing the cavities by 90° . In this case E_C and E_G would be in-phase and would lag or lead E_A and E_E by 90° . The frequencies corresponding to maximum energy

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(a) AVAILABLE SPACES FOR CAVITIES

(b) SINGLE COAXIAL CAVITY
FORMING COMPLETE
ACCELERATING SYSTEM

ACCELERATING GAP

(c) 90° TE₀₁₁ CAVITY

ACCELERATING GAP

(d) 90° TEM CAVITY

Fig. 8.1

gain would then be f_c , $3 f_c$, $5 f_c$, etc. This scheme does not appear practical at the moment, however, because the two cavities must cross in the center of the machine; this would result in coupling between the cavities.

It is also possible to obtain acceleration with cavities in slots A, B, E, and F. If the phasing is such that E_A and E_E are positive and E_B and E_F are negative at any instant, then acceleration is achieved at frequencies of $4 f_c$, $12 f_c$, etc. This corresponds to two 45° cavities operating "in-phase." One cavity would be placed in slots A-B, the other in slots E-F. Placing two more 45° cavities in slots C-D and G-H would produce eight accelerations per turn.

In all of the preceding schemes particles are assumed to be accelerated at the peak of the rf voltage. If acceleration at 0.707 of the peak is considered, other combinations are possible.

Applicable Types of Accelerating Cavities

The first type of cavity considered for use in the Mc^2 cyclotron was a rectangular cavity operating in the TE_{011} mode. (The TE_{011} mode designates a particular electromagnetic field configuration in which the electric field, at any instant of time, is uni-directional. In a plane, normal to the electric field, the magnitude of the electric field is a function of distance, varying from zero to a maximum and back to zero.) A sketch of such a cavity for use in a 90° accelerating system is shown in Fig. 8.1c. If the end plates of the 90° TE cavity are removed and the open ends are joined together by two parallel plates, a TEM, or coaxial, cavity is formed as shown in Fig. 8.1d. These are the two basic types of cavities which are applicable to the Mc^2 machine.

Requirements of the Accelerating System

The basic requirements of the Mc^2 accelerating system are that it provide an energy gain of one Mev/turn and that it accelerate particles having a cyclotron frequency of 6.86 Mc/s. Operation of the

accelerating system at 6.86 Mc/s is impractical due to the excessive height of the cavity at this frequency. Operation at $2 f_c$, $3 f_c$, and $4 f_c$ appears feasible. Problems arising from transit time effects and magnetic field errors effectively prohibit operation at higher harmonics; in fact, operation at $4 f_c$ may be somewhat marginal. Operation at $2 f_c$ implies the use of two 90° cavities giving four accelerations per turn, and the peak voltage required across the cavity is 250 kv. At $3 f_c$ a "straight" cavity is required operating with 500 kv across it. If acceleration at $4 f_c$ proves feasible either two or four cavities could be used, and, for the case of four cavities, a peak voltage of 125 kv would be required.

Cavity Design Considerations

The distance along a spiral slot from the machine center to the extraction radius is about 23 ft; it is desirable that the accelerating field amplitude remain essentially constant over this distance. At 13.72 Mc/s ($2 f_c$) the free-space wave length is 71.7 feet and 23 ft corresponds to about 0.32λ .

Design of TE Cavity. The uniform TE cavity shown in Fig. 8.1c obviously suffers one serious disadvantage in that the electric field along the accelerating gap varies cosinusoidally with radius. Thus, ions at the outer radius receive an energy gain per turn which is a small fraction of that received in the center. This problem has been solved by a cavity design which employs non-uniform spacing between the cavity walls and produces a field along the accelerating gap which has an essentially constant amplitude. A sketch of such a design is shown in Fig. 8.2a. This illustrates a "straight" cavity which would be applicable to a 180° accelerating system operating at $3 f_c$. It should be possible, however, to bend the cavity in the center so as to form either a 90° or 45° accelerating system.

An approximate method of designing the non-uniform TE cavity has been developed and, thus far, has given surprisingly

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(a) NON-UNIFORM TE CAVITY

(b) SECTOR OF
CYLINDRICAL CAVITY

(c) APPROXIMATION
OF SECTOR

Fig. 8.2

accurate results. In the approximation the center section of the cavity (without the circular ends) is treated as a parallel-plate transmission line made up of three sections having different spacings or characteristic impedances (this variation in spacing reduces the required height of the cavity). The center section may thus be analyzed by the use of ordinary transmission line equations. The approximation in the circular end sections may be best understood by considering first a cylindrical TE_{011} cavity. The electric field in such a cavity is given exactly by $E_z = E_0 J_0(kr)$. If only a small sector of the cylindrical cavity is considered, it appears reasonable to approximate the sector by a non-uniform transmission line, as in Fig. 8.2b.

For the stepped-line approximation in Fig. 8.2c the characteristic impedance of each uniform section is $377 \frac{S}{\frac{2n-1}{2} \ell \theta}$

where n is the section number and ℓ is the length of each uniform section. Then it can be shown that, for $\lambda/4$ resonance and five steps,

$$1 - \left[\frac{Z_2 + Z_3 + Z_4 + Z_5}{Z_1} + \frac{Z_3 + Z_4 + Z_5}{Z_2} + \frac{Z_4 + Z_5}{Z_3} + \frac{Z_5}{Z_4} \right] \tan^2 \beta \ell + \left[\frac{Z_2 Z_4 + Z_2 Z_5}{Z_1 Z_3} + \frac{Z_2 Z_5 + Z_3 Z_5}{Z_1 Z_4} + \frac{Z_3 Z_5}{Z_2 Z_4} \right] \tan^4 \beta \ell = 0.$$

Since $Z_n / Z_m = (2m - 1) / (2n - 1)$ the above equation can be solved for $\beta \ell$, and for a specified β ($\beta = 2\pi f/c$) ℓ is then determined.

For five steps the error in diameter of the cavity (10%) is about 2% and the error in power loss is about 9%.

The approximation is of little value in the case of a cylindrical cavity having a constant spacing, S , since the exact solutions for this case are known. However, if the spacing varies with radius, the

approximation would still be valid while the exact solution would, in general, involve a series of Bessel functions. In designing a cavity such as that in Fig. 8.2a the center (parallel plate) section is first specified, giving a certain height, h . The end section is then divided into sectors and the sectors sub-divided radially into uniform sections. The lengths and spacings of the uniform sections are then determined so as to produce a sector having a specified radial length. One further condition, of course, is that only minor differences exist between adjoining sectors, since in joining the sectors it is desired to approximate the azimuthal steps by smooth curves.

A photograph of a model cavity designed by the approximate method is shown in Fig. 8.3. The model incorporated movable plates in the end sections so that the spacing between the plates could be varied. Variation of this spacing changes both the resonant frequency of the cavity and the shape of the standing wave along the accelerating gap. Plots of the standing wave, for various spacings between the movable plates, are shown in Fig. 8.4.

Coaxial Cavity. Design of the coaxial cavity is straight-forward since it operates in the TEM mode. To minimize the height of the cavity the spacing between the walls (or conductors) increases with distance away from the median plane of the cyclotron. The space available for the cavities in the spiral slots of the magnet is about 16 in. Near the median plane of the machine, however, the spacing between the cavity walls should be much less than 16 in. to reduce the transit time. In the cavities which have been investigated the wall-to-wall spacing is assumed to be 3 to 5 in. at the median plane. This spacing is maintained for a distance of about one foot above and

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Fig. 8.3 TE Cavity Model

Fig. 8.4 Voltage across accelerating gap in TE cavity.

below the median plane. The spacing is then increased to 12 in. through the distance to the top (and bottom) of the magnet sectors. Above (and below) the magnet the spacing is increased to 3 or 4 feet. This results, in the case of a coaxial cavity, in a $\lambda/2$ resonant line having three sections of different characteristic impedance. A sketch of a typical 90° coaxial cavity is shown in Fig. 8.5 a.

