PART I

History of the CYCLOTRON

On May 1, 1959, in memory of the late Ernest Orlando Lawrence, two invited lectures on the history of the cyclotron were presented as part of the American Physical Society's annual spring meeting in Washington, D. C. The present article is based on Prof. Livingston's talk on that occasion. The second speaker was E. M. McMillan, whose illustrated account also appears in this issue beginning on p. 24.

By ***M. Stanley Livingston***

THE principle of the magnetic resonance accelerator, now known as the cyclotron, was proposed by Professor Ernest O. Lawrence of the University of California in 1930, in a short article in *Science* by Lawrence and N. E. Edlefsen.[1] It was suggested by the experiment of Wideröe [2] in 1928, in which ions of Na and K were accelerated to twice the applied voltage while traversing two tubular electrodes in line between which an oscillatory electric field was applied—an elementary linear accelerator. In 1953 Professor Lawrence described to the writer the origin of the idea, as he then remembered it.

The conception of the idea occurred in the library of the University of California in the early summer of 1929, when Lawrence was browsing through the current journals and read Wideröe's paper in the *Archiv für Elektrotechnik*. Lawrence speculated on possible variations of this resonance principle, including the use of a magnetic field to deflect particles in circular paths so they would return to the first electrode, and thus reuse the electric field in the gap. He discovered that the equations of motion predicted a constant period of revolution, so that particles could be accelerated indefinitely in resonance with an oscillatory electric field —the "cyclotron resonance" principle.

Lawrence seems to have discussed the idea with others during this early formative period. For example, Thomas H. Johnson has told the writer that Lawrence discussed it with himself and Jesse W. Beams during a conference at the Bartol Institute in Philadelphia during that summer, and that further details grew out of the discussion.

The first opportunity to test the idea came during the spring of 1930, when Lawrence asked Edlefsen, then a graduate student at Berkeley who had completed his thesis and was awaiting the June degree date, to set up an experimental system. Edlefsen used an existing small magnet in the laboratory and built a glass vacuum chamber with two hollow internal electrodes to which radiofrequency voltage could be applied, with an unshielded probe electrode at the periphery. The current to the probe varied with magnetic field, and a broad resonance peak was observed which was interpreted as due to the resonant acceleration of hydrogen ions.

However, Lawrence and Edlefsen had not in fact observed true cyclotron resonance; this came a little later. Nevertheless, this first paper was the initial announcement of a principle of acceleration which was soon found to be valid and which became the basis for all future cyclotron development.

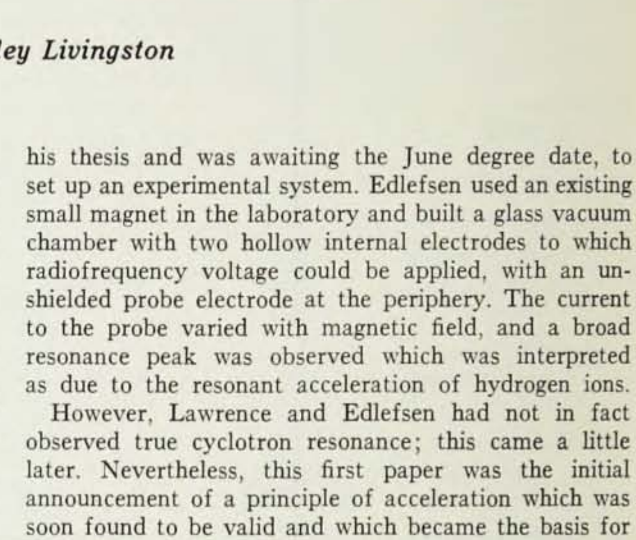

Fig. 1. Vacuum chamber of the first cyclotron. (PhD Thesis, M. S. Livingston, University of California, April 14, 1931)

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Doctoral Thesis

IN the summer of 1930 Professor Lawrence suggested the problem of resonance acceleration to the author, then a graduate student at Berkeley, as an experimental research investigation. In my early efforts to confirm Edlefsen's results I found that the broad peak observed by him was probably due to single acceleration of N and O ions from the residual gas, which curved in the magnetic field and struck the unshielded electrode at the edge of the chamber.

