On the History of Physics at Michigan

This document is recovered from a file of a manuscript adapted by Jens Zorn from the work of Charles F. Meyer, George A. Lindsay, Daniel L. Rich, Ernest F. Barker, and David Dennison that appeared in *The University of Michigan, an Encyclopedic Survey, Vol 2* published in 1951 by the University of Michigan Press. The second part of the manuscript is by Jens Zorn and William Parkinson.

Early History

The subject of physics was first taught in the University in the autumn of 1843, under the name of natural philosophy. Some eleven juniors constituted the first class, and the instruction was conducted by George Palmer Williams (Vermont '25, LL.D. Kenyon '49), who also taught mathematics under the title of Professor of Natural Philosophy and Mathematics. From this modest beginning there has been a continuous evolution into the present Department of Physics, comprising in the various ramifications of its activities a staff of about sixty, including assistants and technicians, and occupying two large buildings.

In Detroit, first as the "Catholepistemiad, or University of Michigania" in 1817, then as the University of Michigan in 1821, the institution had been unable to find sufficient students of collegiate grade. It had therefore confined itself largely to secondary instruction, and for a time continued to do so even when, on Michigan's admission to statehood in 1837, the board of Regents was established and the site at Ann Arbor was determined upon. Regular university instruction began in Ann Arbor only in 1841. At the same time the Regents withdrew a large part of the support which they had been pouring into the several University-sponsored and University controlled secondary schools about the state, called branches.

In anticipation of the opening of the central institution, the Regents, in July, 1841, appointed George P. Williams to be Professor of Languages; but in August, upon his own request, they made him Professor of Mathematics instead, and appointed the Reverend Joseph Whiting to the professorship of languages. Both took up residence in Ann Arbor in September, and announcement having been previously made that college instruction would begin, seven students presented themselves. Only freshman and sophomore classes were organized the first year; the sophomore class consisted of one student, who was later absent for one year, but returned and graduated with the class below in 1845. The subjects of instruction consisted of mathematics and the ancient languages and literature. Professors Williams and Whiting constituted the entire resident staff.

During the next academic year, 1842-43, the same subjects of instruction were continued for the original class, now sophomores, with a brief course in logic perhaps added. Some additional students joined this class from time to time, and a new freshman class had entered.

In the third and fourth years of the curriculum the study of the ancient languages was much reduced and natural philosophy, astronomy, chemistry, zoology, geology, and some of the social sciences were studied. The academic year was at first, and until 1856-57, divided into three terms. By the autumn of 1843, according to the Catalogue, Williams' title had been changed to professor of Natural Philosophy and Mathematics, and, as previously stated, he conducted the instruction of the first class in natural philosophy, consisting of junior students; the instruction was given in the first and second terms of the third year of the curriculum.

The textbook was the two-volume Introduction to Natural Philosophy by Denison Olmsted, professor of natural philosophy and astronomy in Yale College. This was first published in 1832. In 1837 the same author published also a more elementary text in one small volume, for "schools and academies." A copy of the elementary text is at hand, but the college text in its two-volume form is not available. After several revisions, however, the college text was stereotyped in 1844 and was thereafter issued in a single octavo volume of nearly six hundred pages, as occasion demanded. In an 1858 reprint of this text, which is at hand, mechanics, acoustics, electricity, magnetism, and optics are treated.

The text is on the whole thorough and excellent, but under electricity, to which seventy pages are devoted, not a word is said on the subject of electric currents, for the reason that "in Yale College, Galvanism and its kindred subjects are assigned to the chemical department." Thus Ohm's law, which had been announced in 1826, is not mentioned; moreover, under magnetism nothing is said concerning Oersted's epoch-making discovery made in 1820, of the, effect of the electric current on the magnetic needle, nor of the equally momentous discoveries made some twelve years later by Faraday and by Joseph Henry of the phenomena of electromagnetic induction and of self-induction.

This is strange, especially in view of the fact that Joseph Henry's work was carried on first at Albany and then at Princeton, two cities both rather near New Haven. Were the Yale chemists appropriating all of these marvelous advances in physics of the time, or were these great discoveries as yet too little understood to permit of treatment in a college text. In the part of the book which is devoted to optics, the phenomenon of polarization by reflection, discovered by Malus in 1808, is adequately treated, as is also Fraunhofer's discovery of the dark lines of the solar spectrum, announced in 1817. But Young's development of the Principle of interference, 1801-4, is accorded only a few sentences (with no mention of Young's name), and Fresnel's great researches of the years 1815-24 are ignored (though Fresnel is incidentally mentioned in a footnote).

In the early years at Ann Arbor, as elsewhere at the time, instruction was almost entirely from textbooks. Recitation of subjects assigned for study consumed the greater part of the class periods, combined, of course, with discussion. Lectures were only occasional, and there were no demonstration lectures, which we now hold as important in the experimental sciences. Moreover, the student was offered no opportunity whatever to carry out experiments for himself. Laboratory instruction in physics at the University lay as yet nearly forty years in the future.

During the decade 1843-53 the instruction in physics was conducted in the manner just outlined.

Williams, as senior member of the faculty, and through his genial spirit coupled with an alert mind and kindly humor, held a unique place in the University during its first forty years at Ann Arbor. A multitude Of students came to him for counsel, and all loved him. To them he was affectionately known as "Punky." But, though revered, he did not escape the crude Pranks occasionally played by the students in the early days. It is recorded that, early one morning, the students led a donkey into his classroom and tied it behind his desk. When he entered, the students were all in their seats. He bowed and said, "good morning, gentlemen! I see you have no need of me this morning, having already provided yourselves with an instructor fully qualified to instruct you," and thereupon he walked out.

While Professor Williams was now by career a mathematician and natural philosopher, he maintained his interest in languages and in theology, in both of which he was proficient. Throughout his life he was deeply religious and had had and retained a desire to be some day ordained a minister. Once he had been accepted for ordination, but he then refused because of doubts in regard to his own worthiness. At length he was ordained, in 1846, as a minister of the Protestant Episcopal church and subsequently, while retaining his duties at the University, served for about two years as rector of Saint Andrew's Church of Ann Arbor, without salary, in order to help this church out of financial difficulties.

President Tappan, who entered upon his duties in the autumn of 1852, at once wisely stressed the need for augmentation of the faculty. Inasmuch as Williams had become overburdened in his dual professorship of mathematics and natural philosophy, and since a need for an engineering course had developed, Tappan urged the appointment of a professor of physics and civil engineering. The Regents created the proposed professorship and selected a man recommended by the Reverend Erastus Haven, then Professor of Latin in the University and later its President, as well as by the famous botanist Louis Agassiz and others, as an individual of superior and versatile attainments, qualified to hold a professor ship in almost any branch of science.

The man in question was Alexander Winchell (Wesleyan '47, LL.D ibid.'67). He was called in the autumn of 1853, but was delayed until January, 1854, in Alabama, where he had been teaching, by an outbreak of yellow fever. Immediately after his arrival Winchell entered upon his new duties, and by the autumn of 1854, the title and function of George P. Williams had been limited to those of a professor of mathematics, as Winchell was filling the professorship of physics and civil engineering. It devolved upon Winchell, moreover, to select and purchase the first physical apparatus for the University, an initial appropriation of $500 having been made for this purpose.

Unfortunately, Winchell soon fell into disfavor with President Tappan. Probably the chief source of their discord was personal incompatibililty, but in any event Tappan felt that Winchell had been inattentive to his duties, and, after a year, effective in the autumn of 1855, had him transferred to what he considered a less important chair. Another factor in the situation may have been that Winchell's dominant interests were in fields other than physics and engineering. He subsequently had a distinguished career, principally as a geologist.

Simultaneously with the transfer of Alexander Winchell, Lieutenant William Guy Peck (U.S. Mil. Acad. '44, A.M. Trinity [Conn.] '53 LL.D. ibid. '63) was called to the chair of Physics and-civil engineering. Graduated first in his class at West Point, he had served in the Mexican War and then as an assistant professor of mathematics at West Point. He filled his professorship in Ann Arbor for two years, 1855-57, and then was called to Columbia University.

During the period of Peck's incumbency of the chair of physics the first Chemical Laboratory Building was erected. It was a small building which, after numerous and extensive enlargements, is now known as the Economics and Pharmacology Building. The facilities thus provided for laboratory work in chemistry were among the best of the day in America. At this University as well as elsewhere, chemistry was the science which first introduced laboratory instruction.

No provision had been made in the late summer of 1857 for the courses in physics and engineering for the coming year. At that time a recent graduate of the Rensselear Polytechnic Institute stopped over in Ann Arbor, to visit the University, on his way to Chicago, where he intended to seek employment. He called upon President Tappan, and in the ensuing conversation Dr. Tappan suggested that the young man, DeVolson Wood by name, remain in Ann Arbor and for the time being undertake the instruction in the courses in question, with the understanding that he would have to content himself with such remuneration for this service as the Regents might deem proper to allot to him. Wood accepted. He proved himself capable and was soon given an appointment as an assistant professor, which he held for two years. In June, 1859, he was made Professor of Physics and Civil Engineering, but he held this title for only one year.

The time was ripe for the creation of a separate professorship of engineering, and DeVolson Wood (C.E. Rensselaer Polytechnic Inst. '57, M.S. Michigan '59) was chosen for this chair. In 1860 James Craig Watson ('57, Ph.D. Leipzig '70), who had for a year been professor of Astronomy, was appointed to the professorship of physics, a post which he held for the three years 1860-1863. Williams then became Professor of Physics and retained this appointment until his retirement in 1875. But Williams was aging and needed relief from the burden of his post. In view of his long and conspicuous service, however, he was continued in the rank and with the salary of professor of physics, but without duties.

In 1871 George Benjamin Merriman (Ohio Wesleyan '63, A.M. Michigan '64) was transferred from an assistant professorship of mathematics to an adjunct professorship of physics. Merriman, who was born at Pontiac on April 13, 1834, was the first native son of the state to have charge of or take part in the instruction of physics at the University.

The lecture rooms and chapel of University Hall were ready for occupancy in October, 1872 (the auditorium not until a year later), and the locus of the instruction in physics was now transferred to this new building;

space was allotted in the southeast corner of the fourth floor. just previous to this removal the classes in physics had been held in the North College (Mason Hall). In the very early years, when this was the only college building, the instruction in all branches of learning had been given there. Upon completion of the South College (South Wing) in 1848, the classes in some subjects were transferred to it. Rather more likely than not, physics remained in the North College until removed to University Hall. A fact which bears upon this question but yet furnishes no definite clue is that the above-related donkey episode, which occurred in 1857, was reported concurrently in the Detroit Free press as having taken place in the North College. But this episode occurred while Williams was Professor of Mathematics only. Mr. Levi Wines, an alumnus of keen intellect who entered the University in the autumn of 1879, stated that he, as a prospective freshman, went to interview Williams, at that time again Professor of Physics, and that Williams' office and classroom were then in the North College. Accordingly, the instruction in physics was either still or again being given in the North College. Mr. Wines could not recall with certainty just where within the North College Williams' rooms were situated, but he was inclined to believe that they were in the southeast comer of the second floor.

Mr. Wines also said that when he attended the course in physics, probably in 1872-73 and in any event during the years that it was conducted by Professor Merriman in University Hall, the course included lectures as well as recitations, and the lectures were accompanied by ample demonstrations. The students, however, were given no opportunity to perform experiments themselves. Also, the well-known Ganot's Physics was then being used as a text. This continued to be used for many years.

At this period the students annually celebrated at the conclusion of the course the "burning of physics" or the "burning of mechanics," which was a comic ceremony in which an effigy representing physics or mechanics was by way of climax to appropriate obsequies cast upon a burning pyre. This custom originated in 1860 and was continued with perhaps an occasional omission until 1881. The class of 1875, moreover, feeling that the "burning of physics" was not enough, arranged in addition an entertainment in Hangsterfer's Hall in downtown Ann Arbor, of which the principal attraction was a parody on a demonstration lecture in physics featuring experiments which didn't work!

In June, 1875, Merriman terminated his service at the University to accept the professorship of mathematics at Albion College. In the interim the alumni had generously raised a liberal pension fund for Professor Williams, and he was at this same time definitely retired with the title of Emeritus of Physics. He continued to reside in Ann Arbor until his death on September 4, 1881, at the age of seventy-nine years.

John Williams Langley (Harvard '61, M.D. hon. Michigan '77, Ph.D. hon. ibid. '92), a brother of the famous Samuel Pierpont Langley, replaced him. A graduate of the Lawrence Scientific School of Harvard, Langley had studied medicine for a year at Michigan, and had been in the succession an acting assistant surgeon in the United States Navy, an assistant Professor of natural philosophy at the Naval Academy, and a professor of chemistry at the Western University of Pennsylvania. He conducted the instruction in physics here for two years in conjunction with work in chemistry, under the titles of Acting Professor of General Chemistry and Physics for the year 1875-76 and Professor of the same subjects during 1876-77. Thereafter, he was Professor of General Chemistry only.

In the autumn of 1877 Charles Kasson Wead (Vermont '7 1, A.M. ibid. '74) assumed the work in physics under the title of Acting Professor of Physics. He had done graduate study in this country, and this was followed by three years of teaching and a year of study in Berlin. Under C. S. Wead the first instructional laboratory in physics was inaugurated in February, 1878; it extended along the east side of the fourth floor of University Hall. Wead's field of principal interest was acoustics. He remained at the University until 1885 and then, or soon after, returned to the East. After a period of some years he entered the United States Patent Office. During the year 1885-86 the professorship of physics was vacant.

To provide instruction in the interim, however, Mark Walrod Harrington ('68, A.M. '71, LL.D. '94), Professor of Astronomy and Director of the Observatory, assumed temporary charge

of the courses in physics, and DeWtt Pristol Brace was Assistant Professor of Physics from February until June. The latter subsequently became a professor of physics at the University of Nebraska. Henry Smith Carhart (Wesleyan '69, Sc.D. Northwestern '12, LL.D. Michigan '12) assumed his duties in the fall of 1886 with the title of Professor of Physics and remained at Michigan in that capacity until 1909. He came from Northwestern University, where he had been

for fourteen years. Born at Coeymans, New York, on March 27, 1844, he had obtained his bachelor's degree at Wesleyan University, Middletown, Connecticut, and had then studied at Yale for a year before going to Northwestern. When Carhart arrived the time was ripe for the erection of a laboratory building for physics and hygiene. Construction was begun in 1887, and the building was ready for occupancy in the autumn of 1888. The original Physics Building was considerably enlarged on its west side in 1905, the added part including the room known as the West lecture room. The structure is now called the West Physics Building.

The Growth after 1890

With the facilities provided by the completion of the Physics Building in 1888 the functional activities in the field of physics at the University began a rapid advance in status and expansion in scope. Playing equally important roles in bringing about this advance and expansion were two First, the University as a whole was growing and additional factors. maturing rapidly, and second, a great developmental influence was exerted personally by Carhart, through his energy and ability as a scientific investigator. He was internationally known for his contributions to the progress in electricity which was being made in his day. In 1890 the additional title of Director of the Physical Laboratory was conferred upon Carhart.