In the cylindrical portion of the coaxial cavity the wall-to-wall spacing is made 3 or 4 feet to reduce the power loss in this section. The wide spacing also permits the insertion of trimmer capacitors and rf drive elements in this region. An "approximate" model (1/12 scale) of the coaxial cavity was constructed and some preliminary data on its characteristics have been obtained. The model is termed "approximate" since its cross section is triangular rather than sectorial. The triangular cross-section simplifies fabrication but it also results in two sharp 45° corners on the inner conductor, which tend to lower the Q of the cavity. A plot of the relative voltage along the accelerating gap of the model at a particular resonant frequency is shown in Fig. 8.6. As expected, the voltage is essentially constant with radius. The measured Q of the model is about 1500 while the computed value is 4500. The large discrepancy between measured and computed values is due, presumably, to the clamped shorting bars employed in the model.

Since there are several types of accelerating systems applicable to the Mc² Cyclotron, some of the pertinent characteristics of each type are listed in Table 8.1. The calculated rf power listed is based on the use of copper in cavity fabrication. The use of aluminum would increase the power loss by about 25%.

Other Possible Systems. In addition to the systems listed in Table 8.1 there is the interesting possibility of using three cavities in the machine. This scheme would employ a "main" cavity of the 180°

(a) TYPICAL COAXIAL CAVITY

(b) CAVITY ARRANGEMENT
FOR OBTAINING INCREASED
ENERGY GAIN AT OUTER RADII

Fig. 8.5

Fig. 8.6 Relative voltage across accelerating gap of coaxial model.

Table 8.1. Cavity Characteristics

<u>No. of Accel. Gaps</u>	<u>Cavity Type</u>	<u>Operating Freq.</u>	<u>Peak Cavity Volts</u>	<u>Rf Power Loss (Calc)</u>	<u>Half-Height of Cavity</u>
2	180° TE	$3 f_c$	500 kv	~ 700 kw	8.5 ft.
4	90° TE	$2 f_c$	250 kv	~ 400 kw	10 ft.
4	90° TEM	$2 f_c$	250 kv	~ 400 kw	10 ft.
4	45° TEM	$4 f_c$	250 kv	~ 500 kw	7.5 ft.
8	45° TEM	$4 f_c$	125 kv	~ 250 kw	7.5 ft.

TE type plus two "auxiliary" cavities. The electric field in the auxiliary cavities would increase with radius out to the extraction radius and the net result would be to increase the energy gain per turn thus obtaining greater separation between turns. A sketch of cavity location for this scheme is shown in Fig. 8.5c. The auxiliary cavities are electrically phased 90° relative to the main cavity.

In the case of coaxial cavities it should be possible to physically connect the inner conductors at the center of the machine thus forming a single cavity. A sketch of the cross section of such a cavity, operating at $2f_c$, is shown in Fig. 8.1b. The use of a single cavity is desirable; this eliminates the problem of maintaining a specific phase between two high-Q systems.

Cavity Excitation. The rf power required by any of the systems listed in Table 1 could be supplied by, at most, two super-power triodes. The use of a master-oscillator-power-amplifier type of rf system would appear advisable to avoid difficulty with multipactoring and to provide simpler control of amplitude and phase. It would be desirable to employ a power amplifier (and associated drivers) for each separate cavity since all control functions could then be performed at low power levels.

The power amplifier(s) for the accelerating system would be located outside the cyclotron vault and would be coupled to the system through transmission lines. Since only minor changes in frequency are anticipated, the use of long lines should cause no problem. Coupling from the transmission lines to the cavities could be achieved, in the case of coaxial cavities, by either a capacitive probe, a loop, or a physical connection to the inner conductor. For the TE cavities loop coupling appears to be the most practical scheme, although capacitive coupling is still a possibility.

Tuning of a coaxial cavity would be accomplished by trimmer capacitors in the widely spaced cylindrical portion of the resonator. The trimmers would be located near the median plane and could be actuated from outside the vacuum tank since the cylindrical portion of the cavity is adjacent to the tank wall. One method of tuning the TE cavity consists of varying the volume of the cavity slightly through the use of movable plates in the cavity walls. It is essential that the plates be located in an area of the cavity where their motion will have minimum effect on the standing wave along the accelerating gap. The optimum location of the plates will be determined in model tests.

Conclusions and Recommendations

Either of the two cavity types, TE and TEM, would be applicable to the Mc^2 Cyclotron. The type used in the final design of the machine will depend not so much on its electrical characteristics as on its compatibility with the other components of the cyclotron. The primary advantages of the TE cavity are that it occupies a relatively small volume and does not encircle any of the magnet sectors. The attributes of the TEM cavity are its convenience of tuning and coupling and the fact that it may be analyzed by a, more or less, exact method.

9. RESIDUAL RADIOACTIVITY

The problem of residual radioactivity in the Mc^2 accelerator may be a very serious one. Cyclotron components will be highly radioactive and will have to be handled remotely, and the cyclotron vault itself may be so active as to require limited access to it for adjustments and maintenance.

A recent study of the radioactivity in the LRL 184-Inch Cyclotron was carried out to locate the principal source of radiation in that machine, to measure the general background in the vault, and to identify and compare induced activities in various materials of construction. The details of this investigation have been published;¹ we will merely give some results and conclusions.

The Cyclotron Area

The residual radiation level in the 184-inch cyclotron is just about tolerable. Half an hour after beam is shut off the radiation level in the vault varies from 3 r/hr to 20 mr/hr depending on the proximity to the cyclotron and its most radioactive parts. Forty-eight hours later the level is reduced to 10-50 mr/hr over most of the area. It is possible to go into the vault immediately after the beam is turned off to make quick changes or emergency repairs. After cooling for about a day, the radiation level in the cyclotron vault is such that a person can safely spend an 8-hr day in it, provided he stays a few feet away from the one or two most active spots. External radiation sources, such as meson ports, are quite radioactive, but can be handled either by very fast work or with tools which allow the person to be about 3 ft away. The dees and other structures in the magnet gap are, on the other hand, highly radioactive. Since no measurements were made on them, we cannot evaluate just how dangerous they would be. Still, a

¹R. W. Boom, K. S. Toth, and A. Zucker, "Radiation Survey at the LRL 184-Inch Cyclotron", Nuc. Inst. and Methods (to be published). (See also same report in preliminary form ORNL-3158.)

few inches of steel and a few feet of distance make the radioactivity of the dees quite harmless.

The 810-Mev cyclotron would, however, present much more serious radiation problems if it is assumed that its residual radioactivity is 100 times that of the 184-in. cyclotron. Levels of several hundred r/hr would probably prevail immediately after the beam is turned off, and they would decay to background dose rates of about 0.5 r/hr. This means that no quick adjustments or repairs could be made after the machine is shut down, and even after cooling down, a person could only spend an hour or so in the cyclotron vault.

These estimates apply to a cyclotron constructed in a conventional way, with no special provisions for handling the residual radioactivity problem. The situation, however, is not nearly so bleak. Present-day techniques allow a great deal of work to be done in radiation fields between 1 and 100 r/hr.

The choice of construction materials must take both the short-lived and long-lived activity into account. Considering iron, copper, and aluminum as the primary materials of construction, we find that Mn^{56} (2.6h) is the principal short half-life activity in iron, Cu^{64} (12.8h) in copper, and Na^{24} (15h) in aluminum. The yields of these isotopes in Fe, Cu, and Al are in the following ratios $\text{Mn}^{56}/\text{Cu}^{64} = 1/7.8$ and $\text{Na}^{24}/\text{Cu}^{64} = 1/50$. These values are accurate to within a factor of two. Clearly, from the standpoint of short-lived activities aluminum is the preferred material.

