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EARLY HISTORY OF PHYSICS WITH ACCELERATORS

H.L. Anderson

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, U.S.A.

Abstract. - The early history of physics at accelerators is reviewed, with emphasis on three experiments which have had a profound influence on our view of the structure of matter: The Franck and Hertz experiment demonstrating the mechanism of atomic spectra, the Cockcroft and Walton experiment opening practical ways of studying nuclear disintegration, and the discovery of the $\Delta^{++}$ isobar of the proton by Fermi and collaborators, revealing structure in the nucleon. Fermi's work is illustrated by pages from his notebooks.

Introduction

I don't intend to give a comprehensive survey of all the important experiments in elementary particle physics that were carried out at accelerators in the period 1930 - 1960. Instead, I'd like to tell about three accelerator experiments that in a dramatic way, changed physics profoundly, each in its own time. The experiments I have in mind are the following:

1) "Excitation of the the 2536 Å Resonance Line of Mercury," J. Franck and G. Hertz, (1914).1,2

2) "Disintegration of Elements by High Velocity Protons," J. D. Cockcroft and E. T. S. Walton (1932).3,4


The first experiment made it clear that Bohr's theory was correct and thereby opened the way to a proper understanding of atomic spectroscopy. The second opened the field of nuclear spectroscopy. The third, by making evident the significance of isotopic spin and revealing the existence of an excited state of the proton, provided the key to the 3rd spectroscopy, the spectroscopy of the hadrons.

The idea that each successive stage in the development of elementary particle physics was marked by a new spectroscopy is taken from Weisskopf. In an article,6 "What is an Elementary Particle," written in celebration of the 50th anniversary of

Résumé. - L'histoire du début de la physique des accélérateurs est présentée, avec l'accent sur trois expériences qui ont eu une influence profonde sur notre conception de la structure de la matière: l'expérience de Franck et Hertz qui démontra le mécanisme des spectra atomiques, l'expérience de Cockcroft et Walton qui ouvrit des voies pratiques à l'étude de la désintégration nucléaire, et la découverte de l'isobare $\Delta^{++}$ du proton par Fermi et ses collaborateurs, qui révéla une structure dans le noyau. Le travail de Fermi est illustré par des extraits de son journal de laboratoire.
the International Union of Pure and Applied Science, he discusses how structure in an elementary system is always revealed by a spectroscopy. He identified three stages, and wrote, "it is historically interesting that these three progressive steps toward a deeper understanding of the fundamental structure of matter were initiated by discoveries made almost exactly 20 years apart: the discovery of the nuclear atom by Rutherford in 1911, the discovery of the neutron by Chadwick in 1932, and the discovery of the excited Δ-state of the proton by Fermi and collaborators and its interpretation by Brueckner and Watson in 1952." When he wrote this article in 1972 a 4th spectroscopy of quarks and gluons, that occupies a large part of high energy physics today, was emerging.

Franck and Hertz Experiment

The Rutherford scattering experiment gave no suggestion of a spectroscopy until Bohr's theory provided it. The experimental demonstration that atomic spectroscopy could be understood from the point of view of Bohr's theory was made by Franck and Hertz. This was not the classic Franck and Hertz experiment in which it was shown that an electron would lose 4.9 volts, and not less, in inelastic collisions with mercury atoms. It was the one that followed and answered the question "What happened to the lost energy?" Fig. 1 shows the apparatus. It is an accelerator small enough to be held in one hand. There is a platinum filament, labeled D in the figure, that emitted electrons when heated by an electric current. The electrons were accelerated toward the anode N when this was held at positive potential with respect to the filament. The bulb was filled with mercury vapor that served as the target. With anode voltages in excess of 4.9 volts, inelastic collisions between electrons and mercury atoms took place within the bulb. To see what came out of this, an ultraviolet spectrograph was set up to analyze any possible light emission. The spectrogram obtained is reproduced in Fig. 2. The result is shown in the lower spectrum. The darkened continuous region on the right is due to the light emitted by the hot filament. Off to the left there is a single

Fig. 1: The electron accelerator of Franck and Hertz used to excite the 2536 Å resonance line of mercury.