It was my opportunity and responsibility to continue the study and to demonstrate true cyclotron resonance. A Doctoral Thesis [3] by the author dated April 14, 1931, reported the results of the study. It was not published but is on file at the University of California library. The electromagnet available was of 4-inch pole diameter. Fig. 1 is an illustration from this thesis, showing the arrangement of components which is still a basic feature of all cyclotrons. The vacuum chamber was made of brass and copper. Only one "D" was used, on this and several subsequent models; the need for a more efficient electrical circuit for the radiofrequency electrodes came later with the effort to increase energy. A vacuum tube oscillator provided up to 1000 volts on the electrode, at a frequency which could be varied by adjusting the number of turns in a resonant inductance. Hydrogen ions (H_2^+ and later H^+) were produced through ionization of hydrogen gas in the chamber, by electrons emitted from a tungsten-wire cathode at the center. Resonant ions which reached the edge of the chamber were observed in a shielded collector cup and had to traverse a deflecting electric field. Sharp peaks were observed in the collected current at the magnetic field for resonance with H_2^+ ions as shown in Fig. 2, a typical resonance curve taken from the thesis. Also present were 3/2 and 5/2 resonance peaks at proportionately lower magnetic fields, due to harmonic resonances of H_2^+ ions. By varying the frequency of the applied electric field, resonance was observed over a wide range of frequency and magnetic field, as shown in Fig. 3, proving conclusively the validity of the resonance principle.

The small magnet used in these resonance studies had a maximum field of 5200 gauss, for which resonance with H_2^+ ions occurred at 76 meters wavelength or 4.0 megacycles frequency. In this small chamber the final ion energy was 13 000 electron volts, obtained with the application of a minimum of 160 volts peak on the D. This corresponds to about 40 turns or 80 accelerations. A stronger magnet was borrowed for a short time, capable of producing 13 000 gauss, with which it was possible to extend the resonance curve and to produce hydrogen ions of 80 000 ev energy. This goal was reached on January 2, 1931.

The First 1-Mev Cyclotron

LAWRENCE moved promptly to exploit this breakthrough. In the spring of 1931 he applied for and was awarded a grant by the National Research Council (about $1000) for a machine which could give useful energies for nuclear research. The writer was appointed as an instructor at the University of California on completion of the doctorate in order to continue the research. During the summer and fall of 1931, the writer, under the supervision of Lawrence, designed and built a 9-inch diameter magnet and brought it into operation, first with H_2^+ ions of 0.5-Mev energy. Then the poles were enlarged to 11 inches and protons were accelerated to 1.2 Mev. This was the first time in scientific history that artificially accelerated ions of this energy had been produced. The beam intensity available at a target was about 0.01 microampere. The progress and results were reported in a series of three

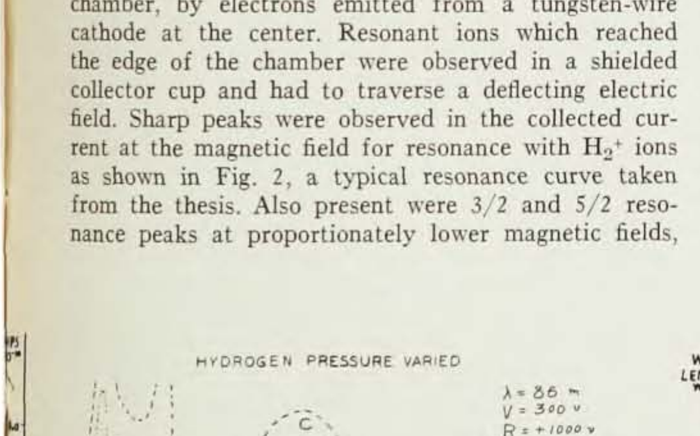

Fig. 2. Typical curves of current at the collector vs. magnetic field, showing resonant H_2^+ ions of 13 000 ev energy (peak D) and the variation of intensity with hydrogen gas pressure. (Thesis—Livingston)