During the decade 1890-1900 several appointments were made in physics in the ranks of instructor, assistant professor, and junior professor, with advance in rank of the incumbents from time to time. There thus evolved during this decade what may properly be called a staff in physics and a Department of Physics. Those holding appointment continued in the department into the new century.

The six men conducting the instruction in physics in 1901-2 included two recent additions and were as follows: Henry Smith Carhart, Professor of Physics and Director of the Physical Laboratory: John Oren Reed ('85, Ph.D. Jena ‘97), Junior Professor of Physics; Karl Eugen Guthe (Ph.D. Marburg '89), Assistant Professor of Physics; Harrison Mcallister Randall ('93, Ph.D. '02), Instructor in Physics; George W. Patterson, Junior Professor of electrical engineering; and Benjamin F. Bailey, Instructor in electrical engineering. Of these six, it is rather remarkable that all have been, or are at present, heads of departments in the University, and three have been deans. Carhart was succeeded as Director of the Physical Laboratory by Reed, Guthe, and Randall, in the order named. Randall continued as Director until his retirement in 1941, when Ernest Franklin Barker (Rochester '08, Ph.D. Michigan '15) was made Chairman of the Department of Physics.

Patterson became the head of the department of electrical engineering in 1905 and continued in that capacity until 1915. He was also head of the Department of Engineering Mechanics from 1914 until his death in 1930. Bailey became the head of the Department of Electrical Engineering in 1922, and held that position for more than twenty years. The three who became deans were John 0. Reed, who was the first Dean of the Summer Session and later Dean of the Literary Department, Karl E. Guthe, who was chosen the Dean of the Graduate School just at the point of its reorganization in 1912, and George W. Patterson, who was Dean of the Engineering College from 1922 to 1927, Acting Dean for the year 1927-28, and Associate Dean 1928-30.

Dean Patterson died May 22, 1920. For many years he had conducted the more advanced courses in electricity in the department of Physics, even after his title became Professor of Electrical engineering. He was joint author with Professor Carhart of a textbook, Electrical Measurements, which was in use for a number of years. Perhaps one of the most popular high-school texts on physics was one known as Carhart and Chute, from the names of the authors. The second author was Horatio Nelson Chute ('72, A.M. '75, LL.D. Denison '09), of the Ann Arbor High School. Carhart’s Physics for University Students was also used as a text in the courses in general physics, especially by engineering classes. His most important contributions to physics were on electrical and electrochemical subjects. He established courses in electrochemistry in the physics curriculum, and was an authority on standard cells. He was made Professor Emeritus in 1909 and died in 1920. Most of his years after retirement were spent in California.

Professor Reed is remembered by all his students as a very vigorous and efficient teacher, who had little patience with sham and nonsense, but who labored with boundless energy to aid those who proved themselves capable and eager to learn. His interest was principally in the subjects of sound and light, and he prepared excellent laboratory courses in those branches. In March, 1912, he obtained a leave of absence because of illness. He died January 23, 1916.

Karl E. Guthe, after having been a member of the Department of Physics for some years, resigned and engaged in research at the Bureau of Standards from 1903 to 1909, then returned as Professor, and later succeeded John 0. Reed as Director of the Physical Laboratory. Together with Reed he published College Physics, a text which enjoyed wide use in courses in general physics. Guthe's reputation for scholarship and research made him the choice for the first Dean of the Graduate School. Unfortunately, his inspiration and services in this capacity were cut short by his sudden death in Oregon, September 10, 1915.

The death of Professor Guthe occurred so near the opening of the school year that there was practically no time left for his successor to make plans to carry the load thus suddenly thrust upon him. Upon H. M. Randall devolved the responsibility of directing the affairs of the department and of providing for the needs of graduate students, who were coming in increasing numbers. How well he assumed these duties was indicated by the enormous increase of the research facilities and activities of the department under his directorship, by the large number of students pursuing advanced work, and by the expansion of the teaching curriculum to include instruction in the most modern and advanced aspects of physics. Randall was a joint author, with N. H. Williams and W. F. Colby, of General College Physics, a text which was used for years in the general physics classes of the University. His major research interest was in radiation, particularly that of the infrared region of the spectrum. Randall's contributions to this field were important not only for the information they yielded, but even more because the methods he devised were developed extensively by others. His own investigations and those of his associates brought to the laboratory high distinction and established it as a leading center for infrared research. Randall was the president of the American Physical Society in 1937.

The Courses of Instruction

Until about 1880 it could scarcely be said that anything beyond elementary physics was offered in the courses of instruction. Under C. K. Wead, however, more work in optics, acoustics, and electrical measurements was initiated. Commercial applications of electricity had been developing rapidly, and soon after Carhart took charge in 1886 new courses began to appear. Thus, in 1888 was instituted a course in dynamoelectric machinery, and in 1889 there were courses in mathematical electricity, in electric batteries, and in the photometry of electric lamps. In 1891-92 were added the study of transformers, more laboratory work in electricity, and the theory of light. A course in the theory of heat was first offered in 1893-94, and advanced studies in sound and light in 1895-96. The courses in sound and light were taught by John 0. Reed; those in electricity were given by Carhart and Patterson.

In the year 1900-1901 a colloquium was added, for which one hour of credit was given each semester. In this colloquium advanced students joiined with the teaching staff in presenting reports on research and on other topics of interest.

Although the courses in general physics have been modified from time to time to meet the needs of those preparing for the different professional schools, it may be said that since 1887 a full year's course of at least five class or laboratory periods per week has been given. The students preparing for medicine, dentistry, and pharmacy took the same course in physics as those in the college of Literature, Science, and the Arts, while engineering students were asked to do additional work in the solution of problems.

The subject of thermodynamics had been well developed for many years previously, but there was not sufficient demand for advanced study in this subject until the year 1901-02, when Karl E. Guthe first offered a course under this name. A course in electrochemistry was introduced by Carhart in 1902-03, and one entitled Advanced Electricity and Magnetism by Patterson in 1904-5. In 1907-8 instruction in the measurement of high temperatures was begun by Randall.

Two courses in advanced physics were given by Guthe, beginning in 1910-11. These have since given way to separate intermediate courses in mechanics, sound, heat, and light. In the same year were announced a seminar and courses on electromagnetic theory by Guthe, on direct and alternating currents by Neil Hooker Williams ('93e, Ph.D. '12), and on radiation by Randall. For ten years following Carhart's resignation the laboratory course in electrochemistry was carried on by William D. Henderson ('03, Ph.D. '06), who later became Director of the University Extension Service.

Courses in German and French reading for students of the sciences were first listed in the physics group in 1912-13.

Post WWI

A course in X rays was first offered by David Locke Webster (Harvard '10 Ph.D. ibid. '13) in 1917-18, and one on the theory of gases by Walter Francis Colby ('01, Ph.D. '09) in 1920-21. Work in modem physics was introduced by Colby in 1921-22, as was also the study of vacuum tubes by Williams.

In 1923-24 appeared announcements of courses in quantum mechanics by Colby, on physical optics by William Warner Sleator ('09, Ph.d. '17), and on atomic structure by Ernest Franklin Barker;

Oskar Klein 1922-3 (?), 1923-4. 1924-5

In 1924-25, geometrical optics by Ralph Alanson Sawyer (Dartmouth '15, Ph.D. Chicago '19), theoretical mechanics by Oskar B. Klein (Fil.Dr., Inst. for teor. Fysik [Copenhagen] '21), spectral series by Randall, X-ray equipment and apparatus by George Allan Lindsay ('05, Ph.D. '13), and electronics and conduction of electricity through gases by Ora Stanley Duffendack (Chicago '17, Ph.D. Princeton '22);

In 1925-26, laboratory work in radioactivity by Arthur Whitmore Smith (Dartmouth '93, Ph.D. Johns Hopkins '03);

In 1926-27, high-frequency measurements by Williams, architectural acoustics by Daniel Leslie Rich (Waynesburg '02, Ph.D. Michigan '15), and theory of spectra by Otto Laporte (Ph.D. Munich '24); in

In 1927-28, quantum mechanics by Laporte, theory of band spectra by David Mathias Dennison (Swarthmore '21, Ph.D. Michigan '24), infrared radiation by Randall, and contemporary physics by George Eugene Uhlenbeck (Ph.D. Leiden '27)

1928-29 a proseminar for the master's degree and a year's work in molecular physics for graduate students not specializing in physics, and quantum theory and atomic structure by Dennison.

In 1929-30 the theory of atomic spectra was introduced by Samuel Abraham Goudsmit (Ph.D. Leiden '27), and some eleven courses of special investigation were provided for graduate students with the idea of offering preliminary investigation in any line to those not quite ready to begin a subject for the doctor's degree.

In 1934-35 a non-technical course in general physics was introduced by Rich especially for students not intending to continue work in physics; in 1937, mechanics of fluids by Lindsay; in 1939, nuclear physics by Horace Richard Crane (California Inst. Technol. '30, Ph.D. ibid. '34); and in 1942, introduction to aerodynamics by Uhlenbeck. Since 1920 Charles Ferdinand Meyer (Johns Hopkins '06, Ph.D. ibid. '12) has had charge of the laboratory in physical optics.

The average numbers of courses listed each year during five-year intervals are given in Table 1.

Interval	Number of Courses Offered
1901-6	23
1906-11	25
1911-16	34
1916-21	38
1921-26	40
1926-31	51
1931-36	64
1936-41	48

Nearly all of the courses which are now considered as advanced work for graduate students have been added since 1920. Among the few exceptions to this are courses in electricity and magnetism and in thermodynamics.

The inclusion of new courses in the curriculum follows rather closely the advance of research in any particular phase of the subject. For example, the great activity in research concerning the structure of the atom in the years about 1920 corresponds with the introduction of a course in atomic structure in 1923, and the development of new types of vacuum tubes and their application to radio communication were followed by a course in vacuum tubes in 1921. In general, there has been a great increase in the amount of theoretical physics offered since 1920. The same period has witnessed a remarkable growth in the research productivity of the department. This growth was unquestionably favored by the unusual conditions in physics during these years, for so many new experimental results were obtained through such agencies as optical and X-ray spectra-in fact, through measurements of electromagnetic radiation, from the greatest wave length down to cosmic radiation at the other extreme of the spectrum-that there was almost unparalleled opportunity for new investigation. The policy of Karl E. Guthe, Director of the Physical Laboratory from 1911 until 1915, and of H. M. Randall since that time, was definitely to encourage research to the fullest extent. This encouragement by word, by example, and by every effort to provide the necessary apparatus for the problems undertaken has been a source of continual inspiration to the members of the staff. Fortunately, the new building (East Physics Building), erected in 1924, afforded more space and other facilities without which many of the investigations since successfully carried on would have been quite impossible. In this new structure, renamed the Harrison M. Randall Laboratory of Physics in 1940, are conducted the advanced classes as well as the research work. The offices of the permanent members of the staff are also located there. The elementary class and laboratory work is carried on in the older West Physics Building.

The number of graduate students in physics has increased rather steadily, and the increase has been rapid since 1925, Because of the different manner of publishing registers of students in different years, it is difficult to obtain complete and reliable figures on the total number specializing in the department for all the years. In Table 11, which has been compiled from various tabulations, the net numbers of graduate students specializing in physics are given for every fifth year. Previous to 1890 the subject of specialization was not recorded in the registers. The record of the master's and doctor's degrees begins in 1891.

TABLE HERE FROM P. 17

*The numbers marked with an asterisk are not net; they are the sums of the attendances for the academic year and Summer school. The number of duplications in these years is not definitely obtainable; it would probably range from five to fifteen each year.

Laboratories

Although the teaching of physics began in 1843, laboratory work was not started until the beginning of the second semester, February 18, 1878. The space then devoted exclusively to the Department of Physics extended, as stated in the catalogues of the time, "in a direct line over 125 feet," was "well lighted from the north, east, and south," and "was provided with gas, steam, and water." This laboratory was in a suite of rooms on the top floor of University Hall adjacent to the office occupied by Professor C.K.Wead, who was then in charge of the instruction in physics.

A new $30,000 physics laboratory, the first unit of what is now known as the West Physics Laboratory, was ready for occupancy in October, 1888. The basement and the second story were occupied by physics and the third story by the laboratory of hygiene. On the completion of the "new" Medical Building in 1903, the laboratory of hygiene was removed to new quarters, thus leaving much needed room for the development of physics.

In 1905 an addition, costing, with equipment, about $45,000, was made. An important feature of this addition was a well-equipped lecture room (the West Lecture Room) accommodating four hundred students. The entire building is still used exclusively by the department. It houses a well-equipped shop employing five full-time instrument makers, a liquid air plant with a capacity of four quarts per hour, a glass-blowing room in which two professional glass blowers work, a large lecture room, six apparatus rooms, a battery room, eight rooms for elementary laboratory work, six classrooms, and a few offices.

In 1920, two large rooms at the north end of the basement in Tappan Hall were taken over. One was used for spectrographic research, and the other served as a light laboratory. These continued to be occupied as physics laboratories for four years.

During 1923 and 1924 a new building, standing in part on the site occupied from 1850 to 1913 by the first Medical Building, was erected. This new structure, the East Physics Building, cost, exclusive of equipment, about $450,000 and was ready for occupancy in February, 1924. It

is an L-shaped building, the outside of the L being 144 feet by 132 feet and the wings 60 feet wide. There are four floors above ground, and a full-lighted basement; under about three-fourths of this basement is a subbasement, and under one-half of this subbasement is a sub-subbasement, making the building, in part, seven stories high. The soil on which the structure stands is good building gavel to a depth of about 300 feet, and the water table is about 80 feet below the surface. This very favorable soil condition makes the lower basements not only dry but also exceptionally free from vibration. These lower rooms, well ventilated, well lighted artificially, and easily kept at a uniform temperature, have proved to be the rooms most in demand for research.

The building is of a skeleton-type construction, the reinforced concrete columns and floor slabs carrying the entire weight and providing almost the entire strength of the structure. This type of construction permits the interior walls and partitions to be of light, easily removable hollow tile. The floors were finished before these light partitions were erected, and the partitions themselves have been kept almost entirely free from permanent wiring and piping. the result is that rooms may easily be made larger or smaller by the removal or by the insertion of a wall. Experience has proven this type of construction to be a very wise one; in spite of careful planning, many changes in the locations of partitions have been found desirable. The skeleton columns were so spaced as to make the natural unit of construction twelve by twenty-four feet; that is, nearly all rooms are either of this size or of a small integral multiple of this size. A two-unit room is twenty-four feet square, a three-unit room, a third larger on one side.

Probably the most elaborate single item in the building is the electrical wiring. In addition to 110- and 220-volt D.C. and 1 1 0- and 220-volt three-phase A.C., the laboratory has three battery rooms and several motor generators. Each unit room, in addition to ordinary lighting and power service, is provided with circuits which permit any of the available sources to be used. On the average about six individual circuits for experimental Purposes are available in each unit room. The interconnecting of this electrical system requires over thirty separate plug- and switch-boards ranging in size from six square feet to eighty square feet each, and literally thousands of circuits. The electricians who wired the building made the remark that reinforcing steel might have been dispensed with, the concrete being sufficiently strengthened with electrical conduits.