Fig. 2: Ultraviolet spectrogram showing the single 2537 Å resonance line of mercury (below) and the comparison spectrum (above).
isolated dark line, identified by the comparison spectrum of mercury above, as the 2536 Å resonance line of mercury. We recognize this line today as coming from the first excited state of the mercury atom and we know that it arises by the emission of radiation following excitation by electron collision. In fact, from their measurement of the electron energy, 4.9 volts, and the wavelength of the emitted light, Planck's constant was determined. The value they obtained, $h = 6.59 \times 10^{-27}$ erg sec, agrees, within errors, with the present value, $6.63 \times 10^{-27}$ erg sec.

If this seems obvious enough now it is because we know Bohr's theory. But it may interest you to know that when Franck and Hertz did their experiment they didn't know about Bohr's theory. It had been published some six months earlier, but they hadn't heard of it. They were negligent not to have read about it in the literature. You know how that happens. There was an active seminar in Berlin at the time at which all the latest developments in physics were discussed. But if Bohr's theory had been presented there it wouldn't have been taken seriously. In fact, in a letter to Bohr, Richard Courant once wrote, "....how glad I was when I read of the Nobel Prize report in the newspapers. It reminded me vividly of that beautiful day in Cambridge in 1913 when you set forth your ideas for me in the quadrangle of Trinity. Thanks to prior suggestion by Harald (Bohr), who had so often told me wonderful things about his brother, I was at that point immediately ready to believe that you might be right. But when I then reported of these things here in Göttingen, they laughed at me that I should take such fantasies seriously." However, the agreement with Bohr's ideas was so striking that no one could deny their correctness. There followed a rapid development in the theory of atomic spectra and a revolution in the understanding of the nature of the atom.

When we think how much modern man depends on the chemistry, the biology, and the technology that grew out of the secure knowledge of atomic structure, we begin to have a measure of the power and the importance of those developments.

Cockcroft and Walton Experiment

While the discovery of the neutron was essential to the understanding of the nucleus, it was the Cockcroft-Walton accelerator and the experiments they did with it that opened the field of nuclear spectroscopy. Both experiments were done in 1932. Already in 1919, Rutherford had shown that the nucleus could be disintegrated by alpha particles. However, his alpha particles were those emitted from naturally occurring radioactive elements. There were not enough of them to carry out an extensive study of the phenomenon. The advances in electrical technology in the years following World War I made it possible to contemplate the production of high speed particles by artificial means. In 1927 Rutherford, as President of the Royal Society, expressed the wish for a supply of "atoms and electrons that have an individual energy far transcending that of the particles from radioactive bodies."

To overcome the Coulomb barrier of the nucleus it would be necessary to have particles accelerated to energies of several million volts or more. This became the goal of those who contemplated building such machines. In fact, by 1932, Lawrence and Livingston at Berkeley had constructed a cyclotron that accelerated protons to an energy exceeding 1 million volts.

Some years earlier, Gamow and also Condon and Gurney showed that wave mechanics explained how alpha particles could escape from the nucleus with an energy far below the Coulomb potential barrier. When Gamow was visiting the Cavendish Laboratory in 1928, Cockcroft inquired about the inverse problem — the energy that would be required for a proton to penetrate the nucleus of a light element. The same principle applied and Cockcroft prepared a memorandum for Rutherford showing that there was a high probability for the boron nucleus to be penetrated by a proton of only 300 kilovolts energy. The conditions for lithium were even more favorable. Rutherford then agreed that work on this project could begin. The result was a d. c. accelerator based on the voltage doubler principle capable of developing 600 kilovolts. Figure 3 is a photograph of the Cockcroft-Walton accelerator showing John Cockcroft sitting inside the small observation box in the foreground.
The disintegration of lithium by protons was demonstrated by Cockcroft and Walton with an energy of only 125 kilovolts. The apparatus they used is shown in Fig. 4. The beam of fast protons was directed against a lithium target and the alpha particles from the reaction $p + Li \rightarrow \alpha + \alpha$ were detected by the well tried tool of Rutherford, the zinc sulphide screen. They then confirmed the reaction by demonstrating that the alpha particles were emitted in pairs. They used a primitive form of coincidence experiment, carried out with two zinc sulphide screens and two observers tapping keys. The resolving time was a second or so, somewhat longer by a factor of 10 than the resolving time of modern coincidence circuits. Disintegrations under proton bombardment were seen also for many other elements, not only with the zinc sulphide screen, but with other detectors that were available in the laboratory: the ionization chamber, linear amplifier and oscillograph of the type described by Wynn-Williams and Ward, and the Shimizu expansion chamber.