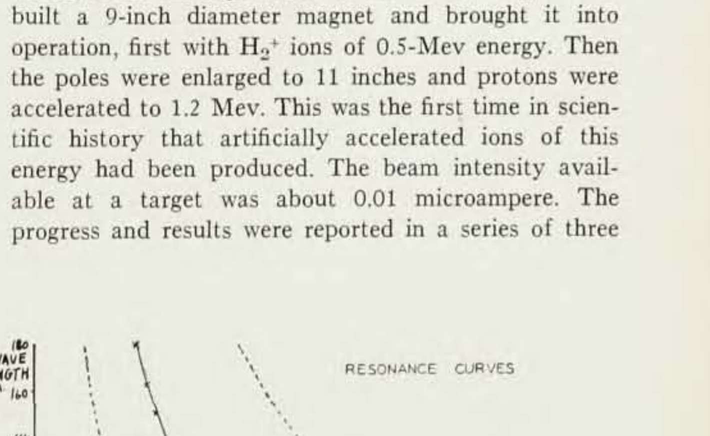

Fig. 3. Experimental values of cyclotron resonance for H_2^+ ions. (Thesis—Livingston)

Fig. 4. 1.2 Mev H^+ cyclotron at the University of California.[4]

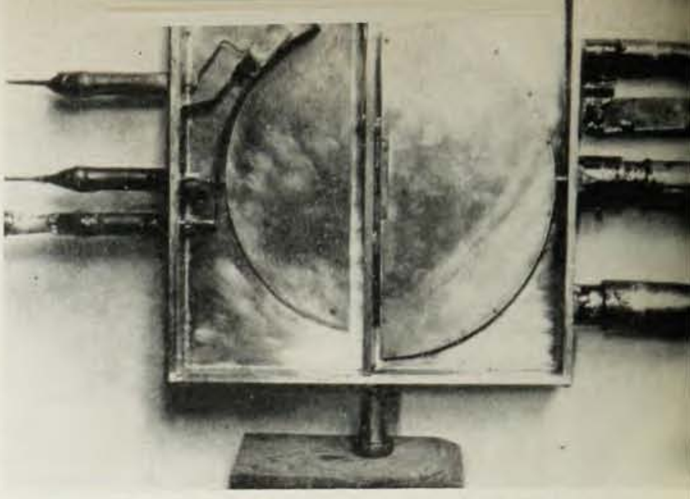

Fig. 5. Vacuum chamber for 1.2 Mev cyclotron with 11-inch pole faces.[4]

abstracts and papers by Lawrence and Livingston in *The Physical Review*.[4] Figs. 4 and 5 show the size and general arrangements of this first practical cyclotron.

Of course, Lawrence had other interests and other students in the laboratory. Milton White continued research with the first cyclotron. David Sloan developed a series of linear accelerators for heavy ions, limited by the radio power tubes and techniques available at that time, for Hg ions and later for Li ions. With Wesley Coates, Robert Thornton, and Bernard Kinsey, Sloan also invented and developed a resonance transformer using a radiofrequency coil in a vacuum chamber which developed 1 million volts. With Jack Livingood and Frank Exner he tried for a time to make this into an electron accelerator. I must again thank Dave Sloan for the many times that he assisted me in solving problems of the cyclotron oscillator.

The Race for High Voltage

TO understand the meaning of this achievement we must look at it from the perspective of the status of science throughout the world. When Rutherford demonstrated in 1919 that the nitrogen nucleus could be disintegrated by the naturally occurring alpha particles from radium and thorium, a new era was opened in physics. For the first time man was able to modify the structure of the atomic nucleus, but in submicroscopic quantities and only by borrowing the enormous energies (5 to 8 Mev) of radioactive matter. During the 1920's x-ray techniques were developed so machines could be built for 100 to 200 kilovolts. Development to still higher voltages was limited by corona discharge and insulation breakdown, and the multimillion volt range seemed out of reach.