Several other unusual features were incorporated, which pen-nit flexibility and expansion of the various services supplying electricity, water, gas, steam, and compressed air; also special wood mounting strips and hundreds of threaded inserts were imbedded in the concrete walls and ceilings, to provide facilities for the rigid attachment of apparatus.

A four-unit, two-story room was provided for high-voltage research; also a separate two-story building on its own separate and very special foundation was provided, within the main building, for work in sound. This sound building contains two soundproof rooms and a large reverberation room, adjacent to other rooms planned for observation in sound. This sound building, a relatively heavy structure, is the most nearly free from vibration of any place in the laboratory. The lower walls and floors of the main building, because of the nature of the gravelly soil in which the building stands, are also nearly vibrationless; but, contrary to expectation, the special piers in the openings of the lowest basement floor are not so free from vibration as are the lower basement walls.

The East Physics Building is used mainly for advanced work. About 55% of it is given over wholly to research. Advanced instructional laboratories occupy an additional 25%, and the remaining 20% is taken up by offices, a library, and three classrooms. The elementary work has remained in the old West Physics Building. According to present plans the East Physics Building will at some future time be extended toward the west and north and will thus, in conjunction with the structure now existing, form a U. Within this U would be two large lecture rooms, and north of these would be an instrument shop. Accordingly, the ground area which is occupied by the present building is less than one-half the area which the contemplated complete structure will occupy. With the realization of this development the West Physics Building would no longer be needed.

Research

The extent of the contributions to the science of physics from the University of Michigan is indicated by a long list of papers and reports, some five hundred in all, originally published in various journals, but now available in collected form. They appear in the following two series: University of Michigan Physical Laboratories, Papers. 1879-1910, 6 volumes, and Contributions from the Physical Laboratory of the University of Michigan. 1911-41, 6 volumes.

Some of these papers are concerned with problems in the teaching of physics, but the great majority deal with fundamental principles, either presenting significant experimental results, or discussing their interpretation, or both. A very few may be assigned to the category of applied physics, since they aim primarily at the utilization of scientific information rather than at the extension of knowledge. The relatively small proportion of such "practical" studies does not by any means signify that research in physics is of little value to the community, nor that the specialists in this field are insensitive to the needs which their science might supply. It is, in fact, the result of a somewhat artificial classification which tends to transfer to the realm of engineering any development the aim of which is primarily utilitarian.

A case in point is provided by the history of the dynamoelectric machinery laboratory. The principle of electromagnetic induction was discovered almost simultaneously by Joseph Henry and by Michael Faraday in the year 1831, but it remained a matter of academic interest until 1876, when the first practical generator was built and later exhibited at the Centennial Exhibition in Philadelphia by its inventor, Mr. Charles Brush of Cleveland, a former Michigan student. For the first time in history it made possible the operation of an arc lamp without batteries. Professor Langley, after seeing the demonstration, returned to the laboratory here and constructed a dynamo of similar design but with some improvements and a larger output, so that three arc lamps could be operated at once. This early machine is still in the possession of the University. It constituted

the beginning of a laboratory of dynamoelectric machinery, organized at first in the Department of Physics and later developed into the extensive laboratories of the Department of Electrical Engineering.

That type of research which aims at a more nearly complete understanding of natural laws, without concern for utilitarian or commercial values, is often called pure science. Investigations of this sort dealing with a very great variety of subjects have been included in the research program of the physics laboratory. The accompanying table provides a rough classification of the departmental research output:

Published Reports	
Mechanics, Optics, Sound and Heat	70
Electricity and Magnetism	95
Radiation and Structure of Matter	375
Mathematical and Theoretical Developments	65

By the end of the nineteenth century the so-called classical physics had assumed a fairly complete and consistent form, the last major developments having been in the field of electricity and magnetism. In 1889 Henry S. Carhart wrote in his vice-presidential address before the American Association for the Advancement of Science: Even popular interest in electricity is now well-nigh universal. Its applications increase with such prodigious rapidity that only experts can keep pace with them. At the same time the developments in pure electrical theory are such as to astound the intelligent layman and to inflame the imagination of the most profound philosopher.

Carhart was himself a profound scholar in this field, and his own researches, together with those of his associates, contributed greatly to its development. Of particular note was his series of studies (1899; 1903) on primary cells revealing experimentally and explaining thermodynamically the relation of the electromotive force in a cell to the temperature and concentration as well as the chemical nature of the constituents. This led directly to the specifications for the famous Carhart-Clark standard cell, and for the legal standard volt. The legal standard unit for the measurement of electric current is the international ampere, which depends upon the electrochemical equivalent of silver. The value of this constant was measured with great precision by Guthe in 1905.

These and similar fundamental researches attained international recognition and contributed materially to the high standard of accuracy which now characterized electrical measurements. In subsequent years, however, the primary interest of the department turned to other fields, and contributions to electrical theory have been less significant. An exception should be made, however, for the recent direct measurements by Neil H. Williams of the charge per electron transported by a current crossing a vacuum gap. Although the electron charge had previously been known, it was only through indirect measurements on ions. Williams's value, of course, agreed with that determined by Millikan in 1913 for the charge upon a monovalent ion. The observations upon electrons were later extended and corroborated by similar measurements upon metallic ions.

Atomic and Molecular Spectroscopy

Infrared Spectroscopy

Researches in electrical conduction through metals, gases, and high vacua, which established the corpuscular nature of electrical charges, led directly to the problem of the fundamental nature of matter, i.e., the constitution of atoms, molecules, and crystals. Bohr's theory of atomic structure, first announced in 1913, supplied a tremendous stimulus to such investigations, indicating a new line of attack through spectroscopic observations. It is not surprising that during the last three decades the major interest, and in fact almost the exclusive research activity, of the department should have been devoted to this field. The first spectroscopic studies at Michigan, published in 1911 by Randall, dealt with the emission of infrared radiations by metallic vapors and the reflection of infrared rays by crystals. His measurements began near the end of the visible spectrum and extended to wave lengths about four times as great. As glass becomes opaque in this region it is necessary to dispense with lenses and use only mirrors in the optical system.

The dispersion is effected by means of a diffraction grating ruled upon a polished metal surface. These infrared rays can be detected neither by the eye nor by a photographic plate, but only through their heating effect, which is extremely minute. The temperature change resulting when they fall upon a sensitive thermopile gives rise to an electric current which is recorded by means of a galvanometer of high sensitivity. Randall brought the technique of these measurements from Tübingen, where he had been associated with one of the greatest of spectroscopists, Professor F. Paschen. No suitable apparatus being available on the market, it was necessary from the first to construct and adapt the equipment, including thermopiles, galvanometers, and mirrors. This development in measuring apparati has been almost continuous in subsequent years, with vital contributions from all members of the group associated with this research including Randall, Sleator, Barker, Meyer, Colby, Firestone, Hardy, Wright, and others.

In 1915 Sleator, working with Randall, set up a prism-grating spectrometer for the study of the molecular absorption of water vapor, the design of which has been frequently copied. The following year this instrument was used by Randall and Imes for their famous analysis of the absorption bands of hydrogen chloride. These studies mark the beginning of a long and continuous sequence of investigations on the characteristic vibrational and rotational motions of various gaseous molecules which have yielded much valuable information about the geometric form and actual dimensions of different molecules. Very important contributions in connection with the interpretation of the observed data have been made by Dennison and Colby.

In all, about one hundred and twenty papers dealing with spectroscopy of the infrared have been published, and this laboratory is generally recognized the world over as the principal center for such work. Major improvements in apparatus have been made from time to time, not only increasing precision and sensitivity, but also very greatly extending the range of wavelengths which may be studied. With an instrument completed by H. M. Randall in 1936, consisting of a large recording spectrometer completely enclosed in a case which may be evacuated, measurements are possible to wave lengths more than two hundred time those of red light, in fact, practically into the region of radio waves.

Visible and Ultraviolet Spectroscopy

A second important type of spectroscopic investigation deals with visible and ultraviolet radiations, both from atoms and from molecules. In these the records are photographic. R. A. Sawyer and 0. S. Duffendack, with their associates, have been responsible for most of this work, which is represented by some ninety-five papers. The earliest of these appeared in 1921. Studies of the excitation of various spectral lines from different atoms and their classification are of great interest not only from the standpoint of atomic mechanics but also because they find applications in rather widely separated fields. Astronomy and astrophysics, for instance, depend very mucy upon spectroscopic information for their determinations of the temperature and other physical conditions in stars and nebulae. Such observations may also be utilized for chemical analysis in the quantitative determination of very small traces of different metals. Duffendack has pioneered in this type of work and also in studies of the critical potentials of atoms and molecules through controlled impacts. Sawyer is responsible for recent developments in precision spectrochemical analysis, particularly of ferrous metals, a contribution of very considerable importance from the industrial point of view. He has been concerned also with measurements in the extremely short-wave ultraviolet region, and with the determination and interpretation of hyperfine structure in spectral lines.

The study of X radiation yields intimate and characteristic information regarding the structure of atoms and their geometrical arrangement in crystals. In 1920, when this field was just beginning to be systematized, G. A. Lindsay adopted it as his special interest, emphasizing particularly the precise measurement and classification of absorption edges. His first report appeared in 1922. Very shortly thereafter J. M. Cork began a program of work in the same field, extending the systematic classification of atomic levels to some of the less well-known elements. Of particular interest in this connection was his work on element No. 61, one of the very last chemical elements to be discovered. Cork also made some of the earliest grating measurements of the wave lengths of X rays, showing an inconsistency in the previous crystal measurements, which demanded a slight increase in the accepted value of the electron charge. This result has since been abundantly confirmed.

The optical gratings, by means of which wavelengths are determined, consist of polished metal surfaces ruled with parallel and equidistant lines. The distances between successive lines must be greater than the wave length measured, but preferably not much greater. Even the finest gratings, having perhaps thirty of forty thousand lines per inch, are very coarse in comparison with X rays. For the far infrared, on the other hand, gratings with twenty-five to one hundred lines per inch are required. Effective work throughout the spectrum is possible only when a considerable selection of suitable gratings is available, and the Department of Physics is peculiarly fortunate in this respect, since it possesses an excellent ruling machine (one of perhaps half a dozen such machines in existence). The development work in connection with this mechanism and in the preparation and ruling of surfaces has been largely under the direction of Barker, since his infrared investigations were among the first which required gratings not obtainable elsewhere.

Microwave Spectroscopy

Entirely different methods must usually be employed for measurements in the range of radio waves. An interesting recent development in Williams' laboratory, however, involves the production of radio waves less than half an inch in length and their measurement by means of gratings built up of narrow metal strips. The problem of producing such waves is one requiring much ingenuity, since tubes having almost microscopic dimensions must be constructed, and never before have grating measurements of this sort been attempted. These radiations are found to yield further information concerning the structure of molecules, particularly NH3.

The prediction in 1932 by Dennison and Uhlenbeck that microwave radiation would be absorbed by NH3, and the subsequent measurement in 1933-34 of this absorption by Cleeton and Williams marks the beginning of microwave spectroscopy. The intricate methods of working with centimeter wave radiation were not part of the repertoire of the usual physicist or chemist of those days, however, so microwave spectroscopy did not come into wide use until after WWII when the techniques and hardware from radar development became generally available.

Theoretical Physics

During the decade 1915 to 1925 the accumulation of experimental data, particularly upon atomic problems, was so enormous and the necessary changes in point of view were so far-reaching that the department came to feel acutely the need for specialists in systematization and in interpretation. Throughout this period W. F. Colby had generously consulted and cooperated with various experimentalists, mean while carrying most of the responsibility for instruction in theoretical physics. In 1923 Dr. Oskar B. Klein was appointed to the staff and assigned courses in mechanics and quantum theory. His contributions, both in the classroom and in the seminar, were of great value during the three years of his residence in this country. Otto Laporte, who had already attained distinction in the field of complex atomic spectra, was appointed in 1926. His analysis and interpretation of the spectrum of iron are especially well known. In 1927 the department materially enlarged the group in theoretical physics by the addition of D. M. Dennison, S. A. Goudsmit, and G. E. Uhlenbeck.

Dennison has made contributions of the very first rank in the field of molecular mechanics, co-operating effectively in the studies of infrared radiation and band spectra. Several of his papers are very well known, in Particular his discussion of ortho- and para-hydrogen, and the prediction regarding their separation, and his masterly summary of the mechanical problem of molecular vibrations.

Goudsmit's field is also that of complex atomic spectra. Uhlenbeck and he were the first to introduce the concept of electron spin which is now an indispensable element in the solution of all spectroscopic problems. This idea and its implications have also been extended by Goudsmit to the realm of nuclear structure and the mutual interaction of elementary particles. Both Uhlenbeck and Laporte have made significant contributions to quantum mechanics and also to purely mathematical development upon which it depends.

Nuclear Physics

Theorists Stimulate Interest in Nuclear Research

Randall, the department chairman, was always alert to new developments in physics and to means of stimulating research. This was reflected in the attention paid to nuclear physics in the Summer Symposia of 1931 and following years. Michigan theorists, Uhlenbeck in particular, became actively interested in the nuclear problems. He and his student Konopinski wrote an influential series of papers on beta decay. Michigan theorists, often in collaboration with visitors, wrote many theoretical papers on nuclear physics, but the resources for experimental work were lacking.

In 1934 only two universities in America, the University of California and the California Institute of Technology, and one in Europe, Cambridge University in England, were successfully developing nuclear research programs using accelerators. J. M. Cork, whose research had been in the field of X-rays, started construction of a primitive Van de Graaff accelerator in 1934 but this was not completed. Randall recognized that more would have to be done if Michigan were to have a program of experimental work, so he moved ahead to get both money and new faculty. he spent the Fall term of 1934-35 at Berkeley and Cal Tech to see their research programs at first hand. He sought advice from every laboratory doing significant nuclear research in this country and Europe; he was in frequent communication with Ferini in Rome and had arranged for Fen-ni and Segr6 not only to attend the summer symposium in 1935 but also to undertake some preliminary experimental work using natural radioactive sources.

One of Randall's important steps was to hire H. R. Crane from Cal Tech where he had just completed his Ph.D under the direction of C. C. Lauritsen. Crane joined the Michigan faculty in the fall of 1935 and, using five 2OOkV, 60 Hz transformers stacked in series, built a 1 MeV linear accelerator. Crane and his students used this accelerator for measurements on artificial transmutation, on nuclear energy levels, and on a search for the neutrino.

The First Michigan Cyclotron

Randall made another important step in deciding that Michigan should construct its own cyclotron. He used the results of work at Berkeley on the application of radioisotopes to medical research to involve the Medical School in getting support for a Cyclotron to be built in Ann Arbor. He solicited a major grant from the newly-established Rackham Trust Fund, and it provided $25,000 per year for three years, $20,000 for the fourth year and $15,000 for the fifth year, very generous amounts for those times. Randall asked Cork, then on leave in Berkeley, to remain there for the fall term of 1935-36 in order to to learn about cyclotrons and to begin a design for one. He also enlisted the help of other faculty members, particularly 0. S.Duffendack and F. A. Firestone, and in February of 1936 he recruited R.L. Thomton from Berkeley to help with the cyclotron.