The disintegration of lithium might have been seen at Berkeley before it had at Cambridge, but the planning of physics experiments did not parallel the construction of the machines that were needed to perform them. Artificial radioactivity and fission could also have been discovered first at Berkeley if the focus and the tradition had been more on the physics than on the machines. Nevertheless, the Berkeley cyclotrons were widely copied and had a profound influence on the development of nuclear physics all over the world.\textsuperscript{10}

Accelerator Development

Figure 5 shows Livingston and Lawrence standing inside the yoke of the magnet for the 37-in cyclotron. The magnet was one of a pair that had been built by the Federal Telegraph Company for a type of radio transmitter, the Poulsen arc generator, made obsolete by the vacuum tube. My own introduction to cyclotrons came through John R. Dunning whose assistant I became. At Columbia University he managed to acquire the second of these magnets and transformed it into a 37-in cyclotron. It was ready, in 1939, for many important experiments that were done on the
Fig. 2: Stream of fast protons

Fig. 3: Thin lithium target

Fig. 4: Apparatus for detecting the disintegration of lithium by protons using a zinc sulphide screen as detector. Coincidence apparatus for $p+\text{Li}$ to $\alpha+\text{He}$ using two ZnS screens.

Fig. 5: Livingston (left) and Lawrence (right) standing in the yoke of the magnet for the 37" cyclotron. It operated initially as a 27" cyclotron in December 1932, and produced 4.8 MeV hydrogen ions.
fission of uranium, following the discovery of that phenomenon at the beginning of that year. Figure 6 is a photograph of the Columbia cyclotron that shows me carrying out an experiment on the resonant absorption of neutrons by uranium.

Figure 7 reproduces a graph taken from a report prepared by W. K. F. Panofsky. It shows how the energy of accelerators developed over the years. The particle energy, either electron or proton, as the case might be, increased tenfold every six years over the 50 year period from 1932 – 1982. For the purposes of the graph, the energy plotted is the laboratory energy of the particles accelerated. For colliders, an equivalent energy is plotted which is the laboratory energy on a fixed target with the same center of mass energy. The plot shows how, as each technology began to reach its limit in energy, a new higher energy technology was invented to succeed it.

In 1960, the cut-off date for this colloquium, the 30 GeV proton synchrotrons at CERN and Brookhaven were just coming onstream, but the 6 GeV Bevatron at Berkeley had been in operation for several years. With it came the discovery of the antiproton and a number of new strange particles. Many important experiments in particle physics were performed with the synchrocyclotrons and the synchrotrons of the 50's with the pions, the muons, and the strange particles they produced. By the end of the decade the physics with these particles was being done almost exclusively with machines. It was no longer fruitful to look at the cosmic rays to study elementary particles.

It seems reasonable to suggest as Alvarez has, that modern particle physics had its start in 1946, during the last days of World War II, when a group of young Italians, Conversi, Pancini, and Piccioni, while hiding from the Germans, carried out a remarkable experiment. They showed that the "mesotron" which had been discovered in 1937 by Neddermeyer and Anderson and by Street and Stevenson was not the particle predicted by Yukawa as the mediator of nuclear forces, but a weakly interacting particle we now call the muon. The Yukawa particle, now known as the pion, was discovered the following year by Occhialini, Powell, and collaborators. This group from Bristol used a new nuclear emulsion technique developed in collaboration with Ilford Laboratories. After exposure to cosmic rays they not only found the pions but showed them decaying into muons.

Fig. 6: The 37" cyclotron built by J. R. Dunning at Columbia University. A bombardment of uranium by neutrons is being carried out by H. L. Anderson. The year is 1939.
While this was going on in Europe and England, two new great accelerators were being built in Ernest Lawrence's laboratory in Berkeley. Both were based on the principle of phase stability as developed by McMillan and independently by Veksler, toward the end of the war. Lawrence's 184-in synchrocyclotron was capable of accelerating protons to an energy of 350 MeV. McMillan's electron synchrotron could reach 330 MeV. The synchrocyclotron delivered its first beam just before midnight, November 1, 1946. Although pions were being copiously produced, attempts to find them failed for lack of the proper emulsion technique. They were found almost immediately after Lattes arrived from Bristol with the technique and the proper Ilford emulsions. Lattes was the young Brazilian who, working with Occhialini and Powell at Bristol, was the first to find pions in the cosmic rays. Now he found them produced artificially in a machine. Figure 8 shows Cesare Lattes and Eugene Gardner preparing an emulsion exposure at the synchrocyclotron.