We classify as long-lived any isotope whose half-life exceeds one week. The summary in Table 9.1 shows that, from this standpoint, Al is again the best material. At saturation, copper has about 40% more γ -rays/g of material. If one bears in mind that the density of Cu is 3.3 times the density of Al, then for equal thicknesses of material Cu is 130% more radioactive. Iron, which is essential in the construction of a cyclotron, unfortunately exhibits very intense activation; stainless steel is slightly worse than cold-rolled steel. Brass is much worse than pure copper, and nickel is the worst of the materials tested.

Table 9.1 Gamma rays observed.

Material	Principal isotopes formed	Energies of main γ -rays (kev)	(γ /min) $\times 10^5$ per gram of material at end of bombardment	$T_B/T_{1/2}$	(γ /min) $\times 10^5$ per gram extrapolated to saturation bombardment
Aluminum	Na ²² (2.6y)	511	3.89	0.385	16.61
Copper	Co ⁵⁶ (77d)*	511	4.37	saturation	4.37
	Co ⁵⁸ (71d)*	800-845	18.71	saturation	18.71
Nickel	Co ⁵⁶ (77d)*	511	14.04	saturation	14.04
	Co ⁵⁸ (71d)*	800-845	48.02	saturation	48.02
Brass	Co ⁵⁶ (77d)*	511	4.51	saturation	4.51
	Co ⁵⁸ (71d)*	800-845	19.28	saturation	19.28
	Zn ⁶⁵ (245d)	1120	6.43	1.5	9.95
Stainless Steel	Cr ⁵¹ (27d)	323	1.78	saturation	1.78
	Mn ⁵⁴ (300d)	840	23.41	1.22	41.01
	Sc ⁴⁶ (85d)	1120	1.61	saturation	1.61
	V ⁴⁸ (16d)	511	3.23	saturation	3.23
	Co ⁵⁶ (77d)*	511	2.31	saturation	2.31
	Co ⁵⁸ (77d)*	800-845**			
Cold-Rolled Steel	Cr ⁵¹ (27d)	323	2.02	saturation	2.02
	Mn ⁵⁴ (300d)	840	23.53	1.22	41.22
	Sc ⁴⁶ (85d)	1120	1.62	saturation	1.62
	V ⁴⁸ (16d)	511	4.82	saturation	4.82

*Co⁵⁶ and Co⁵⁸ activities were not separated because of the similarity of their half-lives and their γ -ray energies.

**The 800-845 kev radiation of Co⁵⁶ and Co⁵⁸ was not separated from the 840-kev Mn⁵⁴ γ -ray.

If one takes short- and long-lived activities together, it appears that aluminum is the best material, iron is preferable to copper in the short run, but for long saturation irradiation copper is better.

In addition to a careful choice of materials, good control of the beam both during acceleration and during deflection should also help in reducing the radiation problem. Altogether, it is not improbable that by these two methods one might reduce the residual activity by as much as an order of magnitude from the 0.5 to 100 r/hr estimate, at least in some parts of the cyclotron vault.

Shielding against this radiation is also possible. Most of the activity lies in the 510-kev and 810 to 845-kev region; the half-thickness in lead for gamma rays of this energy is 0.6 cm. To reduce the radiation by an order of magnitude one needs 2 cm of lead--an amount that can readily be made into a portable shield. Shadow shields of 6 cm of lead would reduce the 100 r/hr radiation field to a quite tolerable 100 mr/hr. The same radiation has a half-thickness of 4 cm for concrete. One might, therefore, have permanent shadow shielding in the cyclotron vault to allow entry soon after beam turnoff and achieve safe access to certain key parts, such as valves, the ion source, and rf components.

Finally, considerable attention will have to be paid to remote handling of highly radioactive parts of the accelerator, such as cavity structures and ports. Shielded aging pits must be provided for cooling, as well as hot cells for repairs of highly radioactive cyclotron components.

Our conclusion is that an 810-Mev cyclotron producing 100 μ a of protons will be highly radioactive, but at a level that can be handled by using fairly straightforward techniques and precautions. Care will have to be taken in selecting construction materials and in designing the layout in the vault, so that the machine can be maintained and repaired safely and most simply.

The Experimental Areas

The primary proton beam will terminate in large water-filled beam stops. Residual radiation in water is short-lived, and in any case the water can be stored in hold-up tanks and purified by well known methods. Recent measurements on the radioactivity of cyclotron cooling water at CERN indicate that this problem can be handled. Care must be taken that the pipes for radioactive water do not pass close to any location where low backgrounds are required for research. The aluminum shell of the beam stop will become radioactive; the principal activities being Na^{24} (15h) and Na^{22} (2.6y). The stops can be allowed to cool long enough for the 15-hr activity to decay, but after a while Na^{22} will undoubtedly build up. Two things can be done about this: make the shell as thin as possible, and make it as cheap as possible so that it can be considered an expendable item.

The situation is not nearly so advantageous with the large steering and analyzing magnets in the corridor. These must be made of iron, and will undoubtedly become quite radioactive, especially along the pole pieces and near the slits. The principal activity in iron is Mn^{54} (300d) and no appreciable reduction in activity can be expected from decay. Care will have to be taken in the design of the magnets to make them as maintenance free as possible, to make disassembly feasible with special long tools, and to provide partial shielding for the most radioactive areas.

Control will need to be exercised over the materials to be used in connection with experiments and the beam-handling system. Wherever possible graphite liners should be employed, while for structural parts aluminum is the preferred material. Special attention must be paid to the constituents of concrete to be used for the main shield as well as for auxiliary shielding blocks.

10. SHIELDING

Historically, the design of shielding for high-energy accelerators has been based on the meager experimental information available and on theoretical considerations. For most installations the original shielding has turned out to be inadequate for a variety of reasons, including improper initial assumptions, technological improvements in the machines, and the need for experimental arrangements not considered in the original design. The experimental areas are now too small in almost every installation. This is one of the problems we hope to circumvent in the design of the experimental facilities for the Mc² cyclotron.

During the past several years the understanding of the basic shielding problems for high-energy accelerators has improved considerably. There is still a lack of accurate experimental data on certain aspects of the problems, for example, the attenuation length for neutrons as a function of energy. Nevertheless, reasonable estimates of the shield thicknesses may be made with the assurance that they will not be grossly in error.

Permissible Radiation Limits

The personnel radiation exposure limits in effect at Oak Ridge National Laboratory, Table 10.1, are those recommended by the National Committee for Radiation Protection, NCRP. The weekly exposure limits are based on the MPD Age Proration Total, that is, 5 rem/year or 100 mrem/week. The permissible fast neutron flux for an integrated dose of 100 mrem/wk is shown in Fig. 10.1 for neutron energies up to 10 Mev. For 10-Mev neutrons, the permissible flux is $17 \text{ n/cm}^2\text{-sec}$. In subsequent sections we assume that the permissible flux is $15 \text{ n/cm}^2\text{-sec}$. In view of constant downward revisions of permissible doses a flux density of $1.5 \text{ n/cm}^2\text{-sec}$ is used as the shielding goal for the regions of the shield adjacent to inhabited areas, such as shops and laboratories.

Table 10.1. Maximum permissible dose (MPD) in rems

<u>Organ</u>	<u>MPD per Calendar Quarter</u>	<u>MPD per Year</u>	<u>MPD Age Proration Total N = Present Age</u>
Total body, head and trunk, lens of eyes, gonads, or blood forming organs	3	12	5(N - 18)
Skin of whole body, thyroid	10	30	30(N - 18)
Hands and forearms, feet and ankles	25	75	75(N - 18)
Bone	30/4 n	30/n	(30/n)(N - 18)
Other single organs	5	15	15(N - 18)

Fig. 10.1 Flux of neutrons to deliver the stated dose as a function of neutron energy.