The start of this ambitious project was particularly remarkable considering that the United States was still in the depths of the depression and that the University had been obliged not only to eliminate faculty positions but also to cut faculty salaries in two successive years. Crane and Thorton were the only tenure-track appointments to the department in the years between 1927 and 1946; their salaries were supported half by the Rackham grant and half from the release of departmental money when Uhlenbeck was called to the physics chair at Utrecht in 1935. [We were fortunate that Uhlenbeck returned to Ann Arbor in 1939.]

The construction of the cyclotron was well underway early in 1936. The pole roots of the 80-ton magnet were 50 inches in diameter and tapered to 36 inches at the gap that mated with the accelerating chamber.

Other components were made in the physics shop under the direction of Hermann Roemer. High power oscillator tubes not being readily available, Thomton designed and Roemer built the 50 KW oscillator tubes needed to drive the dees of the cyclotron.

The Michigan cyclotron started operation late in 1936. It was the first to be built outside of Berkeley and, for a short time, was the largest in the world. It accelerated deuterons to 12 MeV and alpha particles to 24 MeV, and it was used for a wide range of experiments. In 1939 the cyclotron was converted to a 42-inch machine that was capable of accelerating deuterons to 15 MeV, the conversion work being supervised by J. L. Lawson.

Experimental Nuclear Physics Prior to World War II

The first paper describing results of experimental research in nuclear physics carried out at Michigan was a beta decay measurement published in 1936 by H. R. Crane and his students E. R. Gaerttner and J. J. Turin while they were building their 1 MeV linear accelerator and before the cyclotron was completed. The already-substantial interest in nuclear physics within the department y was dramatically increased when the accelerators became operational. Many graduate students were attracted to the programs. Between 1933 and 1941 some 98 papers were published by the faculty and their 23 graduate students.

The experimental programs directed by Cork, Crane, Thornton, and Fajans (from chemistry), combined fruitfully with the work of the theorists Laporte, Dennison, Goudsmit, and Uhlenbeck in the years prior to the outbreak of war in Europe. Postdoctoral fellows T.Y. Wu, C. T- Zahn, M. L. Pool, J. R. Richardson, J. Halpern and J. L. Lawson obtained support from agencies such as the China Foundation, the National Research Council, and the Rackham Fund. The cyclotron was also being used for research on the physiological and therapeutic effects of neutrons and gamma rays, and for the production of radioisotopes used as tracers in diagnostics and treatment.

World War 11 dispersed the faculty and students who had been working in nuclear physics. From 1942 to 1944 only three papers were published, although for six months in 1943-44 Cork directed the cyclotron's round-the-clock operation on an Army contract.

Applied Physics

It was the policy of the Department of Physics to co-operate to the fullest extent with other departments and research units whenever this could be done to advantage. For example, the Department of Engineering Research, since its organization, maintained an extensive program in physics and occupied space in the Randall Laboratory. One member of the departmental staff was assigned to each research project as consultant. These projects originated with various industrial organizations and have included such problems as noise reduction in automobiles and other mechanisms, the development of devices for testing and inspecting bearing surfaces, the improvement of spark plugs and ignition apparatus, and the spectrum analysis of steel and of metallic alloys. Judged by the satisfaction of its clients, the staff had a high record of success in the field of applied physics. Floyd Album Firestone (Case '21, Ph.D. Michigan '31) was appointed in 1923 as the first research physicist under this program, but since 1926 was a member of the regular staff. Most of his contributions were in the field of acoustics, with particular emphasis upon industrial applications.

Another typical co-operative research was carried on for some years with the assistance of the Medical School and a grant from the Rockefeller Foundation. This developed, under Duffendack and Thompson, a spectroscopic procedure for the rapid quantitative analysis of body fluids for minute traces of various metallic constituents. Randall and Wright, also associated with this project, devised spectroscopic means for the detection by infrared measurements of several amino acids which are of great physiological importance.

Another addition to the departmental equipment was the electron microscope operated under Duffendack's supervision. It was an instrument of great promise and wide applicability, providing very much higher magnifications than were available at that time by any other means. It was being applied in investigations on the structure of matter and also in the fields of bacteriology, biology, metallurgy, and engineering.

General Comment

In any field of knowledge the University has two responsibilities: the discovery and interpretation of new truths and the conservation and transmission of existing information. Almost from the beginning of its scholarly activities the Department of Physics has developed both of these functions simultaneously. One of its very important scientific activities was the production of textbooks of the first rank. The texts by Carhart were particularly famous and were very widely used for many years.

The scientific standing which was attained by the Department of Physics during the two decades prior to WWII was due not simply to the individual eminence of various staff members, but arose in large measure from two other factors. One was the spirit or cordiality and co-operation which pervaded the group, and other, even more significant, was Randall's inspiring and sympathetic leadership, extending through almost the whole of this period.

The Instrument Shop

A summary of the research activities in physics would not be complete without mention of the effective service rendered by the instrument shop. Its staff includes five trained instrument makers, under the supervision of Mr. Hermann Roemer, and a very skillful glass blower, Mr. Gunther Kessler. The shop not only supplies a service department, but also undertakes without hesitation and handles in the most competent way the construction of elaborate and delicate apparatus for all sorts of precision work. Of especial note is the ruling machine previously mentioned, which was designed and constructed here, and is now under the charge of Mr. Paul Weyrich, who also builds the sensitive thermopiles and makes the optical mirrors. Vacuum systems, gauges, and other apparatus of glass and quartz also are continually in demand.

The Summer Symposia in Theoretical Physics

The summer symposia had their rather modest beginnings in the summer of 1923. In that year two nonresident lecturers, Professor K. T. Compton, then of Princeton University, and Professor F. A. Saunders, of Harvard University, were invited to give courses in modem physics. The results of this innovation were sufficiently gratifying to warrant a continuation of the policy, and during the next few years the following physicists were called as lecturers to the Department of Physics (the institutional connections given are those which they had at the time they lectured in the symposia at Ann Arbor):

1924: W. L. Bragg, University of Manchester, England

1925: P. D. Foote, Bureau of Standards, W. P. Davey, Research Laboratory of the General Electric Company, and H. Fletcher, Research Laboratory of the American Telephone and Telegraph Company

1926: Dr. C. E. St. John, Mount Wilson Solar Observatory, and K. F. Herzfeld, University of Munich, Germany

1927: E. A. Milne, University of Manchester, England

The year 1927 closed the first period of development of the physics symposia. When this period was reviewed, several points stood out clearly. The nonresident lecturers had been stimulating both to the graduate students and to the regular staff of the department. The influence of the lecturers, however, had been purely local in character; their presence had not attracted any great attention outside of the University. Moreover, those lecturers who were primarily theoretical physicists had been able to give more to their audiences than had the experimental physicists. This was probably caused by the difficulty of satisfactorily describing an experimental technique-it must be learned from actual experience-and by the fact that the principal advances then being made in physics were in the field of theoretical research.

In the summer of 1928 a series of special courses was offered in theoretical physics; these were supplemented by informal colloquia on the most recent developments of the subject. Professor H. A. Kramers, then of the Rijks Universiteit, Utrecht, Holland, gave courses on wave mechanics. Professor E. C. Kemble, of Harvard University, lectured on band spectra. In addition to the non-resident lecturers, S. A. Goudsmit and G. E. Uhlenbeck, who had recently been called to the University of Michigan, gave courses on the quantum theory of spectra and on Einstein-Bose and Fermi-Dirac statistics, respectively.

The success of this first symposium on theoretical physics was unmistakable. Not only were many graduate students attracted to the University to attend the courses, but, better still, a considerable number of distinguished visitors came to participate in the colloquia and hold discussions with the lecturers. These visitors were scientists, all holders of doctor of philosophy degrees, who were themselves actively engaged in productive research. It was possible during the ensuing year to trace in a number of articles in scientific journals ideas which had had their inception in the discussions of the symposium. The influence of this meeting was national and international rather than local.

The character of the summer symposia on theoretical physics was established by the symposium of the summer of 1928, and during the ensuing years it has only become more permanent and definitely determined. Each succeeding year has seen scientists of international reputation in physics come to Ann Arbor as lecturers; these scientists have played and are now playing the most prominent roles in the development of the subject. In addition to the nonresident lecturers, members of the regular physics staff have usually appeared on the programs. In the accompanying table are listed the symposium lecturers and their topics for the years 1929 to

1941. Except where explicitly stated otherwise, the courses ran for the full length of the session.

As has already been mentioned, the summer symposia at Michigan have exerted an influence on physics which is both national and international in its scope. Distinguished guests have contributed much to the discussions and colloquia. These scientists have come from the important centers of physics in the United States and abroad. In the table are listed the numbers of students and guests attending within a sequence of typical years.

Year	Grad. Students	Guests
1928	43	19
1929	59	40
1930	51	25
1931	80	35
1932	79	29
1933	57	47
1934	62	39

The role which the symposia have played in the development of the Department of Physics has been of very real importance. The meetings have been an inspiration to the members of the regular staff as well as a direct practical aid in furthering many research programs. The influence of the symposia upon the number of graduate students in the department enrolled during the summer session is indicated in the foregoing table, although it must be remembered that these years also coincide with a period of rapid expansion of the Department of Physics, and it would be difficult to distinguish between the two effects. In addition to the increase in the number of graduate students, there has been a marked advance in the quality and degree of ability of the students, which may be largely attributed to the symposia.

Following is a tabulation of the lecturers and their topics for the summer symposia between 1928 and 1931.

[TABLE HERE]

The Early Postwar Years

The history of physics at Michigan from its beginnings in the early 1840's until the time of World War 11 was written by Charles F. Meyer, George A. Lindsay, Daniel L. Rich, Ernest F. Barker, and David Dennison. With the exception of a few minor changes and additions, the text above is as they contributed it to part IV of The University of Michigan-An Encyclopedic Survey that was published by the University of Michigan Press in 1944. Their chronicle of our first 100 years describes the manner in which physics at our University grew from a program of undergraduate instruction to a research department with world-wide recognition. Notable steps in this growth include the construction of the first physics laboratory building in 1887-8, the establishment of the infra-red spectroscopy program in 1911, and the summer schools in theoretical physics that started in 1923, grew dramatically in 1928, and continued until 1941. Harrison M. Randall led the department from 1915 and upon his retirement in 1941 the chairmanship passed to Ernest F. Barker.

World War 11 brought many changes to physics and, indeed, to universities generally. Physicists had entered the war effort accustomed to doing research with meager budgets, one-of-a-kind apparatus, and only a modest level of help from engineers and technicians. They returned from- their war-related work knowing that effective research could be done on a massive scale if it were generously supported. Technological innovations, particularly in electronics, brought new experiments within reach. Moreover the public awareness of physics, particularly nuclear physics, brought many new students to the field.

In addition, the universities in the United States underwent a strong growth in the postwar period. The backlog of students, many with GI Bill support, surged on campus. The need for faculty was met in part from the pool of refugee and emigrant academics who in many cases brought previously average faculties to significant strength.

Our department's activity just after the war was dominated by the reestablishment of nuclear physics, infrared spectroscopy, and theoretical physics. This was materially aided by the enthusiasm and energy of persons, both faculty and students, eager to return to academic science. But some of Michigan's physicists found themselves in administrative assignments: Ralph Sawyer, who had established Michigan's reputation in ultraviolet spectroscopy, was the civilian director of the nuclear weapons tests at Bikini Atoll and returned to Ann Arbor to become the dean of the Rackham Graduate School. Samuel Goudsmit did not return but went to Northwestern in 1946 and then to a position of leadership at the Brookhaven National Laboratory. [In 1953 the New Yorker carried a biographical sketch of Goudsmit in its issues of 7 and 14 November.]

Nuclear Physics

The research in nuclear physics carried out at Michigan from the mid1930's to the mid-1980's has been described in detail by William Parkinson in his memoir that accompanies this brief historical overview.

The principal facility for nuclear research available in 1945 was the 42-inch cyclotron, built in the mid-30's, that had been used for some isotope production during the war years. James Cork, who had had major responsibility for the cyclotron, and H.R. Crane were the senior active nuclear physicists on our faculty after the war. But many new faculty interested in nuclear, particle, and cosmic ray physics came to Ann Arbor in the years 1945-1950: Wiedenbeck, Pidd, Parkinson, Lennox, and Hough had major engagement with the cyclotron, while Hazen, Nierenberg, and Glaser worked in other areas of physics at high energies.

In those postwar years, for what was to prove the last decade of his life, Cork turned from the cyclotron to work with radio-active sources and traditional counters and emulsions for his alpha, beta, and gamma spectroscopy. Wiedenbeck and his numerous students, on the other hand, pressed forward with extensive use of electronic instrumentation for their nuclear structure studies; they undertook coincidence measurements and correlation studies, and they did extensive work on the design and construction of double focusing beta spectrometers.

Direction of the cyclotron project in the postwar years passed from Crane to Wiedenbeck and then, in 1949, to Parkinson. Crane, Parkinson and Lennox obtained an Atomic Energy Commission contract for a second remodeling of the Michigan cyclotron and to support high resolution nuclear structure investigations in a range of energy that was somewhat beyond what Van de Graaff accelerators could reach at that time. This cyclotron remained active with AEC support in the first basement of Randall Laboratory until 1963 when it was moved to the North Campus for a brief period of use as an adjunct to the new, 83-inch instrument.

The Electron Synchrotron

In the mid 1940's H.R. Crane, who had much experience with linear accelerators, devised the concept of a cyclic accelerator that had some portions of the particle path being straight, much like the racetrack at a fairground. The advantage of this over a azimuthally homogeneous, circular or spiral trajectory is that the straight line portions are ideal for the insertion of targets, counters, and other instrumentation that are essential for experiments with the accelerated particles. With the assurance provided by detailed orbit stability calculations done by Dennison and T. Berlin, the massive task of constructing a 300 MeV electron synchrotron was undertaken by Crane and his associates in 1946. The synchrotron first worked in 1950 to provide a beam of 70 MeV electrons with which a number of scattering experiments were done; later, with an upgraded power supply, a beam was attained at 140 MeV. As a matter of choice and style, the work on this accelerator was done with a modest budget by faculty and students who also had classroom responsibilities to meet..

Meanwhile, the advantages of the synchrotron concept had been widely recognized and a number of other institutions rapidly constructed their own synchrotrons, often with a generously-supported staff of full-time engineers and technicians. Thus the Michigan synchrotron did not remain competitive and the project wound down in the mid-1950's. It had been an important innovation for physics as a whole, however, and given Michigan prominence in accelerator development. For example, Crane was president of the board of governors of the Midwest Universities Research Association (MURA) that had been formed to establish a regional accelerator, and Jones and Terwilliger had spent a year at the MURA laboratory in Madison working on accelerator design, an experience that was to prove useful later when the 83" cyclotron was being built in Ann Arbor.

g-2 of the Free Electron

A useful by-product of the synchrotron project was a 600 keV electron injector that Crane was able to use for some Mott scattering experiments that he had wanted to do for some time. Crane proposed to his student Louisell that the electron injector be used for a thesis experiment on the polarization that should arise from double scattering. For this it seemed advantageous to confine the electron beam between scatterers with the use of a solenoidal magnetic field, and from their intuitive analysis of the electron behavior in that field they concluded that the electron's magnetic moment would precess in a controlled way and that they could even measure the magnetic moment of the free electron.