Physicists recognized the potential value of artificial sources of accelerated particles. In a speech before the Royal Society in 1927 Rutherford expressed his hope that accelerators of sufficient energy to disintegrate nuclei could be built. Then in 1928 Gamow and also Condon and Gurney showed how the new wave mechanics, which was to be so successful in atomic science, could be used to describe the penetration of nuclear potential barriers by charged particles. Their theories made it seem probable that energies of 500 kilovolts or less would be sufficient to cause the disintegration of light nuclei. This more modest goal seemed feasible. Experimentation started around 1929 in several laboratories to develop the necessary accelerating devices.

This race for high voltage started on several fronts. Cockcroft and Walton in the Cavendish Laboratory of Cambridge University, urged on by Rutherford, chose to extend the known engineering techniques of the voltage-multiplier, which had already been successful in some x-ray installations. Van de Graaff chose the long-known phenomena of electrostatics and developed a new type of belt-charged static generator to obtain high voltages. Others explored the Tesla coil transformer with an oil-insulated high-voltage coil, or the "surge-generator" in which capacitors are charged in parallel and discharged in series, and still others used transformers stacked in cascade on insulated platforms.

The first to succeed were Cockcroft and Walton.[5] They reported the disintegration of lithium by protons of about 400 kilovolts energy, in 1932. I like to consider this as the first significant date in accelerator history and the practical start of experimental nuclear physics.

All the schemes and techniques described above have the same basic limitation in energy; the breakdown of dielectrics or gases sets a practical limit to the voltages which can be successfully used. This limit has been raised by improved technology, especially in the pressure-insulated electrostatic generator, but it still remains as a technological limit. The cyclotron avoids this voltage-breakdown limitation by the principle of resonance acceleration. It provides a method of obtaining high particle energies without the use of high voltage.

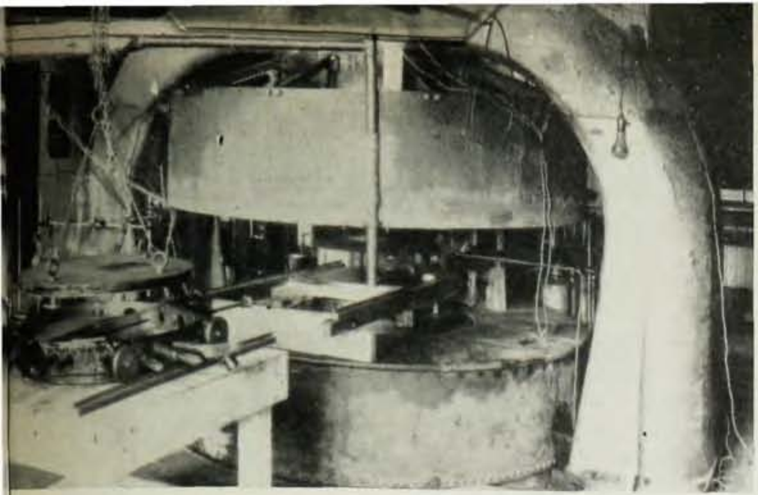

Fig. 6. The "27-inch" cyclotron which produced 5 Mev D^+ ions, with chamber rolled out.[7, 8]

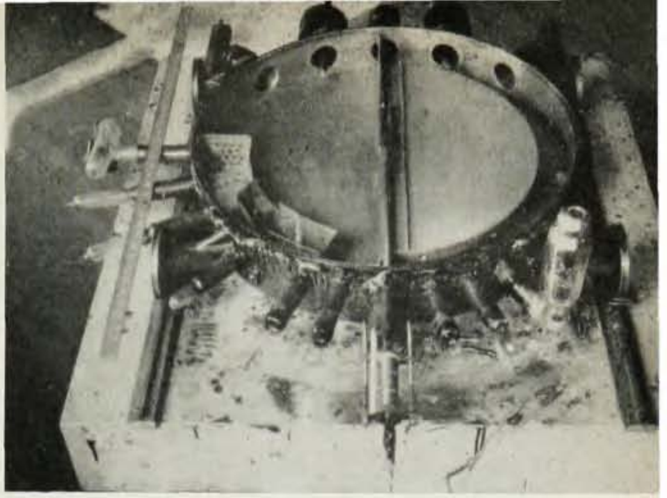

Fig. 7. Vacuum chamber for the "27-inch" cyclotron.[7, 8]