This success was soon followed by the important discovery of the neutral member of the pion family by Bjorklund, Crandall, Moyer, and York at the 184-in machine. They obtained a Doppler-shifted gamma ray spectrum that could only be interpreted as arising from the decay of the $\pi^0$ into two gamma rays. This interpretation was confirmed soon thereafter by a more elegant experiment carried out at the 330 MeV synchrotron by Steinberger, Panofsky, and Steller. They detected directly the coincidence in the emission of the two gamma rays into which the $\pi^0$ was expected to disintegrate. Quite independently, the $\pi^0$ was detected in cosmic rays at Bristol by Ekspong, Hopper, and King who observed the two photon decay in emulsion and measured the lifetime as being less than $5 \times 10^{-14}$ s.
When the cross sections for the photoproduction on hydrogen of $\pi^0$ were compared with those that had been made for $\pi^+$,$^{22,23}$ they were found to be about equal. Moreover, the angular distribution appeared to be isotropic in both cases. This seemed difficult to reconcile with any of the theories being discussed at the time. The first suggestion that the anomalous behavior in photoproduction might be due to the existence of a nucleon isobar was made by Fujimoto and Miyazawa$^{24}$ and also by Brueckner and Case.$^{25}$ The argument did not become convincing until after the discovery of the resonance in the pion-proton scattering. It then became possible for Brueckner and Watson$^{26}$ to put the photoproduction results on a firmer footing.

Many important experiments were done with accelerators during the 50's. Among them, I want to mention the beautiful experiments of Hofstadter$^{27}$ using the electron linac at Stanford. They gave quantitative evidence for the finite size of the proton and a glimmer of the tiny world within and the 4th spectroscopy that has preoccupied us since.

Synchrocyclotron at Chicago

Instead of reviewing these developments more completely, I thought it might be more interesting to tell about the third experiment in some detail. This was the experiment in which the pion-proton resonance appeared unexpectedly in a striking way. The work began in 1951, soon after the construction of the synchrocyclotron was completed at Chicago.$^{28}$ This machine was designed to accelerate protons to 450 MeV, 100 MeV more than its predecessor at Berkeley, so that the intensity and energy of the pion beams it could produce would be substantially greater. During the construction of the machine, I kept Fermi closely coupled to all the developments. It was understood that once the machine was completed, we would resume our work together. When the time came we organized a small group, including some graduate students, and began a series of measurements on pion scattering. John Marshall, who helped design and build the machine formed his own group. Other members of the Institute for Nuclear Studies also formed groups and used the machine according to a schedule that was worked out each week. Figure 9 is a photograph showing Enrico Fermi, myself, and John Marshall, at the cyclotron.
Fig. 9: Enrico Fermi, Herbert Anderson, and John Marshall at the Chicago synchrocyclotron.

Fig. 10: The "Fermi trolley", a movable target for the proton beam inside the cyclotron capable of obtaining the beam intensity from temperature difference measurements.
When I looked among my collection of notebooks for the ones of that period, I
found somewhat to my surprise, that in some sections the entries were almost entirely
in Fermi's hand. It is possible to catch the excitement of discovery in those
pages. They also gave an interesting glimpse of Fermi as an experimenter.

Fermi Trolley

Before using the cyclotron, Fermi wanted to add his contribution to its
construction. He offered to take care of the target arrangements. One weekend, he
went into the shop and built the trolley car shown in the photograph of Fig. 10. It
was an ingenious device and became so useful it remained in operation for many
years. Mounted on the edge of the magnet pole inside the vacuum, the trolley car
could be moved around by manipulating a set of switches outside the vacuum chamber.
Each pair of wheels was on an axle to which was attached a magnet coil. The coils
were set at 90° to one another. Sending current through the coil in the horizontal
position with the cyclotron magnet on would turn it to the upright position. This
rotated the wheels through 90° and brought the second coil to the horizontal
position. By sending current through the second coil, the wheels would rotate by an
additional 90°. Switching the current from one coil to the other would send the car
around the pole in one direction. Reversing the current moved the car in the op-
posite direction. A third coil was used to raise or lower the target in or out of
the beam.