Attenuation of Neutrons

The attenuation of neutrons in thick shields has been extensively investigated only for nuclear reactor shields where the energy spectrum of interest extends to only about 20 Mev. Only a few measurements of high-energy neutron attenuation in thick shields have been made. Moyer and co-workers at LRL measured the half-value thickness in ordinary concrete for 90- and 300-Mev neutrons and reported values of 9.5 and 18.0 in., respectively. For the purpose of this calculation we have used a curve by Panofsky, Fig. 10.2, which gives the half-value thickness as a function of energy up to 1 Bev.

Energy Spectrum and Angular Distribution

Nuclear emission in high-energy nuclear reactions consists of two parts, the emission of one or more high-energy particles (cascade particles) in the forward direction, which occurs before the excitation energy is distributed throughout the target nucleus, and second, the emission of several "evaporation nucleons" which occurs as thermal equilibrium is achieved. Metropolis, et al, and Friedlander have investigated the cascade and evaporation process theoretically, using a Monte Carlo method. Of particular interest for the calculation of accelerator shielding are their results for the energy spectrum and angular distribution of the cascade nucleons. The evaporation particles have low kinetic energy, ~10 Mev, are rapidly attenuated, and do not significantly affect the shield thickness.

The results of Metropolis show that the angular distribution of the cascade particles is relatively independent of energy (for particles $T > 90$ Mev) and target element. As suggested by H. B. Knowles, the energy spectra of the cascade particles can be fitted by an exponential

$$\frac{dN(E)}{dE} \sim e^{-kE/E_0}$$

Fig. 10.2 Half-value thickness of ordinary concrete for fast neutrons.

where E_0 is the energy of the incident proton. A value of $K = 4$ fits the Metropolis data at $E_0 = 480$ Mev while a value of 6 would be more appropriate for the 1840-Mev data. In our calculations we have used $K = 4.0$ for the energy range to 800 Mev. Metropolis also calculated the ratio of neutron-to-proton emission, f_n/f_p . A value of $f_n/f_p = 1.0$ is appropriate for medium weight elements.

Calculation of the Source Strength

For the results in this section, a copper target is assumed. For protons impinging on a thick copper target, the number surviving to depth x in a target of thickness at least equal to the ionization range is

$$N = N_0 e^{-x/\lambda}$$

where λ is the inelastic removal length, i.e., $\lambda = 1/N\sigma$. The reaction rate, the negative of the removal rate is

$$\frac{dN}{dx} = -\frac{N_0}{\lambda} e^{-x/\lambda}$$

If a cascade particles are produced per inelastic event, the secondary particle production S is

$$S = -\frac{N_0}{\lambda} \int_0^R e^{-x/\lambda} a(x) dx$$

$a(x)$ is computed from $a(E)$ (Metropolis, et al) and the range energy relation for protons in copper. Of these secondaries, half are neutrons. The function $S_n = 1/2 S$ is plotted in Fig. 10.3 as a function of incident proton energy as obtained by numerical integration of the above equation.

The energy spectrum of the neutrons produced in a thick target may be obtained by summing the contributions, to each energy group, from neutron produced at each proton energy in the target. The distribution in energy, the number of neutrons per 100-Mev energy

Fig. 10.3 Cascade neutron yield as a function of proton energy, for thick copper target.

interval produced by 100 μ a of protons on a thick target is shown in the histogram of Fig. 10.4.

Knowles has carried the process a step further and calculated the cascade neutrons produced by the secondary protons, which adds another 20% to the total neutron production; however, the substantial attenuation of the neutrons in the target is neglected. In subsequent calculations we have neglected both the secondary production, and target attenuation still resulting, in a conservative estimate within the precision of other data.

The angular distribution of the cascade neutrons is that computed for aluminum by Metropolis. The angular distribution of flux density at a distance of one meter from a target with an incident proton beam of 100 microamperes is shown in Fig. 10.5.

Attenuation in the Shield

For a point source, the flux density at distance R, after passage through a shield of thickness T may be calculated as follows:

$$\frac{d\phi}{dE} = \frac{d\phi_0}{dE} \frac{1}{R^2} e^{-T/\lambda(E)}$$

where $d\phi/dE$ is the flux density per unit energy at unit radius. The above equation has been evaluated numerically using the attenuation curve of Panofsky. Fig. 10.6 shows the flux density distribution of 0° through 35 ft of ordinary concrete, or equivalent. An additional 5 ft of removable blocks are included in the back of the beam stop, both to give an additional safety factor and to permit their removal if induced radioactivity becomes a problem. Ten feet of shielding on both the top and sides of the beam stop provide additional shielding primarily to reduce the background in the room. A roof thickness of 25 ft will be adequate for targets a few Mev thick. For targets 100-Mev thick a 5 ft overhead shield of small area may be required.

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Fig. 10.4 Cascade neutron yield and energy distribution for 800-Mev protons on thick copper target.

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Fig. 10.5 Angular distribution of neutrons for 100 μ a of protons on thick copper target.

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Fig. 10.6 Energy distribution of 0-deg neutrons from 100 μ a of 800-Mev protons on thick copper target - after attenuation by 35 ft of concrete.

The end plug for the beam transport corridor and the midwall which separate the proton and pion-muon sections will each be equivalent to at least 35 ft of ordinary concrete. The corridor roof and exterior side wall will be 30 ft thick.

The main accelerator room is shielded by 35 ft of ordinary concrete on three sides, and on the fourth, toward the shops and laboratories, by 40 ft of concrete. The roof of the accelerator room is 25 ft thick. The low emission near 90° and the shielding of the magnet contribute to the reduction from the requirement for the forward direction.

Other Shielding Requirements

Shielding against radiation other than neutrons must also be considered. In the proton room, the cyclotron vault, and the corridor π^0 mesons will be produced, resulting in an intense flux of 70-Mev γ -rays. Positive and negative pions, muons from their decay, and low energy γ -rays must also be contained. It was found that the shielding required by the neutrons is more than sufficient to render all the other radiation harmless.

A maximum of 10^{11} pions/s will enter the two more lightly shielded experimental rooms. The average pion energy is about 300 Mev. The pion-induced cascades can be treated as the proton-induced ones in the previous section, except that the energy is decreased and the intensity lower by a factor of 6×10^3 . At these energies it is again the neutrons in the cascade which determine the shielding; the muons are stopped completely by the shield. For these considerations the shielding specified in the π and μ experimental rooms is a minimum of 15 ft of concrete, or equivalent, in the forward direction, and 12 ft on the side walls and roof.

11. BUILDING

The Mc^2 Cyclotron facility consist of the shielded areas, the office and laboratory area, and the utilities areas, all arranged in an economical and convenient manner (Fig. 11.1 and 11.2). The approach used in the development of this facility was to design the shielded areas first. These were designed with due regard for the planned experimental program and to allow for possible future programs. The other areas were then designed for the best economy and convenience.

The shielded area contains the cyclotron, three large experimental rooms, and the beam corridor. The cyclotron is housed in the south end of the high-bay building. This building will also provide space for a machine shop and for initial construction and assembly of the cyclotron. After the machine is in operation this space will be used for maintenance and for assembly and fabrication of experimental equipment. This building also provides space for storing the roof blocks from the vault and the head of the cyclotron vacuum tank when major repairs are required.

The cyclotron is in a vault with internal dimensions of 100 by 90 ft. and 65 ft. high. The vault is located adjacent to the proton room; thus, one wall is used for shielding both rooms. Due to the size, weight, and accuracy of alignment required for the cyclotron components, an overhead crane will be provided for assembly and maintenance. For this reason the vault will be roofed with blocks which can be moved with a 150-ton crane provided in the high-bay building. To keep the number of blocks to a minimum the roof opening will be less than the vault internal dimensions. A 10-ton monorail will be used for moving equipment within the vault in areas not accessible to the overhead crane.