This unprecedented research on properties of the free electron was done by Louisell, Pidd and Crane in 1953 and put on a solid theoretical basis by Mendlowitz and Case. The reports of these results at the spring meeting of the American Physical Society aroused much controversy because they contradicted a long and widely held belief that experiments of this sort were impossible in principle. However the g-2 experiment and its later refinements, which encompassed both electrons and (under the direction of Arthur Rich) positrons, were spectacularly successful; they provided both an important test and a strong confirmation for modem quantum electrodynamics.

Atomic and Molecular Spectroscopy

The number of faculty working actively in infrared spectroscopy, long an area of strength in the department, was somewhat diminished after the war. Barker had become department chairman and was managing a rapidly-changing department with a minimum of administrative assistance. Randall, who had retired in 1941, had shifted his attention to biophysics. So for a few years Dennison not only did theory but also directed experimental research in the infrared. The number of infrared experimentalists increased when Lincoln Smith came on the faculty for the years 1946-1949 and when C. Wilbur Peters arrived in 1948. Among the research pursued was a generalization of the hindered motion problem that Dennison, Uhlenbeck, Cleeton, and Williams had attacked with their development and first application of microwave spectroscopy in their landmark study of NH3 in the early 1930's.

A major impetus to molecular spectroscopy within the department came with the arrival of G.B.B.M. Sutherland in 1949 who quickly built up a large and active group. Their work began with studies of relatively simple molecules including those of industrial interest; the work later extended to studies of more complicated molecules of biophysical importance. Although Sutherland returned to England to head the National Physical Laboratory in 1957, some of his associates, notably Samuel Krimm, carried on with broad generalizations of these early directions in molecular structure analysis.

Ernst Katz joined the faculty in 1946 to do experimental work in solid state, particularly studies of reciprocity failure in emulsions and of motion of charge carriers in solids.

Work in atomic spectroscopy, another field in which Michigan had a considerable reputation, was carried on by Ralph Wolfe and Wallace McCormick. Wolfe and his associates had a long standing interest in industrial applications of atomic spectroscopy. McCormick, who had been a student of Ralph Sawyer's, continued the program of work in ultraviolet spectroscopy. Sawyer, a mainstay of Michigan spectroscopy for many years, returned from his wartime duties to be dean of the graduate school and, later, vice president; he also served as chairman of the governing board of the American Institute of Physics from 1959 to 1971.

Otto Laporte, distinguished for his contributions to the theory of spectra, joined the Michigan faculty in 1928. He enlarged his range of research to encompass experiments with shock tubes in the early 1950's. His students constructed a series of instruments with which they studied shocks in gases over a temperature range of 80K to 80OK; the interpretations and theoretical conclusions that Laporte drew from this work were widely recognized. Laporte died in 1971 while still on active faculty status; his election to the National Academy of Sciences was posthumous.

Theoretical Physics Evolves

George Uhlenbeck, David Dennison and Otto Laporte were the major figures in theoretical physics at Michigan in the early postwar period. Uhlenbeck continued to work on problems in statistical physics, on gamma-gamma correlations in nuclear decay, and on selected aspects of field theory. Dennison continued his work on the theory of molecular structure while branching out to do some nuclear theory and an important series of calculations on particle trajectories in accelerators. Laporte continued to exert a strong influence in setting the general tone of the more classical theory done in the department while, at the same time, directing the experimental program in shock tube research.

Kenneth Case, who joined the department in 1950, had an interest in the more formal aspects of particle theory and did extensive work in mathematical physics. Both Uhlenbeck and Case were later hired away by the Rockefeller University, Uhlenbeck in 1961 and Case in 1969. Dennison, who served as department chairman from 1955 until 1965, retired in 1970 but continued as an active member of the department until his death in 1976.

In the period 1954-1962 there were a number of theorists brought on the faculty: J. Luttinger came in 1954 for a three year period during which time he worked on condensed matter theory. K.T. Hecht, who worked in molecular theory but who was later to shift his interests to nuclear physics was appointed in 1956. Noah Sherman returned as a faculty member in 1957 to do work on electron scattering and on nuclear theory. G.W. Ford and R.R. Lewis came in 1958; Ford worked in statistical physics, in condensed matter physics, and in the theory of the g-2 experiments. Lewis did an important series of papers on the tests of symmetry, particularly in the weak interaction; he also contributed in a major way to the discovery of level crossing spectroscopy. Herbert Überall (1960-62) specialized in high energy electron scattering theory. Peter Fontana worked on the theory of interatomic forces and on the interaction of resonance radiation with atoms during his time (1962-1966) in Ann Arbor. Paul Phillipson did work on molecular theory during 1960-1962. A.C.T. Wu, who came in 1962, worked principally in the formal aspects of field theory and in mathematical physics. The research done by these theorists covered a broad spectrum and the work tended to be done in a fairly individual manner; programmatic research and extended collaborations were not common.

In 1964, however, Marc Ross came as a senior high energy theorist from Indiana, and this was followed in short order by the hiring of a number of younger high energy theorists: Gordon Kane, Yukio Tomozawa, Frank Henyey, Y.P. Yao, Leo Stodolsky, H.S. Mani, and David Williams. Their research was characterized by frequent collaborations and by a highly competitive climate in which preprints were the usual way of disseminating results and in which telephone contact with experimenters at the national laboratories was essential. The work of this group of theorists included the development of phenomenological Regge/adsorption models that proved quite useful for the classification and prediction of experimental results in strong interaction physics. Their work also included detailed calculations in quantum electrodynamics, theories of weak and electromagnetic interactions, and developments in field theories. The pattern of group collaborations was also seen to some extent in the condensed matter theorists who came to the faculty from 1967 onward: Harvey Gould, Victor Wong, Leonard Sander, and Thomas Witten, along with G.W. Ford, worked together frequently in obtaining their results on electron-hole pair phenomena, collective excitations, critical point phenomena, and aspects of the physics of liquid helium.

High Energy Physics

The postwar period saw a strong growth in the study of fundamental particles at high energies. Physicists in large numbers were convinced of the importance of this research, and the government was convinced that it was worth supporting. The possibilities for cosmic ray experiments were evident, and accelerators attained the energies necessary for the creation of new particles. Advances in electronics and other instrumentation made it possible to carry out imaginative, ambitious experiments. Michigan's physicists were quite active in this pusuit, and developments in particle detectors were among their notable contributions.

The Bubble Chamber

The bubble chamber is the best known of Michigan's contributions to the methods of particle detection. It was developed by Donald Glaser with the aid of Phoenix funding in the early 1950's, and he received the Nobel Prize for this work in 1960.

Glaser had come to Michigan to work in the general area of nuclear and particle physics; he, along with many others, was keenly aware of the limitations of cloud chambers, nuclear emulsions, and gas-filled counters that were the conventional detectors of that time. He then thought of using a superheated liquid as a target so that bubbles could form around ionization centers. After his theoretical analysis of bubble fon-nation had given encouraging results, he began experiments with small glass bulbs that were filled with liquid ether. The results achieved with these in 1952-3, particularly tracks produced by cosmic ray muons in I cm diameter bulbs, encouraged Glaser and his colleagues to construct metal chambers with glass windows from which truly useful photographs could be obtained. The success of the bubble chamber and the general enthusiasm for high energy physics led to a dramatic increase in the number of experimentalists working in Randall. Martin Perl, George Trilling, Don Meyer, Daniel Sinclair, John Kadyk, Donald Gilbert, Fred Hendel, Jack Vander Velde, C.Tristram Coffin, Byron Roe, Oliver Overseth, and Michael Longo were added to the faculty in the 1956-1962 period, although Glaser, Kadyk, and Trilling left to accept professorships at Berkeley before 1960 and Perl went to Stanford in 1963.

The first bubble chambers were small, only several inches across, and used a variety of liquids for bubble formation. All the bubble chambers built at Michigan have used heavy Hquids: the first chamber to yield real physics used propane. Glaser and his colleagues subsequently constructed a bubble chamber that used 20 liters (more than $200,000 worth!) of liquid Xenon. And in 1960-64 the group headed by Sinclair, Roe, and Vander Velde constructed a 40 inch chamber that used freon as the working liquid; the design and construction was done at Randall and at an assembly area in a hanger at the Willow Run Airport. During the construction time, the group kept active in research physics by becoming users of bubble chambers already in place at the Brookhaven National Laboratory. In 1964 the freon chamber was moved to its destination at the Argonne Zero Gradient Proton Synchrotron where it was used until 1971.

The bubble chamber was the most productive particle detector of the 1955-1965 decade but it had the limitation that each of the photographs taken had to be scanned individually for events of interest; each event then required painstaking measurement. Since a single experiment could require the scanning of hundreds of thousands of photographs, there was an obvious need for automation in the scanning process. Rooms on the third and fourth floors of Randall were given over to the scanning machines and the persons who ran them. Considerable work was done toward the construction of scan-and-measure systems, at various levels of automation, that would not require a human observer, but these were not available until rather late in the era of the bubble chamber work.

It was recognized from the very beginning that other particle detectors would be of interest, particularly if they could be triggered only in coincidence with signatures of the event of interest in a given experiment. Perl and Meyer, who had initially been with the bubble chamber effort, turned to the development of alternative detectors. Perl, with Jones, worked on luminescent chambers and image intensifiers. Meyer and Terwilliger and their colleagues did work with spark chambers. Initially these detectors had photographic readouts that required scanning and measurement, but the next step was to use wire chambers so that the events could be detected and measured electronically. In this way it was possible to analyze results even while the experiment was in progress. In recent years, developments with spark, streamer, and wire techniques have made it possible to construct large volume detectors with completely electronic readout; experiments using such detectors continue to be pursued vigorously by many of the Michigan high energy experimentalists.

It is interesting that Perl originally came to Michigan to work with Glaser but quickly changed the focus of his effort to collaborate in an extended way with Jones. Glaser received the Nobel Prize in 1960; Jones and Perl were thesis cochairmen for Samuel C.C. Ting (Michigan PhD 1964) who shared the 1978 Nobel prize for the discovery of the J/yparticle. Perl received the 1983 Wolfe Prize and the 1995 Nobel Prize for his discovery of the tau lepton.

Experiments in high energy physics continued to form a large fraction of the department's effort. The experiments were done at accelerators both in the U.S. and abroad; indeed Michigan groups had participation in many of the first experiments done with the Fermilab accelerator and they will be among the first users of the colliding beam facility at Stanford. The experiments have included a study of p-p polarization at the Cosmotron by Neal and Longo; a search for charmed particles by Meyer, Akerlof and Thun; n-p elastic scattering by Longo and Jones; high energy neutrino-proton interactions studied with a 15 foot hydrogen bubble chamber by Roe, Vander Velde, Sinclair, Coffin, Chapman, and Seidl; proton-deuteron and pi-proton, pi-deuteron interactions by Chapman, Roe, Vander Velde, and Seidl; and tests of time reversal invariance and measurement of hyperon magnetic moments by Overseth.

Krisch was among the first experimentalists to exploit the CERN intersecting storage ring in order to get data on inclusive production of pions, kaons, and protons. Also, in collaboration with Terwilliger, he has done an extensive series of p-p scattering experiments at the Argonne ZGS; when the experiments were done with a polarized beam and a polarized target, a surprising spin dependence of the p-p cross section was found. [The history of the ZGS, which involves many Michigan physicists, is the subject of Vol 60 of the AIP Conference Proceedings.]

The close interaction of the experimentalists with the particle theorists in the department has been important to the overall development of the high energy experimental program. Cosmic rays offer the physicist an opportunity to do experiments at energies far higher than are available from accelerators. Such experiments have been carried out since the mid1940's by Wayne Hazen, briefly in 1948-50 by William Nierenberg, and by Alfred Hendel as a collaborator of Hazen's since 1958. Hazen and Hendel have worked with cloud chambers, spark chambers, nuclear emulsions, and also with directional UHF/VHF antennas to study showers and radio pulses that are associated with the arrival of very energetic primaries. In 1965, Lawrence Jones initiated a cosmic ray program to study p-p interactions from 100 to 1000 GeV at an observatory on Mount Evans in Colorado; he and his collaborators used a 600-liter liquid hydrogen target and a 100 ton calorimeter with a wide gap spark chamber for studies of inclusive particle distributions, for a quark search, and other experiments.

Nuclear Physics and Astrophysics

The 83-inch Cyclotron

It had been increasingly evident through the 1950's that a new accelerator would be required if the experimental program on nuclear structure were to be continued. A proposal for a new 83-inch spiral ridge cyclotron, together with the analyzing magnets needed to do high resolution work with 45 MeV protons, was accepted by the Atomic Energy Commission, and the State of Michigan agreed to provide a new building on North Campus. (The building was constructed to house the new cyclotron on one side and the electron synchrotron on the other, but with the phase-out of the synchrotron project it was decided to move the old cyclotron to the new building, a process during which it was upgraded from 42 to 50 in.)

Construction of the 83-inch cyclotron required about four years, with the first circulating beam being obtained in 1962. Parkinson, his colleagues Tickle, Bardwick, Janecke, Gray, Polichar, Bruns, Lambert, and their students did a series of nuclear structure measurements with the new cyclotron. The good energy resolution of the instrument permitted detailed studies of elastic, inelastic and particle transfer reactions with p,d,T, and a projectiles incident on relatively heavy nuclei. Closely related theory was done by K.T. Hecht and his associates. Nuclear research with activated sources continued with increasingly sophisticated instrumentation. Wiedenbeck worked with a series of junior faculty (Chagnon, Fishbeck, Reidy) and had a long series of graduate students associated with him in this work. They used ever larger multichannel analyzers and higher resolution particle detectors for the nuclear spectroscopy program. In 1962 a high precision bent crystal gamma ray spectrometer was an important addition to their facilities. The nuclear spectroscopy work continued for a number of years during which time investigations with correlation methods and precision energy determinations were used to elucidate the decay -schemes of medium mass radioactive nuclei.

Concurrent with the larger-scale efforts in nuclear physics, Crane directed a laboratory for radiocarbon dating from 1953 until 1972; this work done on hundreds of samples was often in collaboration with Professor James Griffin of the Anthropology Department.

Continuation of Nuclear Research

In the 1970's, it became a matter of national science policy to concentrate the resources for medium energy nuclear physics in a few regional facilities, much as had been done in high energy physics two decades previously. Federal funding of the nuclear laboratories at dozens of universities, including Michigan, was sharply curtailed. The result was the phase-out in the mid 1970's of the cyclotron facility on North Campus and also of the nuclear spectroscopy laboratory that had been on the 6th floor of the Dennison building. The nuclear experimentalists from Michigan then became users of accelerators far away from Ann Arbor, again following the example of the colleagues in high energy particle physics.