The Cyclotron Splits its First Atoms

THE above digression into the story of the state of the art shows why the 1.2-Mev protons from the 11-inch Berkeley cyclotron were so important. This small and relatively inexpensive machine could split atoms! This was Lawrence's goal. This was why Lawrence literally danced with glee when, watching over my shoulder as I tuned the magnet through resonance, the galvanometer spot swung across the scale indicating that 1 000 000-volt ions were reaching the collector. The story quickly spread around the laboratory and we were busy all that day demonstrating million-volt protons to eager viewers.

We had barely confirmed our results and I was busy with revisions to increase beam intensity when we received the issue of the *Proceedings of the Royal Society* describing the results of Cockcroft and Walton in disintegrating lithium with protons of only 400 000 electron volts. We were unprepared at that time to observe disintegrations with adequate instruments. Lawrence sent an emergency call to his friend and former colleague, Donald Cooksey at Yale, who came out to Berkeley for the summer with Franz Kurie; they helped develop the necessary counters and instruments for disintegration measurements. Within a few months after hearing the news from Cambridge we were ready to try for ourselves. Targets of various elements were mounted on removable stems which could be swung into the beam of ions. The counters clicked, and we were observing disintegrations! These first early results were published on October 1, 1932, as confirmation of the work of Cockcroft and Walton, by Lawrence, Livingston, and White.[6]

The "27-inch" Cyclotron

LONG before I had completed the 11-inch machine as a working accelerator, Lawrence was planning the next step. His aims were ambitious, but supporting funds were small and slow in arriving. He was forced to use many economies and substitutes to reach his goals. He located a magnet core from an obsolete Poulsen arc magnet with a 45-inch core, which was donated by the Federal Telegraph Company. Two pole cores were used and machined to form the symmetrical, flat pole faces for a cyclotron. In the initial arrangement the pole faces were tapered to a 27½-inch diameter pole face; in later years this was expanded to 34 inches and still higher energies were obtained. The windings were layer-wound of strip copper and immersed in oil tanks for cooling. (The oil tanks leaked! We all wore paper hats when working between coils to keep oil out of our hair.) The magnet was installed in the "old radiation lab" in December 1931; this was an old frame warehouse building near the University of California Physics Building which was for years the center of cyclotron and other accelerator activities. Fig. 6 is a photograph of this magnet with the vacuum chamber rolled out for modifications.

Other dodges were necessary to meet the mounting bills for materials and parts. The Physics Department shops were kept filled with orders for machining. Willing graduate students worked with the mechanics installing the components. My appointment as instructor terminated, and for the following year Lawrence arranged for me an appointment as research assistant in which I not only continued development on the cyclotron but also supervised the design and installation of a 1-Mev resonance transformer x-ray installation of the Sloan design in the University Hospital in San Francisco.

The vacuum chamber for the 27-inch machine was a brass ring with many radial spouts, fitted with "lids" of iron plate on top and bottom which were extensions of the pole faces. This chamber is shown in Fig. 7. Sealing wax and a special soft mixture of beeswax and rosin were first used for vacuum seals, but were ultimately replaced by gasket seals. In the initial model only one insulated D-shaped electrode was used, facing a slotted bar at ground potential which was called a "dummy D". In the space behind the bar the collector could be mounted at any chosen radius. The beam was first observed at a small radius, and the magnet was "shimmed" and other adjustments made to give maximum beam intensity. Then the chamber was opened, the collector moved to a larger radius, and the tuning and shimming extended. Thus we learned, the hard way, of the necessity of a radially decreasing magnetic field for focusing. If our optimism persuaded us to install the collector at too large a radius, we made a "strategic retreat" to a smaller radius and recovered the beam. Eventually we reached a practical maximum radius of 10 inches and installed two symmetrical D's with which higher energies could be attained. Technical improvements and new gadgets were added day by day as we gained experience. The progress during this period of development from 1-Mev protons to 5-Mev deuterons was reported in *The Physical Review* by Livingston [7] in 1932 and by Lawrence and Livingston [8] in 1934.