A maze will be provided for personnel entry and for small equipment. This maze can be reached by an elevator from the shop floor. The cyclotron beam will be deflected from the machine and pass through a beam pipe into the first section of the beam corridor. To provide the maximum experimental versatility, a 6-ft high slot filled with removable blocks, is used in the separating shield wall. The shield wall between the two sections of the beam corridor and between the corridor and three

Fig. 11.2 Ground floor level

experimental rooms also contains block-filled 6-ft high slots the full length of the walls. Each beam corridor room is provided with a 50-ton bridge crane.

Entry into these rooms will be through large rolling plug doors (Fig. 2). These doors are large enough to permit the passage of large trucks for delivery or removal of equipment. The three experimental rooms are also provided with these large doors and with personnel mazes. The mazes will be used for quick entry and for moving in small equipment. Each of these rooms contains a 40-ton overhead bridge crane to provide maximum versatility and speed in the set up of experiments.

Full utilization of the intense proton beam requires heavier shielding than is generally found on most other accelerators. This shielding represents a considerable part of the cost of the facility, and, therefore, warrants very careful study. Preliminary studies indicate a considerable cost reduction can be made by utilizing compacted crushed rock and compacted earth in appropriate places. For instance, to form the 35-ft thick walls two relatively thin curtain walls (Fig. 11.1) with compacted rock fill between will effect a large savings over solid concrete. Earth shielding can be used where the additional thickness required is not important; such as the roof and external walls. Constructing the facility partially below ground level will allow most of the external walls to be thinner.

A study of four different possibilities for the roof design for the experimental areas indicates that the thin arched roof with an earth cover would be the most economical; in Fig. 11.3a the controlling cost factor is the quantity of concrete; in Fig. 11.3b the increase in reinforcing steel partially offsets the reduction in concrete. Fig. 11.3c offers a lower cost, but is not as economical as Fig. 11.3d, which places the concrete in compression, where it is the strongest and, therefore, greatly reduces the total amount of concrete and steel. Additional studies will be made to determine the optimum shielding materials for all areas of the facility.

The office and laboratory building is located adjacent to the experimental area to provide a central location for experimental and operating

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(a) CAST CONCRETE

(b) CAST CONCRETE, WITH EARTH FILL

(c) PRE-CAST CONCRETE, WITH EARTH FILL

(d) CAST CONCRETE ARCH, WITH EARTH FILL

Fig. 11.3 Shielding studies

personnel. This feature has the additional advantage of providing the shortest length for instrument and control wiring. The building will have three floor levels. The basement floor, (Fig. 11.2) on the same level as the experimental rooms, provides space for building utilities and for the three plug doors in the open position. The three personnel mazes also open onto this floor. This design offers the advantage of a complete weather cover for entry into these rooms. The first floor contains the central control room and the counting room as well as offices and laboratories. A personnel elevator is provided adjacent to the counting room, for access to either the basement or the second floor. The second floor (Fig. 11.4) contains additional offices and laboratories.

The utilities buildings for this facility are located at each end of the shielded areas to provide the shortest connections. These buildings will have crane facilities for erecting and maintaining the numerous large motor-generator sets and other heavy equipment. At the present time, two possibilities are being studied for utilities shield penetrations into the shielded areas. One is to cast the conduits in place, as was done on ORIC, and the other is to use tunnels similar to a maze. One advantage of a tunnel is that it offers a way to introduce the large volume of air from the air conditioning system to each of the shielded rooms. Probably these systems will be used in combination, where the advantages of one outweighs the other. In general it is planned to run the utilities for each beam pipe in a trench in the floor. Studies will be made to determine the most economical solution.

Fig. 11.4 Second floor level

12. RESEARCH AND DEVELOPMENT

A machine of the complexity of the Mc^2 Cyclotron will require a continuing vigorous development program to insure a design of maximum economy and reliability with highest available performance characteristics, and to find solutions to many detailed engineering problems. The further effort can be conveniently described within the following categories: analogue and theoretical studies, machine development, shielding and neutron activation studies, and the design of external beam handling and experimental facilities. In the following sections, our plans in these various areas are briefly reviewed.

Analogue and Theoretical Studies

The Cyclotron Analogue II is proving to be a rich source of new information. Its dynamics correspond closely to those intended for the Mc^2 Cyclotron; virtually every anticipated problem can be investigated experimentally. For example, the tolerable level of imperfection harmonics at the $\nu_r = 4/3$ and $\nu_r = 3/2$ radial resonances can be determined. These resonances, not now observed at all in the Analogue, presumably because of the high precision of the Analogue magnetic field, can be excited by introducing small amounts of third and fourth harmonics with additional coils.

The beam loss beyond $\nu_r = 1.4$ must be understood and eliminated. Although the beam loss is undoubtedly a result of large radial oscillations in the beam induced by the relatively poor optics now present in the central region, this needs to be confirmed.

Extraction of the beam from the Analogue is perhaps the most important activity to be undertaken. The Analogue is an ideal experimental device for this work, especially when combined with a suitable computing program. The method used will be a resonant extraction system employing a second-harmonic bump in the magnetic field to

develop coherent radial oscillations of sufficient amplitude to direct the beam into a magnetic channel. This effort will include studies of the effects (1) of rf accelerating voltage stability, (2) phase history of the particles, and (3) possible space-charge influences on the extraction of the beam, all of which need to be elucidated experimentally.

Ion optics at the center of the cyclotron will require careful study, both theoretical and experimental. Ion injection from an external source seems to be desirable but a detailed study of the necessary conditions for good acceptance should be made. In particular, the effects of finite transit time of ions crossing the cavity gaps need further examination. Preliminary studies indicate that an injection energy of between 100 and 200 kev is necessary for good operation. The effects of radial electric forces arising at the center from the finite width of the gaps has been examined, from which it is concluded that phase disturbances are produced but that the effects rapidly diminish with increasing orbit radius.

Radial electric forces are produced by the spiral of the gaps. It can be shown that these radial forces just compensate for the spiral of the gap in such a manner as to cause no resultant effect upon the phases of the ions relative to the rf. A preliminary study, however, indicates that if the gap voltages in two neighboring cavities vary in amplitude with radius then a mechanism resembling phase stability is introduced under certain conditions. If the gap voltage in the cavity first crossed by an ion increases with radius and in the next cavity decreases with radius, the ion, in successive passes through these cavities, will gain energy at both gaps but owing to the variation in gap voltage with radius, the effective gap is no longer along the gap spiral. It appears that a weak phase-sensitive radial electric force results from this arrangement which can cause ions to become "focused" upon a chosen phase angle. The early studies of this effect indicate that some nontrivial advantages might be obtained, particularly in reducing the

perturbing effects of the inevitable magnetic field errors and phase and frequency variations of the rf upon the phase of ions during acceleration. A detailed examination of these effects is desirable, together with a test of any usable results, on the electron model analogue.

Related to the above subject is that of varying the shape of the spiral, especially at large radii. An increase in the rate of spiralling would cause an increase in the aforementioned phase-focusing forces and would also permit a reduction in the magnitude of the required flutter field. A detailed study of these effects would be necessary to find the optimum amount of spiral.

Cyclotron Development

The magnet is central to the whole design effort. Modeling the magnet is more difficult due to the small gap and large radius planned. The model studies now underway are for evaluation of the yoke geometry, pole-face shape, magnetic forces, and methods for adjusting the flutter and average field independently. Some of the techniques and equipment from the ORIC magnet work can be adapted for the Mc^2 model program, but for an eight-sector model of precision suitable for orbit studies, improvement in both the speed of data acquisition and the precision of probe location are desirable. In addition, a method for quickly and precisely mapping the field of the full-scale magnet needs to be planned.

A sizeable effort will also be necessary to develop specifications and compatible fabrication procedures to assure uniformity of magnet steel and to obtain the desired mechanical tolerances.