Astrophysics and Geophysics

Research related to astrophysical problems have been carried out by many members of the department, but often concurrently with the pursuit of other problems. Sander has done work on the theory of neutron stars, and Rich and Williams have done measurements on the circular polarization of radiation from white dwarfs, for example. Crane devoted considerable time in the years after his chairmanship to laboratory experiments on geomagnetism, and Meyer worked on the application of counter physics methods to geophysical questions. It was with the arrival of Dennis Hegyi in the mid 70's, however, that the department had a faculty member with a principal commitment to experimental/observational astrophysics; Hegyi's research is on the distribution of mass in galactic halos.

Low Energy Physics

The Electron and Positron g-factors

It was clear from the first electron g-factor experiment in 1953 that substantially better results could be obtained. Crane and Pidd together with students Schupp and Wilkinson made the refinements necessary to get a g-factor result that was of major importance to the theorists. Then in the early 1960's Arthur Rich measured g-2 of the positron for his dissertation. In 1965 Crane was chosen to be the new department chairman, and Rich was named to the faculty and gradually assumed leadership of the group. John Gilleland did an improved version of the positron experiment, and JohnWesley did a fourth generation electron experiment to achieve 3 parts per million precision for the measurement. Rich and his students then moved with their expertise in positron/positronium physics to do a test for TCP invariance, a redetermination of the lifetime of positronium, and other experiments with polarized positrons.

Infrared Spectroscopy and Coherent Fiber Optics

Wilbur Peters, with a series of graduate students, continued the Michigan tradition of high precision infrared spectroscopy of small molecules with the spectrometers in the second and third basements of Randall Laboratory. He also supervised the operation of the ruling engine until 1961 when Paul Weyrich retired and the ruling engine was sold.

An interesting and useful result emerged in the mid- 1950s when Peters, with H. M. Pollard and B. Herschowitz of the medical school, wanted to make a coherent fiber optic bundle for use as a gastroscope. They hired Lawrence E. Curtis, a sophomore undergraduate, as a helper. The first bundles were made from simple glass fibers and were completely unsatisfactory. Peters then suggested that the individual glass fibers be coated with a low-index varnish to reduce the crosstalk; this gave some improvement but the overall result was still not adequate for practical use.

Curtis, after suggesting that the fibers be drawn with an outer sheath of low index glass, was able to draw composite fibers and form them into a fiber optic bundle that gave a satisfactory image; this is the principle behind almost all coherent fiber optics that are in use today.

The Resonance Group

In the years following 1955, many of the physicists working in the three basements of Randall Laboratory began an affiliation in what became known as the "resonance group." The affiliation arose from the circumstance of adjacent laboratory space and a common research interest in atomic, molecular, and condensed matter phenomena that occurred at energies below 50 eV; the affiliation was later formalized by common financial support under a large, umbrella contract from the Atomic Energy Commission. At its peak, in 1967, the resonance group was quite large, comprising ten faculty (Franken, Sands, Peters, Weinreich, Sanders, Springett, Williams, Robiscoe, Ward, and Zorn), on the order of thirty PhD candidate graduate students, two postdoctoral fellows, and half-dozen or so undergraduate research assistants. Not all of the funding was from the AEC, but there was a strong communal spirit that pervaded the Randall basements at that time.

The resonance group had its origins with Peter Franken and Richard Sands who had come to Michigan, in 1956 and 1957 respectively, from postdoctoral experience at Stanford. They established their complex of laboratories adjacent to the infrared research laboratories in the sub-basement of the Randall Building. Franken had been involved in cyclotron resonance studies of the proton and Sands had been doing EPR work and this work continued, but they initiated a new, common effort on the interaction of light with dilute atomic vapors that led to studies of spin exchange, optical pumping, and (with Colgrove and Lewis) to the discovery and application of the level crossing method of fine structure spectroscopy; they hosted an international conference on optical pumping in 1959.

When lasers became available in the early 1960's, a collaboration from the resonance group (Franken, Peters, Weinreich, and the undergraduate Alan Hill) published the first report of the generation of optical harmonics. Indeed the work on non-linear optics continued for many years under the leadership of John Ward who, together with Franken, published the first review of the field in 1963.

The orbiting of the Sputnik satellite in 1958 stimulated a strong response in the American public. The physicists who had entered the field on the post-WWII wave found themselves with the resources to attract a new generation of graduate students and young faculty. Sharing in this growth, the Resonance Group became significantly larger in the early 1960's.

Atomic and molecular beam research was started in the department when Jens Zorn came in the summer of 1962 to begin a program in high resolution radiofrequency spectroscopy. He was given room 49 of the sub-basement as a laboratory space, a lab that had just been vacated, in the spring of 1962, by Harrison Randall who had decided that it was time to stop the biophysics research that he had been doing since his retirement in 1941. Zorn and his students did studies of molecular hyperfine structure and of atomic polarizability. In 1967, a part of his group, with Denis Donnelly and David Crosby, turned to research in collision physics; they developed the time-of-flight method for the determination of inelastic electron-atom cross sections and for the study of molecular dissociation. A notable result was the discovery of new excited states of molecular hydrogen by Martin Misakian.

W.L. Williams joined the faculty in 1965 and began his research program with studies of the lifetime of excited helium atoms and with experiments on charge transfer collisions. When R.T. Robiscoe came for the 1966-69 period, he and Williams embarked on a redetermination of the hydrogen fine structure with an atomic beam experiment. Hydrogen fine strucutre was also the subject of a level crossing experiment that was done as a thesis problem by William Wing under the direction of Peter Fontana. In the early 1970's, Williams began an extended collaboration with R.R. Lewis to search for parity-violating effects in atomic hydrogen with their beam experiment notable both for its elegance and its difficulty.

Franken undertook a number of other experiments, including tests of the absolute neutrality of unionized matter and a search for fractionally charged particles, tests for the deviation of the electrostatic force from the pure $1/r^2$ form, and an attempt to use laser ranging as a detector of clear air turbulence.

Work in condensed matter physics had been done in the pre-1963 resonance group with Sands doing EPR on solids at high pressure and with Weinreich doing experiments on the acousto-electric effect. In 1964, T. Michael Sanders came from Minnesota to begin liquid helium work in the department. He and his students Jan Northby, Christie Zipfel and George Wang determined the properties of the bubbles that surround free electrons in helium. From measurements of the charge trapped in vortex lines, Sanders and his student Richard Packard were able to observe the creation and destruction of quantized vortex lines as the angular velocity of rotating helium changed. His group has also worked on surface tension in helium and on the magnetic properties of microcrystals. Work on the mobility of charges in liquid helium was done by Springett during his time (1965-1969) in the department. Then, in the early 1970's, Michael Bretz and his group started extensive studies of the thermodynamic behaviors of two-dimensional helium films.

By the early 70's, however, the resonance group began to lose its sense of identity. As a matter of policy, the umbrella research grant from the AEC had been phased out with arrangements to pick up the individual groups on individual NSF grants; support was also picked up from NASA and from the Air Force Office of Scientific research. Peter Franken left to be director of the Optical Science Center at the University of Arizona in 1973, and Sands, who already had major commitments to the biophysics laboratory on North Campus, became department chairman in 1977. And some faculty changed their area of major interest. The overall result was that a number of smaller groups arose in the later 1970's to cover the areas of physics that were once spanned by the resonance group.

Macromolecular and Biophysics

For a period of years following WWII, Robley Williams, Charles Thomas and Cyrus Levinthal formed an active biophysics group in the comer rooms of the first basement. They had active collaborations from Crane and Lennox as well as from other physicists and biologists on campus. Williams eventually persuaded the University to create a biophysics institute of which he was to be head, but when this did not come to fruition, he left for Berkeley, Levinthal left for Columbia, and that group of biophysicists dispersed.

Other physicists with biophysical interests tended to build on spectroscopic methods. The momentum established by Sutherland's group continued even after he left. The optical and infrared methods used for biophysical and macromolecular studies in the early postwar years were augmented by x-ray and neutron diffraction, microwave and double resonance spectroscopy, and Raman spectroscopy in the times that followed.

In the later 60's and early 70's Samuel Krimm and his colleagues did both experimental and theoretical studies on vibrations of polypeptides, on chain organization in crystalline polyethylene and in collagen, and on the structure of biopolymers and membranes. The research is done in close collaboration with members of other university departments with facilitation from the Macromolecular Research Institute. Examination of electron transfer mechanisms in biological processes and general studies of the structure and function of proteins have been pursued by Richard Sands and his colleagues since the late 1950's. This work was innovative in its use of ESR in its early days, and since that time a much broader range of spectroscopies have been brought to bear on the questions of interest: electron-nuclear double resonance, electron-electron double resonance, and Mossbauer techniques have all found application. This research was carried out both in the Randall and Dennison laboratories on Main Campus and, increasingly, on North Campus in the building that houses the Institute for Science and Technology.

Buildings and Shops

The two buildings available to the department after the war were West Physics and Randall Laboratory. In West Physics were classrooms, a few small workspaces, and the instrument shop which at that time was under the direction of Hermann Roemer. Randall housed everything else including the 42" cyclotron, the synchrotron, and the library. It was clear that more space was required and the state agreed to supply it. A large, ten-story building with a long, low extension was then built to house physics classrooms, laboratories for teaching and for research, offices for some of the physics faculty, and the entire astronomy department. The physics/astronomy library, a colloquium room, and two large lecture halls occupied the low portion of the building. It was completed in 1962-63 and provided considerable relief from the earlier space constraints. Originally called the Physics-Astronomy Building, it was renamed in honor of David Dennison in 1979.

At about the same time, the north campus cyclotron building was also nearing completion and most of the nuclear research facilities, including the 42-inch cyclotron, moved to the north campus; this opened up still more space in Randall. The instrument shop was moved to the first basement in Randall in the area that encompassed the space formerly occupied by the small cyclotron. West Physics was used briefly by the Psychology Department and then, just as its demolition began, caught fire and burned to ruins.

The glassblower Guenther Kessler and the shop supervisor Hermann Roemer retired in the early 60's. [It is a mark of the regard in which instrument makers were held that the department honored Roemer and Ralph Sawyer (former dean of the graduate school, vice president of the University, and Chairman of the American Physical Society) with a joint retirement dinner.] August Wagner then became supervisor of the instrument shop for four years before his own retirement in 1975. Paul Halloway was Wagner's successor, and was only the third supervisor of the shop since its major growth in 1925.

Teaching and Adminstration

The department chairmen who followed Barker were David Dennison (1955-65), H. Richard Crane (1965-72), Daniel Sinclair (1972-77), Richard Sands (1977-82), Lawrence Jones (1982-1987), and Homer Neal (1987-), all of whom have had able assistance of AdaMae Newton in managing the departmental operations. Bernice Behrends had provided office management until her retirement due to illness in 1963. Among the mainstays of the laboratory instruction staff have been Arthur Dockrill, George Newton, and Leslie Thurston; Thurston has also served for many years as the department's illustrator, and his characteristic style graces the figures of many of Michigan's publications.

The number of teaching faculty, which was at low ebb of about a dozen at the end of the war, rose to 35 in 1955 and to 45 in 1965, a level that was to remain about constant for the following decade. Undergraduate instruction has high priority in the work of the department: almost all of the classroom instruction (including recitations from large, introductory courses) is given by members of the professorial faculty. Ralph Wolfe and W. Wallace McCormick were particularly well known for their regular offerings of these introductory courses.

The department has also worked toward the development of instruction in physics, hosting two national conferences on the subject in the post-sputnik years and then, in 1963-66, serving as the national headquarters of the Commission on College Physics with their half-dozen staff members and numerous visitors. Work on the preparation of college, high school, and elementary school physics instructors has been done by Sands and others of the department's faculty, sometimes with internal financial resources and sometimes with NSF support for Academic Year Institutes. Noah Sherman was engaged in the early phases of computer-aided instruction durimg 1964-68. Methods of and material for self-paced (Keller) instruction have been intensively developed, particularly by A. Hendel.

The graduate program has continued to concentrate on the training of students at the doctoral level; a master's degree program, as such, has not been a part of the department's offerings. The number of graduate students has remained near 100 for many years, even as far back as 1930. A principal difference between the early times and the post-war era, of course, is the vastly increased level of financial support for physics graduate students; in the post-war time it has usually been possible for a student to be paid, at least with a survival-level stipend, for doing the dissertation research. The graduate courses consist of a basic sequence that is required of all candidates plus a generous offering of specialized, advanced courses from which the candidates can choose. For some years (mid-60's to early 70's) the department made the experiment of letting satisfactory course performance in the basic sequence serve as an equivalent to the PhD qualifying examination on the theory that nothing really new was learned from the traditional rite of passage. However, the return to more conservative examination procedures was made in 1974 even though the graduates of those more relaxed times seemed to do quite well as professional physicists.

In the years prior to 1967, universities with Michigan's prestige tended to place many of their PhD graduates in academia. In the late 1960's and early 70's there was a sharp contraction of the academic job market, and it became increasingly difficult for young physicists to get positions in universities and colleges. But physics PhD's seemed to find positions that utilized their training, though sometimes in non-traditional ways. A consequence of this is that physics students are not as narrowly focused on academic futures as they were in earlier years. Challenging industrial positions are highly regarded and, indeed, compete strongly for the best young people. This has made it particularly important that academic institutions across the country, including Michigan, make the academic positions sufficiently attractive to recruit the teaching and research faculty of the future.

Acknowledgements (Zorn)

I am grateful to the faculty and staff of the Physics Department for their help in preparing this augmentation of the 1951 departmental history. I am particularly indebted to H. R. Crane, L. W. Jones, and W. C. Parkinson for their sustained interest, for help with specific questions, and for providing many of the photographs.

The brief historical summary presented here necessarily omits many of the details, both technical and personal, that are interwoven with the larger threads of chronological development. Our department, with its extraordinary heritage, deserves a narrative in which those details and insights can speak strongly, not only to those with nostalgia for the past, but also to those who are malting choices for the future. William Parkinson's Nuclear Physics at Michigan, which follows in this volume, is an important contribution to such a narrative; we hope that his will be only the first of many such monographs that will enrich our understanding.

Jens Zorn September, 1988

Nuclear Physics at Michigan (by William Parkinson)

The Early Years

The birth of nuclear physics dates from Becquerel's discovery in 1896 of the radioactivity of uranium. The atomic nucleus was discovered to be a small, massive, positively charged core of the larger atom by Rutherford, Geiger, and Marsden in their 1911-1913 scattering experiments, and six years later (1919) Rutherford and his colleagues first induced a nuclear transformation and identified the proton. More than a decade later, in 1932, Cockroft and Walton induced the first transmutation with artificially accelerated particles. It was not until 1936, 40 years after Becquerel's discovery, that the first paper describing results of experimental research in nuclear physics carried out in the Physics Department at Michigan was published by H. R. Crane and his students E. R. Gaerttner and J. J. Turin. Michigan's relatively late entry into this field was primarily because the research effort in the department had been in other fields. At that time Ann Arbor was recognized worldwide as a center for atomic and molecular spectroscopy, and particularly for infrared spectroscopy.