The general scheme was to provide negative and positive pion beams at various
energies as shown in Fig. 11. Fermi calculated the trajectories from a map of the
cyclotron magnetic field and slots were cut in the steel shield that separated the
cyclotron from the experimental room according to his prescriptions. The negative
pions emitted in the forward direction came out of the cyclotron through a thin
window in the vacuum chamber. Positive pions came out if they were emitted in the
backward direction. The positive pion beams were of lower intensity but they came
out readily when the magnetic field of the cyclotron was reversed.

On the other side of the shield, in the experimental area, a deflecting magnet
was set up. It could be moved into position at any one of the slots and was used to
make the final selection of pion energy. By requiring an extra bend, backgrounds
from other particles coming through the slot, especially neutrons and gamma rays,
were greatly reduced.

![Fig. 11: Pion beams at the Chicago synchrocyclotron. Slots were cut in the
steel shielding to accept pions from the target with different energies. The
final energy selection was done with a dipole magnet on the experimential area side of the shield.](image-url)
Fig. 12: Cyclotron behind its steel shield. The slot pattern cut in steel plates for the pion beams is seen in the foreground. The thin windows through which the pions emerged are central in the photograph. A long window to the right, a short window in the center. Both windows have their protective cover in place. Above and below the central window are the connection terminals for the "trolley car" and lucite windows to observe its position.

Figure 12 is a photograph of the cyclotron behind its steel shield showing the slots in the shield. The thin window for the pions is behind its protective shield in the long port cover to the right. There is also a thin window behind a protective shield in the smaller port cover in the center of the photograph. There are lucite windows above and below for viewing the trolley inside. The connection terminals for the trolley are mounted on these windows. The battery for energizing the coils may be seen below the port.

The trolley car was moved to maximize the pion beam intensity. It was also used to monitor and measure the pion beam intensity in an absolute way. This was done by measuring the temperature of the target and determining the energy deposited by the proton beam from a knowledge of the heat flow characteristics of the target mount. Some of the calculations that Fermi made for this purpose are reproduced here. A sketch of the trolley design is shown in Fig. 13. This shows the location of the thermocouple hot junction at the target, and its cold junction at the heat sink. Details of the heat flow calculations are given in Figs. 14 and 15. These are from pages of one of Fermi’s notebooks, dated May 25 and 28, 1951. The relaxation time of the cylindrical heat sink is calculated on page 44, the response of the target per microampere of beam current is given on page 45.

Detectors

When the new high energy machines, the synchrocyclotrons and the synchrotrons of the post war period, came into operation there was an urgent need for detectors better adapted to them. The scintillation counter arrived on the scene just in time. They differed from the ZnS screen of the Rutherford era by being transparent to their own radiation. Hence, they were usable in thicknesses great enough to be sensitive to minimum ionizing particles, even gamma rays. They were made of organic
Fig. 13: Design sketch for the "Fermi Trolley" from Fermi's notebook.
Target cylinder, 788 grams
4.9\text{ in} \quad 3.70 \quad \text{Difference and}
4.7\text{ in} \quad \text{Heat sink}
6\text{ in} \quad 106\text{ cal}

Target: Copper, 4\times 1.5\times 8\text{ in}

Volume = 3\text{ in}^3 = 4.92\text{ cm}^3

\frac{4.92\text{ g}}{44.09\text{ g}}

Heat capacity = 0.92 \times 4.92 = 4.0\text{ cal/degree}

k (Copper) = \frac{\text{314}}{\text{416}}

Heat leak, 5\text{ cm} long at 8\text{ grams}

Area = \frac{8}{5\times 8.9} = 0.189\text{ cm}^2

\frac{5.0}{0.189 \times 314} = 30.5\text{ degree/cal/sec}

\frac{4 \times 5}{0.91 \times 18} = 120\text{ sec}

7.5^\circ\text{C corresponding to target heat leak}

Total area of cylinder = 75.6\text{ cm}^2

Thermal capacity = 106\text{ cal/deg}

Relax time of cylinder = \frac{106}{4.2 \times 10^7 \times 756 \times 300} = 2.76\text{ sec}

Sensitivity 20.5\text{ mm per degree C (This graph due to resistance 15+9 ohms heat leak from heat to cold function)}