Several interesting and important facets of the design of the radio-frequency cavities are apparent. Optimizing the design of the previously described system and achieving adequate mechanical stability will require attention. A significant reduction in cavity power may result from an unconventional wall geometry. If the walls of the cavities

are corrugated in a direction parallel to the direction of current flow, then the cavity power losses should be reduced. Such an effect has been observed in a model test, and it is expected that cavity losses at full scale might be reduced by 30% to 50%. The advantage from such a reduction would be in the possibility of using only one high power tube for driving the cavities, whereas two might otherwise be needed. The possibility of using partial cavities to increase the maximum possible energy gain per turn at large radii is being investigated.

Other problems to be considered are de-tuning effects, beam-loading effects, and phasing problems. Maintaining a cavity at resonance will require good mechanical stability since a preliminary calculation indicates that a 0.001-in. uniform deflection along the accelerating gap would de-tune a particular cavity to the half-power point. Deflections due to thermal effects should be easily compensated, but rapid vibrations could be more difficult.

After a final design for the accelerating system is selected, a larger scale model (1/4 to 1/2) will be constructed and tested. A model of the complete rf system (including controls) will be developed in conjunction with the large scale model.

The mechanical design of the Mc^2 Cyclotron will be a major undertaking. The design departs from the conventional in almost every aspect. The components of the machine are large, heavy, and require precise alignment. Very high reliability of components is a necessity and provisions must be made for maintenance in a radiation field. Particular attention must be given to the effects of radiation damage. In particular, the advantages of metallic vacuum seals and inorganic insulation materials will require departure from conventional design. The vacuum system will require no new techniques, but, because of its large size and cost, an optimization study to determine a suitable compromise of cost with pump-down time will be necessary. The effects

of radiation on the diffusion pump fluids will undoubtedly require study.

Shielding and Neutron Activation

The shield design, although adequate, is perhaps not optimum. Work on this aspect of the design of the Mc^2 facility will be continued. High-energy accelerator shielding studies now in progress in the Laboratory are expected to make a contribution to this effort. Measurements of the energy spectra and angular distribution of the neutron flux now being obtained at the synchrocyclotron installation at CERN will be of considerable value.

The neutron activation of the machine and the environs of the facility will be further evaluated both experimentally and theoretically. A continuation of our work at the LRL 184-Inch Cyclotron coupled with the continuing effort at CERN can be expected to further define the activation hazards.

Ion Optics

Considerable study will be required for the design of beam steering and ion optics of primary and secondary beams. In particular, a very long strong-focusing channel to contain muons over a 250-ft flight path will have to be designed. Such a channel, and the power associated with it, can be extremely expensive, so that considerable effort will have to be exerted to optimize the design. The ion optics for the medical facility, where pure low-energy pion beams are wanted, must also be investigated. In a neutrino experiment large numbers of pions must be contained over a considerable flight path, whereas the muons must be steered in a different direction. Good control must be exercised over the intense external proton beam to minimize activation of beam handling apparatus and large magnets.

Appendix A: SITE FOR Mc^2 CYCLOTRON

In the immediate vicinity of ORNL there are essentially three geological formations. There are shale formations to the southeast and dolomite rock to the north of the Laboratory. The valley in which the Laboratory is located contains a mixture of shale and limestone.

On the site selected, rough geological information indicates a limestone formation about 20 ft. below the surface. Core drillings will be made and evaluated in detail to determine the underground rock structure before a definite site selection is made.

The proposed site is about 1500 ft. east of the main laboratory (X-10) area and directly south of the new Oak Ridge Isochronous Cyclotron installation (Fig. A.1). It is close to an existing road; only a short approach road need be constructed. It provides a reasonably flat area about 2000 ft. long and about 1000 ft. wide (Fig. A.2). This area is parallel to a large hill and is of sufficient elevation to be well above the existing water table and to provide excellent drainage. The cyclotron is arranged so that the proton beam is directed east, away from the Laboratory. An open area about 1000 ft. long beyond the end of the beam corridor is available for future expansion or experiments. The facility personnel will have bus transportation to the main Laboratory on an existing bus route. Therefore, the existing facilities of the Laboratory can be utilized.

Fig. A.1 Proposed site of the Mc² Cyclotron with respect to other Laboratory installations.

Fig. A.2 Topography of proposed site

Appendix B. PERSONNEL ESTIMATES

The personnel estimates given in this section are for the personnel directly associated with the Mc^2 facility. These estimates assume normal support from the Laboratory organization in such matters as procurement, accounting, and other services ordinarily included as a part of operating overhead.

Research Personnel

The manpower estimate for research was developed by first estimating the size of an average research group (using experience at ORNL and information from other installations) and second, determining the number of research groups a facility such as the Mc^2 Cyclotron could properly support.

The average group consists of 2 senior scientists, 3 scientists, 2 engineers, and 2 technicians. In practice, the size of the group would be determined by the research problem and by the characteristics of the people working on the problem.

The senior scientists would be experienced doctoral level, physicists or chemists, and would provide the leadership for the various groups. The scientists, postdoctoral fellows or graduate students, would assist generally in the work and would develop solutions of individual problems of the research. The engineers would be experienced mechanical or electrical engineers of B.S. level and would provide the planning for devices and instruments and would assist in the experiments. The technicians would provide normal operational assistance. The secretaries would support two or more groups each.

The medical research group, as considered in this estimate, would be only the resident personnel and does not include personnel at other locations using Mc^2 research facilities.

Research Support Personnel

A single separate group for the support of the scientific research groups is considered most desirable and efficient for the following reasons:

- 1) The size of some of the research groups will certainly differ from the average, so that some groups will be small and all groups will probably

Table B. 1. Research Personnel

	<u>Per Group</u>	<u>Total for 6 Groups</u>
<u>Research in High Energy Physics</u>		
Senior Scientists	2	12
Scientists		
(Graduate Student + Postdoctoral)	3	18
Engineers	2	12
Technicians	2	12
Secretary	<u>.5</u>	<u>3</u>
Total	9.5	57
<u>Medical Research</u>		
Scientists		2
Technicians		1
Clerical		<u>1</u>
Total		4
<u>Research Support</u>		
Engineers		
Electrical		3
Mechanical		3
Draftsmen		5
Technicians		2
Instrument Mechanics		8
Clerical		<u>1</u>
Total		22

vary in size with time. This makes assignment of adequate support personnel to the research groups difficult. 2) The support group can more readily provide assistance to groups or individuals from outside or off-site locations. 3) This group can also give assistance to the operations group by providing maintenance of special apparatus, while their primary responsibility remains the development and design of new and novel components and systems necessary in order to keep the research in the forefront of experimental technology.

Operations Personnel

This manpower estimate is based on operations for 3 shifts, 7 days/week and is an extrapolation of experience on the 86-Inch Cyclotron, 63-Inch Cyclotron, and ORIC. The shift personnel indicated on the tabulation are the only personnel that would significantly change with modification of the operating schedule of the cyclotron.

The superintendent of operation would be responsible for the Mc^2 facility. His primary concern would be with operation of the cyclotron; responsibility for the building would be delegated to the building engineer. The three mechanical and three electrical engineers would be concerned with keeping the cyclotron operating properly a high percentage of the time, improvements in the cyclotron, preventive maintenance, and assistance to experimentalist in their setup. The crew chief would be responsible for the shift operation of the cyclotron and personnel safety. The cyclotron operating crew consist of: assistant crew chief, health physicist, technician, instrument mechanic, millwright, pipefitter, and electrician. The day shift would have the following additional personnel: 1 technician, 3 machinists, 1 pipefitter, 2 electricians, and 2 utilities operators. Actual operation of the cyclotron would normally be performed by the assistant crew chief aided by the technician.

Development, Design, and Construction Personnel

The manpower estimate for the development and design of Mc^2 is based, to a large extent, on a comparison of manpower requirements experienced on ORIC. The size of the design and development group will remain essentially constant throughout the Mc^2 design period, thus eliminating undesirable fluctuation in manpower level.