Professor Harrison M. Randall, the department chairman, had initiated and guided the development of infrared research at Michigan, and he was always alert to new developments in physics and to means of stimulating research. Of his many initiatives perhaps the most significant was the assembling in 1926 and 1927 of a group of young theorists: D. M. Dennison, S. A. Goudsmit, 0. Laporte, and G. E. Uhlenbeck. Together with Walter Colby they were to have a signal influence on the development of the department. One consequence was the expansion of the Michigan Summer Symposia in Theoretical Physics: in the early-years(1924-1930) the emphasis of the symposia remained on atomic and molecular problems, but beginning in 1931 nuclear physics began to receive attention. In 1931 Pauli lectured for four weeks on "Problems of Nuclear Physics", in 1933 Fenni lectured on "The Structure of the Atomic Nucleus", and in 1934 G. Gamow, J.Oppenheimer, and E. 0. Lawrence lectured on "The Atomic Nucleus", "The Theory of the Positron", and "Artificial Disintegation of Atomic Nuclei", respectively.

Stimulated by interaction with the visitors and by the discoveries of the neutron, the positron, deuterium, and artificial transmutation during the golden year of nuclear physics (1932), our theorists became actively interested in the problems of nuclear physics. In 1933 Fermi and Uhlenbeck published a paper on the recombination of electrons and positrons. In 1934 Wu and Uhlenbeck published a paper analyzing Cavendish Laboratory data on the disintegration of 6 Li by protons and deutons (as deuterons were then named), and in 1935 Uhlenbeck and his student E. J. Konopinski published the first of their famous papers (soon known as the KU theory) on a modification of Fermi's theory of beta decay. There were other theoretical papers on nuclear physics from Michigan, but experimental work was not yet started because both manpower and money were lacking. Professor J. M.Cork, whose research had been in the field of X-rays, did begin construction of a primitive Van de Graaff accelerator in 1934 but this was not completed. Professor Randall recognized that nuclear physics was to become an important research field and decided that Michigan should have a program of experimental work, even though accelerator equipment was expensive and progress would require a group research effort.

Starting Experimental Nuclear Research in Ann Arbor

In 1934 only two universities in America, the University of California and the California Institute of Technology, and one in Europe, Cambridge University in England, were successfully developing nuclear research programs using accelerators. Professor Randall elected to spend the fall term of 1934-35 at Cal Tech and Berkeley, and he recognized immediately that the University of Michigan could not support an experimental program with its own funds; accordingly, he undertook the task of finding outside sources of research support.

Using the results of work at Berkeley on the application of radioisotopes to medical research as a selling point, he interested Dean Furstenberg of the Medical School in "collaborating in the initiation of this work at the University". Randall wrote an eloquent letter to Dr. Mark Knapp, director of the Rackham Trust Fund that had just been established in December of 1934, requesting financial assistance for the Departments of Physics and Roentgenology. It seemed to him "that the work, being the most fundamental possible, namely the understanding and control of atomic processes, and certain to affect profoundly not only all the physical sciences but also the biological sciences, and especially medicine, is peculiarly of the type the Rackham Foundation might care to support." The trustees were impressed, particularly with the clinical possibilities of this research: They gave Randall all he asked for: $25,000 per year for three years, $20,000 for the fourth year and $15,000 for the fifth year in order to "build a cyclotron and high potential equipment" to produce "high speed particles."

The Rackham grant which totalled $110,000 (an extremely large sum for those times) started in July 1935, but Professor Randall, not wanting to waste time, had started much of the groundwork even before the funds were available. He had sought advice from every laboratory doing significant nuclear research in this country and Europe; he had faculty candidates in mind. Randall had been in frequent communication with Fermi in Rome and had arranged for Fermi and Segré not only to attend the summer symposium in 1935 but also to undertake some preliminary experimental work using natural radioactive sources. On July 30, 1935 Randall wrote to J.M. Cork who was in Berkeley for the summer: "Fermi is of the opinion that artificial radioactivity can be produced more efficiently starting out with high potential sources rather than by the cyclotron method. Thus we should rely on this method for an early supply of radioactive material for the hospital. You at Berkeley are overoptimistic about the amount that can be produced by the cyclotron method." This is surely one of the few times when Fermi's judgment was not borne out!

Meanwhile, Randall had recruited H. R. Crane from Cal Tech where he had just completed his Ph.D. under the direction of C. C. Lauritsen. Crane joined the Michigan faculty in the fall of 1935 and immediately began construction of a 1 MV alternating-current generator for the acceleration of light ions. This linear accelerator used five 2OOkV, 60 Hz transformers stacked vertically and connected in a cascade circuit to produce its million volts for particle acceleration. The ion source was at the top of the stack, and protons were accelerated down a glass vacuum column to ground potential. The glass column consisted of five sections, each 24 inches long and 16 inches in diameter. (These sections will be remembered by many more recent students as being used in a variety of apparatus that required a volume at high vacuum.) The 1 MV linear accelerator was used in a number of measurements involving artificial transmutation, the measurement of energy levels, absorption and scattering of electrons, and for the famous search for the neutrino. It was while the accelerator was still under construction that Gaerttner, Turin and Crane published their 1936 paper "The Beta-ray Spectra of Several Slow Neutron-Activated Substances", the results of which were in reasonable agreement with the Konopinski-Uhlenbeck theory.

Professor Randall continued to press with the cyclotron project. He wrote again to Cork in Berkeley and asked if he would be willing to remain there for the fall term of 1935-36 in order to to learn about cyclotrons and to begin a design for one. He also enlisted the help of other faculty members, particularly 0. S. Duffendack and F. A. Firestone, and in February of 1936 R. L.Thornton from Berkeley joined the Michigan faculty to assist Cork with the construction of the cyclotron.

Half of the money for the faculty appointments of Crane and Thornton came from the Rackham Fund; the other half came from the departmental teaching budget. The departmental half became available in 1935 because Uhlenbeck had been called to the Physics chair at the University of Utrecht by Queen Wilhelmina I of The Netherlands. (He returned to Michigan in the fall of 1939.) Randall's leadership and achievement were remarkable considering the times: it was the middle of the great depression and the University had undertaken heavy retrenchments that included cuts in faculty salaries in 1932-33, more salary cuts in 1933-34, and the elimination of 66 teaching positions. In fact, Crane's and Thornton's were the only tenure-track appointments to the Physics Department between 1927 and 1946.

By February of 1936 the steel and copper were ordered and much shop work was done. The cyclotron as originally constructed consisted of an 80 ton H-type iron magnet with 15 tons of copper in the coils. The pole roots of the magnet were 50 inches in diameter, tapering to 36 inches at the gap containing the vacuum tank or accelerating chamber. Other components were made in the physics shop under the direction of Hermann Roemer. Because none were available commercially, the 50 KW oscillator tubes, designed by Bob Thornton, were made by Hermann Roemer and were items of great beauty.

On November 11, 1936, Randall wrote Furstenberg: "The entire equipment for nuclear research is now installed and in operation", and invited him to come and see it. Randall continued: "The medical phase of the work is about to begin. Some work for the botanists has already been underway. Apparently everything is set for a very vigorous program." The program of research continued to be supported by the Rackham Fund, the R13 account, over the next several years. When the account was closed in 1953 the grant had totaled $160,200.

The cyclotron was the first to be built outside of Berkeley and for a short time was the largest in the world. It accelerated deuterons to 12 MeV and alpha particles to 24 MeV and was used for the production of radioisotopes for the study of nuclear energy levels, production and measurement of gamma radiations, beta-decay, the scattering of neutrons and the determination of atomic masses. In 1939 the cyclotron was converted to a 42-inch machine, accelerating deuterons to 15 MeV. This conversion was supervised by J. L. Lawson, who had just completed his Ph.D. under Cork and was hired as a Research Physicist on the R13 grant. It was Lawson's very precise measurements using a magnetic beta spectrometer that showed that the Fermi theory of beta decay was in fact the correct theory.

The Research Prior to World War 2

The combined activity of experimentalists Cork, Crane, Thornton, and Fajans (from chemistry), and theorists Dennison, Goudsmit, Laporte, and Uhlenbeck generated great excitement in nuclear physics research at Michigan in the years prior to the outbreak of war in Europe. Money was still a problem because there were no federal grants in those days, so the postdoctoral fellows T.Y. Wu, C. T. Zahn, M. L. Pool, J. R. Richardson, J. Halpern and J. L. Lawson obtained support from agencies such as the China Foundation, the National Research Council, and the Rackham Fund. Many graduate students were attracted to the programs. Between 1933 and 1941 some 98 papers were published by the faculty and their 23 graduate students.

In addition to this work in pure physics, Drs. F.L. Hodges and 1. Lampe of the Department of Radiology, Medical School, were using the cyclotron in research on the physiological and therapeutic effects of neutrons and gamma rays on mammalian systems and for the production of radioisotopes used as tracers in diagnostics and treatment. Radioactive sources of phosphorus and iron were prepared for use in pharmacology and at the Simpson Memorial Clinic for the treatment of patients with leukemia and polycythemia (increase in total red cell mass of the blood). A variety of sources were prepared for Botany, Chemistry, Biological Chemistry and Metallurgy.

This splendid activity was interrupted by World War 11; the faculty and students dispersed, the majority engaging in research related to the war effort. From 1942 to 1944 only three papers were published, although for six months in 1943-44 the cyclotron was operated around the clock on a contract supervised by Cork for the Army through the University of Chicago.

The Post WWII Era

The post-war period saw a major, nationwide change in the modus operandi of physics and the hard sciences. The impact of physicists and other scientists and engineers on the war effort was recognized by the military who, to maintain the supply of well-trained scientists, and following a prospectus prepared by M. A. Tuve and Vannevar Bush, initiated a program of support for basic research in universities. One of the first beneficiaries was Crane, whose wartime contract with the Bureau of Ordnance, U.S. Navy, was modified to provide for the development and construction of the racetrack synchrotron. In 1947 Cork received financial support from the Office of

Naval Research. The Atomic Energy Commission, established in 1946, and the National Science Foundation, established in 1950, soon became major sources of support for research in nuclear physics, including support of students and of faculty summer salaries.

To cope with the large post-war influx of students, both undergraduate and graduate, it was necessary to expand the staff. The nuclear physics faculty was augmented by M. L. Wiedenbeck in February 1946; W.C. Parkinson and R. W. Pidd in the fall of 1947; E. S. Lennox and W.A. Nierenberg in 1948; P. V. C. Hough in 1949; C. Levinthal and M.Slotnik in 1950; L. W. Jones and K. M. Terwilliger in 1952; P. Chagnon, J. Fregeau and N. Sherman in 1956; and D. A. Gilbert in 1957.

In the immediate post-war period research in nuclear physics centered on the 200 MeV electron synchrotron (Crane and Pidd); beta-ray spectroscopy (Cork); nuclear spectroscopy (Wiedenbeck), and with the second remodeling of the 42-inch cyclotron in 1950, nuclear structure (Parkinson and Hough). Of necessity much effort in those days went into building not only the accelerators, spectrometers and other instruments of research, but also the detectors and, in particular, the electronics. Because they were not yet commercially available, scaling circuits, fast amplifiers, power supplies, coincidence circuits, and current integrators had to be designed, built and tested by the faculty and their students.

The synchrotron was completed and put in operation in early 1950 and used for measurements of high energy electron scattering from nuclei. It was soon recognized, however, that the most interesting problems of nuclear physics were not readily solved using the electron accelerator. But its use did lead in a natural way into the field of high energy physics and in fact the "race-track" design became the prototype for all of the large synchrotrons that have since been built.

Cork's group in beta-ray spectroscopy was concerned with the determination of energy levels in middleweight and heavy nuclei by measuring beta- and gamma-ray energies. The principal instruments were permanent-magnet, photographic-plate beta spectrometers. By measuring the energies of conversion electrons produced by gamma rays in radioactive nuclei, the physicists deduced the energies of the gamma rays and fit them into level schemes.

The thrust of the research of Wiedenbeck's nuclear spectroscopy group, funded by the AEC and later by the NSF, was the determination of energy levels and in particular their spins and parities, knowledge essential for the construction of any theory of nuclear structure and for testing the predictions of the theory. In addition to extensive electronic instrumentation, magnetic beta-ray spectrometers were constructed, and an 800 kV Van de Graaff funded by the NSF was installed about 1958. Beginning in 1961, two precision curved-crystal gamma ray spectrometers were constructed, one of 2 meter radius and one of 6 meter radius. These crystal spectrometers permitted the very accurate determination of gamma-ray energies (10 eV at 50 kV). This extensive instrumentation was used with a wide variety of techniques, not only for the accurate measurement of gamma-ray energies, but also for the measurement of conversion coefficients, beta spectra, beta-gamma correlations, gamma-gamma directional correlations, gamma ray polarization correlations, beta-gamma circular polarization, and (d,p-gamma) angular correlations. By the time research in this area was terminated in 1978 some 42 Ph.D. theses in physics and one in nuclear engineering had been completed, and well over a hundred papers published. Faculty additions to Wiedenbeck's group included P.R. Chagnon in 1956, H. Fishbeck in 1960 and J. Reidy in 1964.

Remodeling the 42-inch Cyclotron

In February 1950 a grant was received from the U.S. Atomic Energy Commission to support the remodeling of the 42-inch cyclotron and to initiate a research program. (The funding was increased for the second year on the plea that the graduate student stipend be increased from $1,000 per 12-month year to $1,800 to be commensurate with the salary for teaching fellows!) Prior to the remodeling, the research focused on studies of the (p,p') and (p,n) reactions (in an attempt to decide which of the various models used in the statistical theory of nuclei would yield more valid results), on measurement of gamma rays emitted by light nuclei on proton bombardment, and on (d,p-gamma) angular correlation studies. Radioisotopes were produced for the nuclear spectroscopy groups, for H. Gomberg for radiography in conjunction with the medical school, and for W. Meinke in nuclear chemistry.

The 42-inch cyclotron was located in the north end of the first basement of Randall Laboratory in the space now occupied by a part of the instrument shop. In keeping with the way physics was done in those days the actual work of remodeling-the plumbing and electrical installations and electronic construction-was done by the faculty and students. Four graduate students, E.

H. Beach, J. S. King, D. R. Bach and W. J. Childs, devoted many hours of labor to the remodeling effort. Precision machine work was done by Hermann Roemer, August Wagner, and the other excellent instrument makers in the Physics Instrument Shop; glassblowing was done by Gunther Kessler.

Research and Instrumentation

In the time when the 42-inch cyclotron was being remodeled, the technique for the determination of the energies of the charged particle reaction products was to determine their range in absorbers. The resolution in energy at energies of 10 MeV was so poor that individual states in nuclei had to be separated by the order of 500 keV to be clearly resolved. The goals in remodeling were not only to obtain a reliable beam of particles extracted from the cyclotron but also to obtain, by means of magnetic analysis, high resolution in energy of the extracted beam and of the reaction products. Jones and Terwilliger took an active part in setting up the focusing magnet system. The analyzer magnet, constructed from spare synchrotron Hsection magnets, provided a dispersion at 10 MeV of 5 keV/mm, so that with 1 mm source and image slits a calculated resolution of 5 keV could be obtained. Such resolution gave cyclotrons a competitive edge over Van de Graaff accelerators of that time when maximum beam energies were considered.