I am indebted to Edwin M. McMillan for a brief chronological account of these early developments on the 27-inch cyclotron. (It seems that earlier laboratory notebooks were lost.) These records show, for example:

June 13, 1932. 16-cm radius, 28-meter wavelength, beam of 1.24-Mev H_2^+ ions.

August 20, 1932. 18-cm radius, 29 meters, 1.58-Mev H_2^+ ions.

August 24, 1932. Sylphon bellows put on filament for adjustment.

September 28, 1932. 25.4-cm radius, 25.8 meters, 2.6-Mev H_2^+ ions.

October 20, 1932. Installed two D's in tank, radius fixed at 10 in.

November 16, 1932. 4.8-Mev H_2^+ ions, ion current 10^{-9} amps.

December 2–5, 1932. Installed target chamber for studies of disintegrations with Geiger counter. Start of long series of experiments.

March 20, 1933. 5 Mev of H_2^+; 1.5 Mev of He^+; 2 Mev of $(HD)^+$. Deuterium ions accelerated for first time.

September 27, 1933. Observed neutrons from targets bombarded by D^+.

December 3, 1933. Automatic magnet current control circuit installed.

February 24, 1934. Observed induced radioactivity in C by deuteron bombardment. 3-Mev D^+ ions, beam current 0.1 microampere.

March 16, 1934. 1.6-Mev H^+ ions, beam current 0.8 microampere.

April–May, 1934. 5.0-Mev D^+ ions, beam current 0.3 microampere.

Those were busy and exciting times. Other young scientists joined the group, some to assist in the continuing development of the cyclotron and others to develop the instruments for research instrumentation. Malcolm Henderson came in 1933 and developed counting instruments and magnet control circuits, and also spent long hours repairing leaks and helping with the development of the cyclotron. Franz Kurie joined the team, and Jack Livingood and Dave Sloan continued with their linear accelerators and resonance transformers, but were always available to help with problems on the cyclotron. Edwin McMillan was a major thinker in the planning and design of research experiments. And we all had a fond regard for Commander Telesio Lucci, retired from the Italian Navy, who became our self-appointed laboratory assistant. As the experiments began to show results we depended heavily on Robert Oppenheimer for discussions and theoretical interpretation.

One of the exciting periods was our first use of deuterons in the cyclotron. Professor G. N. Lewis of the Chemistry Department had succeeded in concentrating "heavy water" with about 20% deuterium from battery acid residues, and we electrolyzed it to obtain gas for our ion source. Soon after we tuned in the first beam we observed alpha particles from a Li target with longer range and higher energy than any previously found in natural radioactivities—14.5-cm range, coming from the Li^6 (d,p) reaction. These results were reported in 1933 by Lewis, Livingston, and Lawrence,[9] and led to an extensive program of research in deuteron reactions. Neutrons were also observed, in much higher intensities when deuterons were used as bombarding particles, and were put to use in a variety of ways.

We had frustrations—repairing vacuum leaks in the wax seals of the chamber or "tank" was a continuing problem. The ion source filament was another weak point, and required continuous development. And sometimes Lawrence could be *very* enthusiastic. I recall working till midnight one night to replace a filament and to reseal the tank. The next morning I cautiously warmed up and tuned the cyclotron to a new beam intensity record. Lawrence was so pleased and excited when he came into the laboratory that morning that he jubilantly ran the filament current higher and higher, exclaiming each time at the new high beam intensity, until he pushed too high and burned out the filament!