Table B.2. Operations Personnel (3 Shifts, 7 Days/wk.)

	<u>Day Shift</u>	<u>Rotating Shift</u>	<u>Total</u>
Engineers			
Superintendent of Operations	1		1
Building Engineer	1		1
Mechanical Engineer	3		3
Electrical Engineer	3		3
Crew Chief		4	4
Asst Crew Chief		4	4
Health Physicists		4	4
Clerical	4		4
Technicians	1	4	5
Instrument Mechanics	2	4	6
Machinists	3		3
Millwrights	2	4	6
Pipefitters	1	4	5
Electricians	2	4	6
Utilities	2		2
Janitors	3		3
	<hr/>	<hr/>	<hr/>
Total	28	32	60

B.5

The manpower listed includes that which would function as a development and design team, including both the personnel charged as operating costs and those charged as capital costs. The criteria for distinguishing between capital and operational charges is whether a component being designed will or will not be a part of the final machine. Development, testing, model work, and the direction of the work would be operating-type charges. Design, drawing, fabrication, and installation would be capital-type charges. The manpower listed under capital will be included in the capital cost of the cyclotron and will not be a part of operating costs.

The architect engineer personnel who design the buildings and facilities and the CPFF contractor personnel who perform the major installation of cyclotron components and control circuits are not directly the responsibility of ORNL and therefore are not in this report. Of course, allowance for the cost of these activities will be included in the cost estimates.

The estimate is made by breaking the work into a number of logical categories. This breakdown is also influenced by the experience and capabilities of groups and individuals in the Laboratory. The general responsibilities of the various sections would be as follows.

Management - The project director and assistant project director would be responsible for the direction of work. The budget and purchasing clerk, secretary, and clerk would assist all sections.

Orbit Dynamics - This section would conduct all theoretical, computational, and particle-motion studies. This section, working very closely with the magnetic section, would compute the properties of model magnet fields and help decide the direction of model work.

Mechanical - This section would produce all mechanical designs and would supervise the work of the design engineers and draftsmen.

Magnetics - This section would perform all magnet model work, determine final magnet shape, make all magnet measurements, and design ion optics components.

Electronics - This group would be responsible for electronic systems, such as rf cavity design, rf drive system for the cavities, ion-phase detectors, and special regulators.

B.6

Instrumentation - This group would be responsible for all controls, positioners, and instrumentation.

Building and Installation - This group would carry out the Laboratory's responsibility for building layout, checking of the architect engineer drawings, inspection of building, and provide representatives at the building site at all times to answer technical questions and to aid in the flow of information to the construction group. The installation of the cyclotron in the building will be the responsibility of this group. It should be pointed out here that the office and laboratory building, the shielded area, air conditioning, cyclotron water system, a-c power supply systems, d-c power supply system for the main magnet, and the mechanical (roughing) vacuum systems should be included in the lump-sum contract.

Table B.3. Personnel for Development and Design

	Development S&T	Development Clk.	Development Cfts.	Development Total	Capital S&T	Capital Cfts.	Capital Total	Development and Capital Total
<u>Management</u>								
Project Director	1							
Assistant Project Director	1							
Budget and Purchasing		1						
Secretary		2						
Clerk		1						
				6				6
<u>Orbit Dynamics</u>								
Group Leader	1							
Co-Group Leader	1							
Junior Math	2							
Programmers	2							
				6				6
<u>Mechanical</u>								
Group Leader	1							
Co-Group Leader	1							
Engineers					5			
Design Draftsmen					10			
				2			15	17
<u>Magnetics</u>								
Group Leader	1							
Co-Group Leader	1							
Engineers	2							
Technicians	4							

Table B.3. (Continued)

	Development S&T	Development Clk.	Development Cfts.	Development Total	Capital S&T	Capital Cfts.	Capital Total	Development and Capital Total
<u>Magnetics, cont'd.</u>								
Instrument Mechanic			1					
Millwright			1					
Machinist			5					
Electricians			4					
				19				19
<u>Electronics</u>								
Group Leader	1							
Co-Group Leader	1							
Engineers	4							
Technicians	2							
Instrument Mechanics			8					
Millwrights			2					
Machinists			4					
				22				22
<u>Instrumentation</u>								
Group Leader	1							
Co-Group Leader	1							
Design Draftsmen					4			
Instrument Mechanic			2					
				4			4	8

Table B.3. (Continued)

	Development	Development	Development	Development	Capital	Capital	Capital	Development and Capital
	<u>S&T</u>	<u>Clk.</u>	<u>Cfts.</u>	<u>Total</u>	<u>S&T</u>	<u>Cfts.</u>	<u>Total</u>	<u>Total</u>
<u>Building and</u>								
<u>Installation</u>								
Group Leader	1							
Co-Group Leader	1							
Draftsmen	2							
Technicians	2							
Millwrights						4		
Electricians						3		
Pipefitters						2		
Welders						1		
Instrument Mechanics						4		
				<u>6</u>			<u>14</u>	<u>20</u>
Total	34	4	27	65	19	14	33	98

Appendix C: TENTATIVE SCOPE AND COST ESTIMATES

The general outline of the scope of the Mc^2 project is based on demonstrated technological developments which will yield a workable and practical accelerator. Future modifications in scope will lie in the direction of achieving the desired performance and reliability with greater economy.

The tentative scope as outlined in following paragraphs does not yet provide an adequate basis for an accurate cost estimate for the Mc^2 facility; more detailed engineering study will be required. A study of the scope and comparison with recently completed facilities, components, and equipment suggests, however, that the total cost of Mc^2 facility will be more than \$20,000,000 and less than \$40,000,000.

 Mc^2 Building

Offices, Laboratories, Control, and Counting Building - There will be 73 offices with a gross area of about 9500 ft², 40 laboratories with a gross area of 23,000 ft², and a control and counting area of 8000 ft². Utility areas and corridors will add about 23,500 ft². There is also a basement area of some 28,000 ft². The building will require about 900 kw of lighting and equipment power.

Site Preparation - The site, as described previously, will entail removal of some 250,000 yd³ of earth and 100,000 yd³ of rock.

13.8 kv Power Station - The sub-substation will be equipped with transformers, breakers, and equipment necessary to handle 25 Mw of power.

Shielded Area - The area will require 35,000 yd³ in walls, 15,000 yd³ in arched ceilings, 2500 yd³ in floors, and 2600 yd³ in personnel mazes and retaining walls. A large amount of the required shielding will be provided by 84,000 yd³ of compacted rock and 170,000 yd³ of compacted earth.

Shielding Doors - There are five large shield doors. Each provides a minimum opening of 20 X 20 ft and is stepped for radiation safety. Three doors are 35 ft thick and have a volume of 600 yd³; two doors are 15 ft thick with a volume of 235 yd³. The medical facility will have one smaller shield door for personnel.

Bridge Cranes - Two corridors will each have a 50-ton main and a 10-ton auxiliary bridge crane of 30-ft span. The three experimental rooms have 40-ton main and 10-ton auxiliary hoist bridge cranes of 80-ft span. The cyclotron vault and service area will have a 150-ton main and 25-ton auxiliary hoist bridge crane of 100-ft span. The two utilities buildings each have a 20-ton main and 5-ton auxiliary hoist bridge crane of 80-ft span. The medical area will have either a bridge crane or monorail crane of about 10-ton capacity.

Mechanical Vacuum Pumps - There will be 7 Roots-type blower pumps, with Freon baffles and compressors for each. Total power required is about 265 hp or 200 kw. In series and/or parallel will be 7 KD-780 Kinney pumps with Freon baffles and compressors. These require about 290 hp or 235 kw. The ion optics will require 6 Kinney pumps, baffles, and compressors. These require 100 hp or 80 kw.