The high-resolution magnetic-analysis system used nuclear emulsions placed at the focal surface of the magnetic spectrograph to detect the charged-particles from a nuclear reaction. The counting of tracks in the emulsions, a tedious and slow job, was carried out by a bevy of scanners who spent their days peering into microscopes. In 1954 P.V.C. Hough devised an electronic scheme for automatically scanning emulsions. This development of pattern recognition captured his interest to such an extent that by 1959 his total effort was devoted to the problem. In 1962 he left Michigan for Brookhaven to continue the development and to apply the techniques to problems in high energy physics.

To complement the charged-particle analysis system, a high resolution neutron-time-of-flight spectrometer was developed for neutrons in the MeV range. Previously the energy of neutrons emitted from nuclear reactions was determined by measuring the energy and angular distribution of recoil protons, a technique that did not pen-nit a resolution better than 500 keV. This time-of-flight spectrometer made use for the first time of the natural phase bunching of the charged particles accelerated in the cyclotron to produce very narrow pulses of particles onto the target nuclei. The velocity, and hence the energy of the corresponding narrow pulses of neutrons emitted from the target were measured with a "chronotron" coincidence circuit capable of 0. 1 nanosecond resolution. The work on the spectrometer was carried out by Roger Grismore, and an improved version of the instrument was developed later by Glenn Knoll.

For the next several years Parkinson, Hough and their graduate students carried on an active program which included not only the measurement of energy levels in a variety of nuclei, but also measurements of polarization in the (d,p) reaction, spin-flip stripping and (d,p-gamma) angular correlations.

The remodeling of the cyclotron coincided with the rise of the nuclear shell model with strong spin-orbit coupling, a model proposed by Maria Mayer and, independently, by Haxel, Jensen and Suess in 1949. It also coincided with the advent of S. T. Butler's theory for the stripping action that occurs with (d,p) and (d,n) reactions as, for example, in the Oppenheimer-Phillips process. Butler's theory permitted a determination of the orbital angular momentum carried into the nucleus by the captured or "stripped" nucleon. Bethe and Butler then showed how it was possible to check experimentally on the accuracy of the independent-particle picture's ascription of orbital angular momentum to nucleons.

The first thesis research using the remodeled cyclotron, carried out by E. H. Beach on the 31P(d,p)31P reaction, was a remarkably good verification of the shell model concepts. The model was further tested by J.S. King in a study of the (d,p) reaction on a series of nuclei as proposed by Bethe and Butler.

A New 83-inch Cyclotron

It was already evident during the remodeling of the 42-inch cyclotron that experimental tests of nuclear models, particularly the shell model and the collective model in all but light nuclei, would require an accelerator that could provide particle beams of high resolution in energy (a few keV) at a mean energy well above the highest Coulomb barrier (15 MeV for protons and deuterons on uranium).

It was known that conventional, uniforrn-field cyclotrons operating at a fixed frequency were limited in energy by the de-synchronizing effects of relativistic mass increase. Frequency-modulated cyclotrons and multiplestage linear accelerators were in operation but these instruments produced only pulsed beams with low duty cycles and relatively large energy spreads, obvious disadvantages. Needed was an accelerator, combined with ancillary magnet systems, that could produced a continuous beam of high energy particles, say 40 MeV deuterons with a spread in energy of less than 10 keV.

Research on accelerator theory was being carried out in several laboratories in those years and by 1956 it appeared that ideas of L. H. Thomas, published in 1938, could be adapted to overcome the energy limitations of fixed frequency cyclotrons: Introducing azimuthal variations into the magnetic field could provide axial focusing of the ion beam. An isochronous cyclotron based on this sector-focusing principle was under design at Berkeley, and these ideas were adopted in planning a new cyclotron facility at Michigan. An important and unique feature of the proposed facility was the incorporation of instrumentation for studies at high resolution in energy of nuclear reactions.

A joint, two-year effort by Fregeau, Gilbert, Hough, Jones, Parkinson, and Terwilliger resulted in a proposal for the construction of an 83-inch isochronous-cyclotron facility with high resolution capabilities that was submitted to the Atomic Energy Commission in 1958. The building to house it was to be funded by the State of Michigan. The crucial element in the cyclotron design was the "strong-focusing" magnetic field, and the preliminary design for this field was carried out by Terwilliger and Jones who were knowledgeable on the matter as a result of their work on accelerator design with the Midwest Universities Research Association [MURA] during 1953-1958.

The proposal was received favorably by the AEC, but because of the recession of 1958 the building was not built. This chicken and egg problem was solved in 1960. A special hearing before the Appropriations Subcommittee of the U. S. House of Representatives was arranged in the spring of 1960 by our Congressman, George Meader. Vice-President for Research R.A. Sawyer, along with Dennison and Parkinson, testified to the desirability of funding the Michigan proposal. Dennison's remarks on the value of research in physics so completely captured the attention of the Committee that the allotted time for testimony was stretched from 15 minutes to about an hour, with the last 30 minutes being off the record.

T'he result was that the proposal was funded in the amount of $1,941,670 in July 1960 by the AEC, and the State of Michigan then provided funds in the amount of $1,158,700 for the building. As originally planned in

1956, the building was to house both the synchrotron and the new cyclotron, but by the time the proposal was submitted in 1958, it had been decided to dismantle the synchrotron. T'he synchrotron bay was then modified to house the 42-inch cyclotron which, when moved to North Campus in 1963, was converted to a 50-inch machine.

By the time the proposal for the new cyclotron facility was funded in 1960, many of the faculty involved in the earlier phases of the project had turned their attention to other areas. New faculty were recruited for the 83-inch cyclotron project: R.S. Tickle joined the staff in 1960, C. A. Bruns and J. M. Lambert in 1961, J. Bardwick and R. Kenefick in 1964, J.W. Janecke and W. S. Gray in 1965, R. Polichar in 1968 and F. Becchetti in 1973. The final design and the supervision of the construction of the facility was carried out by the faculty with the assistance of a small professional staff and many students, both graduate and undergraduate. P. J. T. Bruinsma and, later, D. DuPlantis were responsible for much of the electrical engineering and the electronic development. W. E. Downer provided technical support and supervision for the cyclotron group for over 26 years.

Research with the 83-inch Cyclotron

The first internal beam in the 83-inch machine was obtained in November 1962, the cyclotron was completed in August 1963, and the high-resolution magnetic-analysis system and shielding were completed in July 1965 at which time $106,362 was returned to the Atomic Energy Commission.

The first two dissertations on research with the new facility were written by A. S. Polterak and G. Muehllehner on the 208Pb(d,p)209Pb reaction with 15 to 25 MeV deuterons, and the 208Pb(d,t)207Pb reaction with 15 to 25 MeV deuterons, respectively.

The research program centered on the 83-inch facility was funded by the Atomic Energy Comission and its successor agencies from 1964 to 1977. The 50-inch facility became operational and productive of research but, because of funding and manpower limitations, it never lived up to expectations.

Research on problems in nuclear structure continued with the 83-inch cyclotron throughout the period of the contract and formed the major part of the total research program. Much of the early work centered on single-nucleon transfer reactions. Over the years a systematic investigation, enlisting the combined efforts of theorists and experimentalists, was carried out in the region of closed-shell nuclei, the N=20, N=50, and N=82 isotones in the tin and the lead regions, and in later years using proton-transfer reactions (d,3He), (p,He) and (alpha,t) in the rare-earths. These reactions provided the most direct information about single-particle states in deformed nuclei.

Such detailed investigations were time consuming, but were precisely the kind of in-depth studies amenable to attack in a university atmosphere. In addition to the systematic investigations, a number of selected problems were attacked, including elastic scattering, multi-particle transfer, in-beam gamma-ray spectroscopy (3He,n) reactions, studies of isobaric analog states via (3 He,t) reactions and cluster transfer reactions such as (d, 6Li). In later years heavy received increasing attention.

Concurrent with the ongoing research program, improvements were made to the facility. A major alteration was the addition of a bay to the building in 1971 to house a low resolution beamline designed for in-beam, gamma-ray spectroscopy, neutron time-of-flight spectroscopy, and radio-biological experiments. A PDP-15 computer for on-line data analysis was installed in 1972.

To better understand the problem of internal beam stability, an intensive study of particle orbits was undertaken in 1972, and the last remaining problem of beam stability was solved by two students, J. F. Petersen and R. H. Day. The total facility, as completed, represented a pioneering effort in high-resolution charged-particle nuclear spectroscopy. In 1977 its capabilities significantly exceeded the original design specifications. With the addition of the low-resolution beam line, experiments were carried out in radiation physics, radiation biology, and radiation therapy.

Interaction between Theorists and Experimentalists

Over the years the work of the experimentalists was enhanced by close contact with theorists. E. S. Lennox and G.E. Uhlenbeck, with his students D. L. Falkoff and D. S. Ling, Jr., developed the theory of gamma-gamma and beta-gamma angular correlations. This work was of great help to Wiedenbeck's research. The Ph.D. thesis by R. R.Lewis on electron scattering from nuclei was of considerable interest to the synchrotron group. Murray Slotnick, a promising young theorist, was taking an active interest in the work of the cyclotron group, particularly in developing the then-current statistical theories of nuclei, at the time of his tragic death in a sailing accident. Close contact between the cyclotron group and S. T. Butler provided the stimulus for the experimental verification of the shell model, and the presence of Maria

Mayer during the summer of 1952 was a further stimulus. G.R. Satchler spent the year 1956-57 here as a Research Associate and continued for many years thereafter to provide great help in interpreting the data from studies of nuclear reactions and d,p-gamma angular correlations. Beginning about 1958 K. T. Hecht, trained as a molecular theorist, became interested in the collective model of A. Bohr and

B.Mottleson and soon was contributing in a significant way to all theoretical aspects of experimental research. His lectures on current topics in nuclear models and problems in nuclear structure, and his close association with both staff and students, was and continues to be without question an enormous help to the experimentalists.

The Post-War Symposia

The post-war Summer Symposia, supported in part by the University, served to keep both staff and students up-to-date on developments in physics. They were a modified continuation of the Michigan Summer Symposia of the 1920's and 30's. Their character necessarily changed after World War H because physicists became "too busy" to take time for summer-long sessions (summer salaries became available!). The post-war symposia at first had taken the form of one-week conferences, but beginning in 1961 the symposia on nuclear physics were modified to working sessions during which four or five people prominent in the field of nuclear spectroscopy and nuclear structure were in residence for a three-week period. Other distinguished visitors were attracted for shorter periods of time. The formal obligations were minimal: Each person gave one advertised lecture. Otherwise the sessions were informal with one, or at most two talks being scheduled each day. This format permitted ample time for the exchange of ideas and led to more detailed discussions by individuals.

Symposia on nuclear physics were held in 1961, 1962, 1966, 1969, and 1973. In 1966 the participants invited for the full three-week period were: S. A. Moszkowski (UCLA), M. Macfarlane (Argonne National Laboratory), D. M. Brink (Oxford University), M. Baranger (Carnegie Tech.), and E. Baranger (University of Pittsburgh). Others who joined the symposium for shorter periods were: G. R. Satchler (Oak Ridge National Laboratory), R.H. Bassel (Brookhaven), G. M. Temmer (Rutgers) and P. Donovan (Rutgers and Bell Laboratories).

In 1969 the visitors were T. T. S. Kuo (SUNY, Stony Brook), M.Baranger, E. Baranger, and M. Macfarlane. Others who joined the group for shorter periods were P. J. Ellis (Rutgers), B. Barrett (University of Pittsburgh), J. C. Hardy (Califomia-Berkeley), W. Greenlees (Minnesota), G. Temmer, J. B.Ball (Oak Ridge), R. H.Bassel, and J.P. Schiffer (Argonne).

In 1973 the visitors were G. R. Satchler, B. F. Bayman (Minnesota), A. Arima (Tokyo), R. Y. Cusson (Duke), and R.C. Johnson (Surrey). Shorter term visits were made by G. Temmer, P. H. Stelson (Oak Ridge), F. D. Becchetti (Califomia-Berkeley), and J. C. Hardy (Chalk River).

Continuing the Tradition at Michigan

By the late 1960's it was evident at the national level that accelerators of still higher energy, with capabilities of accelerating a great variety of ions, including heavy ions, were required. The cost of the proposed facilities was such that universities could not afford them and only a few could be supported by the federal government as national laboratories. Starting in the mid 1960's the Department of Energy began to phase out support for, facilities located at the universities. The funding for the Michigan 83-iiich facility was terminated in 1976. Both the 50-inch and the 83-inch cyclotrons were dismantled in 1978; thus came the end of a long history of nuclear research using in-house accelerators for experimental nuclear physics at Michigan. Now nuclear physicists found themselves, like their colleagues in high energy physics, traveling to remote sites in order to do their experiments.

While the mode of operation for doing research in the field has changed, the tradition of nuclear physics at Michigan is being continued by Janecke, Becchetti, Tickle and their students. Janecke and Becchetti do research at the Indiana University Cyclotron Facility (IUCF), the Argonne National Laboratory Heavy-Ion Linac (ATLAS) and the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. For some time their work concentrated on the investigation of cluster structures in the low-density surface region of atomic nuclei by means of cluster-transfer reactions, particularly on alpha-clusters. It is interesting to note that the first alpha-cluster model (for the nucleus 160) was introduced by Dennison in 1940 with great success. More recently there has been close collaboration with Hecht and his post-doctoral research fellows who have done extensive studies of nuclear substructures (cluster structures) by means of group theory. Hecht has extended these theoretical techniques to quark substructures in nuclei. One important aspect of the work relates to cluster states in 160 which are relevant for carbon burning in old stars.

Some recent experiments have looked at particle-induced fission of medium mass nuclei (at IUCF), alpha-transfer reactions at high bombarding energies (at IUCF), and heavy-ion transfer reactions (at ATLAS and at NSCL). In addition, a large superconducting solenoid spectrometer has been developed and is being used at ATLAS to study reaction products emitted near zero degrees scattering angle in heavy ion collisions. Recently Janecke has been investigating the slow, low energy beta decay of 187 Re which serves as a "cosmochronometer" for the age of the universe and which may also be interpreted as setting an upper limit for the neutrino rest mass. Their research program has been funded by the National Science Foundation and involves, in addition to Professors Becchetti and Janecke, a postdoctoral scholar, graduate students, and several undergraduates.

Professor Tickle's current research, funded by a Rackham Grant, includes determination of the nuclear matter equation of state from studies of central collisions between high energy heavy ions (for example 93Nb + 93Nb at 200 MeV/nucleon). This work is being done at the Bevalac streamer chamber facility at the Lawrence Berkeley Laboratory. He is also determining nuclear temperatures by measuring the relative populations of particle-unstable states of Li and Be ions emitted in heavy ion reactions 14N on Ag at 35 MeV/nucleon). This work is being carried out at NSCL (MSU) and TRIUMF, Vancouver, B.C.

Many people have contributed to the long and productive history of nuclear physics research in the department. Literally hundreds of publications have resulted from the efforts of some 38 faculty members, over 30 postdoctoral research scholars, and 140 Ph.D. students. Many other graduate and undergraduate students have benefited from the experience of working in this important part of our department's effort.