We made mistakes too, due to inexperience in research and the general feeling of urgency in the laboratory. The neutron had been identified by Chadwick in 1932. By 1933 we were producing and observing neutrons from every target bombarded by deuterons.[10] They showed a striking similarity in energy, independent of the target, and each target also gave a proton group of constant energy. This led to the now forgotten mistake in which the neutron mass was calculated on the assumption that the deuteron was breaking up into a proton and a neutron in the nuclear field. The neutron mass was computed from the energy of the common proton group,[11] and was much lower than the value determined by Chadwick. Shortly afterward, Tuve, Hafstad, and Dahl in Washington, D. C., using the first electrostatic generator to be completed and used for research, showed that these protons and neutrons came from the $D(d,p)$ and $D(d,n)$ reactions,

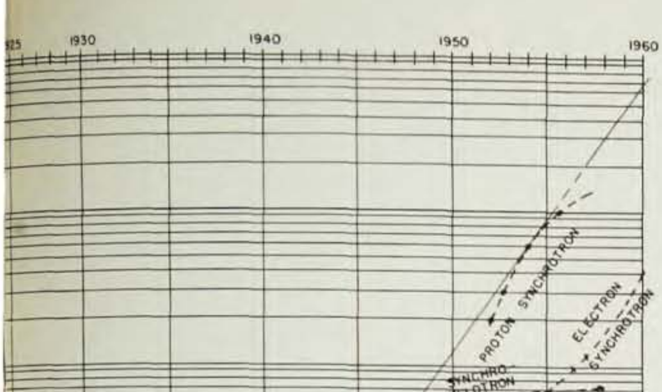

Fig. 8. Energies attained with accelerators as a function of time.

in which the target was deuterium gas deposited in all targets by the beam. We were chagrined, and vowed to be more careful in the future.

We also had many successful and exciting moments. I recall the day early in 1934 (February 24) when Lawrence came racing into the lab waving a copy of the *Comptes Rendus* and excitedly told us of the discovery of induced radioactivity by Curie and Joliot in Paris, using natural alpha particles on boron and other light elements. They predicted that the same activities could be produced by deuterons on other targets, such as carbon. Now it just so happened that we had a wheel of targets inside the cyclotron which could be turned into the beam by a greased joint, and a thin mica window on a re-entrant seal through which we had been observing the long-range alpha particles from deuteron bombardment. We also had a Geiger point counter and counting circuits at hand. We had been making 1-minute runs on alpha particles, with the counter switch connected to one terminal of a double-pole knife-switch used to turn the oscillator on and off. We quickly disconnected this counter switch, turned the target wheel to carbon, adjusted the counter circuits, and then bombarded the target for 5 minutes. When the oscillator switch was opened this time, the counter was turned on, and click-click--click---click----click. We were observing induced radioactivity within less than a half-hour after hearing of the Curie-Joliot results. This result was first reported by Henderson, Livingston, and Lawrence [12] in March, 1934.

I left the laboratory in July, 1934, to go to Cornell (and later to MIT) as the first missionary from the Lawrence cyclotron group. Edwin McMillan overlapped my term of apprenticeship by a few months, and stayed on to win the Nobel Prize and ultimately to succeed Professor Lawrence as director of the laboratory which he founded. McMillan can tell the rest of the story.

But it would be unfair to the spirit of Professor Lawrence if I failed to indicate some gleam of great things to come, some vision of the future. Recently I prepared a graph of the growth of particle energies obtained with accelerators with time, shown in Fig. 8. To keep this rapidly rising curve on the plot, the energies are plotted on a logarithmic scale. The curves show the growth of accelerator energy for each type of accelerator plotted at the dates when new voltage records were achieved. The cyclotron was the first resonance accelerator to be successful, and it led to the much more sophisticated synchronous accelerators which are still in the process of growth. The over-all envelope to the curve of log E vs time is almost linear, which means an exponential rise in energy, with a 10-fold increase occurring every 6 years and with a total increase in particle energy of over 10 000 since the days of the first practical accelerators. The end is not yet in sight. If you are tempted to extrapolate this curve to 1960, or even to 1970, then you are truly sensing the exponentially rising spirit of the Berkeley Radiation Laboratory in those early days, stimulated by our unique leader, Professor Lawrence.

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