Cooling Tower - The cooling tower will have a capacity of 105×10^6 btu/hr and requires 12 high volume low pressure circulating water pumps.

Water System - The water system will require 2 large and 2 small heat exchangers having a total tube capacity of 2.5×10^6 lbs/hr of water. Tube pressure of the large exchangers is 175 psi and of the small exchangers is 300 psi. The system will have reusable filters at both operating pressures, pH and conductivity monitoring, demineralizers for make-up supply, the associated valving and piping, and large storage tanks for quick change-over when water goes bad. There will also be a steam-operated water still and a 500 gal storage tank.

Utilities - The East Building will be $14,400 \text{ ft}^2$ of high bay area with a bridge crane. The West Building will be 8000 ft^2 of high bay with bridge crane and 8000 ft^2 of low bay area without crane service. Both buildings require a total of about 200 kw of lighting.

Service Area Building - This area is attached to the north side of the cyclotron shield and has approximately $12,750 \text{ ft}^2$. It is high bay and has the use of the 150-ton bridge crane. It will contain a machine shop and change house.

Air Conditioning - The facility requires a total of 1700 tons of air conditioning, as follows: cyclotron, 400 tons; proton room, 200 tons; pion room, 200 tons; muon room, 200 tons; corridors, 200 tons; medical facility, 50 tons; and offices, laboratories, control and counting room, 450 tons.

Accelerator

Yoke and Tips - The magnet will consist of eight yokes and eight pairs of tips with a total weight of 4800 tons. A magnet support structure which penetrates the bottom of the vacuum tank will be required.

Main Field Coils - Eight pairs of coils, requiring 3000 kw, will provide the main field. The windings of the coils will require 40 tons of copper and will be water cooled at 300 gpm and $\Delta T = 90^\circ\text{F}$. These main coils will be sealed in stainless steel vacuum cans.

Radial Gradient Coils - As above, there will be 8 pairs of vacuum-canned coils requiring 4000 kw of power in 40 tons of copper windings.

Flutter Coils - These coils require 3000 kw and 40 tons of copper windings.

Resonator - The two resonators or cavities will require extensive trimmers and servo controls. We estimate the resonators to have about 9000 ft^2 of copper sheet surface, all of which is water cooled to maintain $\Delta T = 20^\circ\text{F}$.

Power Amplifier - This unit will be similar to the ORIC power amplifier system in that it contains an oscillator, two buffer stages, two intermediate stages, two drivers, and two final amplifiers using RCA 6949s. The total power will be 500 to 800 kw. The amplifier will require the appropriate water and air cooling and controls system.

Vacuum Tank - The vacuum tank will be thin-wall carbon steel with appropriate stiffening members along the outside. It will be 60 ft in diameter and 50 ft high and will have a thin-wall concave bottom and a thin-wall concave removable top. There will be thirty-two, 32-in ports for diffusion pumps plus other ports for observation and roughing pump connections. The net volume is 2.6×10^6 liters.

Ion Source System - This system will include a vacuum lock, filament supply, arc supply, injection supply, automatic extraction system, and remote controls. Approximately 10 gpm of cooling is required. Facilities will be provided for rapid change of an ion source without going into the cyclotron vault. Several complete source assemblies would be provided.

Beam Extraction - The extraction system will consist of a pair of harmonic coils and a magnetic channel. Each will require about 1000 kw and 100 gpm cooling. In addition, there will be a system for measuring energy and beam-rf phase relationship.

Diffusion Pumps, Baffles, and Compressors - The high vacuum will be maintained at 1×10^{-6} torr by 32 5-stage, 32-in oil diffusion pumps. Each pump requires 16 kw of power, 4 gal of oil, 4 gpm of cooling, an air-operated 32-in valve, a 32-in optically opaque Freon baffle, and a 2-hp Freon compressor.

Vacuum Piping - Piping will be required to connect the diffusion pumps into four groups of eight which then tie to a large foreline leading back to the mechanical pumps. Large roughing lines will also be required to bring the pressure down to the diffusion pump range in a reasonable time.

Motor-Generators - Motor-generators include those for the 3000-kw main field coils, the 4000-kw radial gradient coils, the 3000-kw flutter coils, the 1000-kw harmonic coils, and the 1000-kw magnetic channel coils.

Control System - The system includes a completely wired console and control panel with operating communications and multi-station closed-circuit television; it will be about threefold larger than ORIC.

Ion Optics

Beam Vacuum System - This system includes 85 4-in oil diffusion pumps, each with air-operated valves. It also includes the vacuum pipe system for all the deflected beams.

Auxiliary Vacuum System - This system includes piping and controls to connect the various segments of the beam pipe system to remotely located mechanical pumps. This also includes separate roughing lines from the various experiment rooms to individual mechanical pumps.

Magnets - The characteristics, including power and water, of all magnets in the ion optics system are listed in Table C.1.

Table C.1. Magnets for ion optics system.

Name	Aperture (in.)	H _p (gauss - in.)	Max field (kgauss)	Arc length (in.)	Elements	Water flow for 90° F ΔT (gpm)	Power (kw)	Number
Proton quadrupole	5				3	10	100	11
Proton positioner	5	2×10^6	15,000			5	50	1
Proton analyzer	5	2×10^6	15,000	105		20	195	1
Proton analyzer	5	2×10^6	15,000	210		30	330	1
Proton switching	5	2×10^6	15,000	140		20	195	1
Proton positioner	5	2×10^6	15,000	25		5	50	1
Proton positioner	5	2×10^6	15,000	200		25	300	1
Pion analyzer	8	1×10^6	15,000	105		18	185	1
Pion quadrupole	8					10	100	1
Pion switching	8	1×10^6	15,000	70		18	185	1
Muon quadrupole	8				126	425	5,000	1
Muon analyzer	8	1×10^6	15,000	105		25	285	1
Muon quadrupole	8				40	150	1,600	1
Muon switching	8	1×10^6	15,000	75		30	330	1
Muon quadrupole	8				35	135	1,400	2
Muon analyzer (medical)	8	3×10^5	15,000	32		15	150	1
Muon positioner (medical)	8	3×10^5	15,000	32		15	150	3

Magnet Power Supplies - The power supplies required for the ion optics system are listed in Table C. 2. Provisions will be made to switch power supplies from one magnet to another in cases where the magnets are comparable and will not be in use at the same time.

Table C. 2. Ion optics power supplies.

<u>Number of Supplies</u>	<u>Maximum Power (kw)</u>	<u>Magnets to be Energized</u>
1	50	Proton positioner
7	125	(11) Proton quadrupoles
		Proton positioner
		Pion quadrupole
3	195	Proton analyzer
		Proton switching
		Pion switching
		Pion analyzer
4	330	Proton analyzer
		Proton positioner
		Muon analyzer
		Muon switching
		Muon analyzer (medical)
		(3) Muon positioners
1	1, 400	(2) Muon quadrupoles
1	1, 600	Muon quadrupole
1	5, 000	Muon quadrupole

Appendix D: SCHEDULE FOR DESIGN,
FABRICATION, AND CONSTRUCTION

The schedule for the development, design, fabrication, and construction of the Mc² facility is based on our experience with the ORIC and other Laboratory projects and on the manpower levels and tentative scope outlined in Appendices B and C. The schedule, Table D.1, places much of the preliminary design prior to the date of authorization, which is assumed to be FY-1965. This more extensive preliminary design should result in more realistic cost estimates at the time of authorization.

Table D.1 Suggested schedule

Appendix E. LIST OF CONTRIBUTORS

This status report, prepared under the overall guidance of R. S. Livingston, represents the contributions of many individuals.

1. Foreword

A. H. Snell

2. Contributors to the Research Sections, in which the experimental program, layout of major equipment including the arrangement of shielded rooms, and beam properties and beam handling are discussed.

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3. Contributors to the Accelerator Sections, which describe accelerator design, engineering of allied facilities, and model studies.

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