Fig. 14: Relaxation time of cylinder used as heat sink in the trolley.
Fig. 15: Computation of heat leak and calculation of response to beam intensity.
materials, originally napthalene crystals, and when connected optically to a photomultiplier tube they provided a pulse output of very short duration, well suited to high speed electronic counting and coincidence circuitry. The scintillator, only a few millimeters thick, could be shaped to cover a large and precisely defined area. With all these desirable properties, the scintillation counter became an instant success. The man who discovered the organic scintillation counter was Hartmut Kallmann. A short report of his work appeared in the July 1947 issue of "Natur und Technik". A complete report of Kallmann's research reached MIT, and in October Martin Deutsch made it available, in translation, to the American scientific community. He also published a short note in the March 1948 issue of "Nucleonics". Kallmann came to New York University in 1949 and soon thereafter reported his development of liquid scintillation counters, extending greatly the usefulness of this technique. The Na(Tl) high Z inorganic scintillator that became so important in gamma ray spectroscopy, was discovered by Hofstadter, who took inspiration from the report of Kallmann's success with low Z organic materials.

Pion Scattering

The scintillation counter was just what we needed for the measurement of the pion-proton cross sections. The first results were reported at the International Conference on Nuclear Physics and the Physics of Fundamental Particles, held at the University of Chicago, September 17 to 22, 1951. The Conference was organized, in part, to celebrate the successful completion of the Chicago synchrocyclotron. The work had been done by Fermi, Nagle, Long, Martin, and Yodh, besides myself, but I presented the report. The arrangement shown in Fig. 16 used two 1 inch square scintillation crystals (terphenyl) to measure the incoming pions. The target was liquid hydrogen, behind which were placed two larger liquid scintillator counters to measure the number of pions remaining in the beam after traversing the hydrogen. The transmission is obtained by measuring the ratio of the quadruple to double coincidences, with and without hydrogen in the target,

\[
T = \frac{(Q/D)_H}{(Q/D)_{NoH}}.
\]

This is simply related to the total cross-section \( \sigma \) in cm\(^2\) through the relation,

\[
T = \exp (-\sigma x),
\]

where \( x \) is the number of nuclei per cm\(^2\) in the target. For accurate values, corrections have to be applied for backgrounds, purity of the beam, and other effects. Six values of the cross-section were reported for \( \pi^- \), one for \( \pi^+ \). The \( \pi^- \) cross-sections shown in Fig. 17, rose steeply with energy, exceeding the geometric value at 176 MeV and dropping slightly at 217 MeV. The \( \pi^+ \) cross-section, measured at 50 MeV was 4 times larger than the value for \( \pi^- \) at the same energy. However, the experimental error was quite large for the \( \pi^+ \) value, making the true ratio uncertain.

Fig. 16: Arrangement for measuring total cross sections of pions on liquid hydrogen at Chicago.
Average Energy | Cross section milibarns
---|---
50-Mev $\pi^+$ | 20 ± 10
50 $\pi^-$ | 5 ± 15
89 $\pi^-$ | 29 ± 8
112 $\pi^-$ | 36 ± 9
135 $\pi^-$ | 56 ± 6
176 $\pi^-$ | 69 ± 7
217 $\pi^-$ | 60 ± 5

Fig. 17: Early results on total cross sections for $\pi^-$ on liquid hydrogen.

Following the Conference, we went back to work determined to do everything much more carefully, especially the more difficult $\pi^+$ measurements.

Pion Beam Energy

In my notebooks of this period there were several in which Fermi had affixed his name. The title page of one of these is shown in Fig. 18. The first pages of this notebook, dated September 29, 1951, show how Fermi calibrated the deflecting magnet to measure the pion momentum. He used the stretched wire method. A current carrying wire held under tension in a magnetic field will follow the same trajectory as a charged particle with a momentum that may be deduced from the ratio of the tension to the current. Fermi measured how the trajectory shifted with wire current. The measurements begin on page 1 (Fig. 19), continuing on page 2 (Fig. 20). On page 3 (Fig. 21), the scale used in measuring the tension is calibrated. On page 4 (Fig. 22), a formula is given that relates the momentum to the weight and current. The result of the calibration is given for different target positions and for different magnet currents. The momentum is given as $p$ in units of $m\nu c$, the rest mass of the pion times the velocity of light.

Figure 23 shows a design of the liquid scintillation counter. This particular one came later and was used to measure the incoming pions in the angular distribution measurements. We used a prescription from Kallmann\textsuperscript{34} for the liquid. Figure 24 is a photograph that shows me setting up the counters in the pion beam beyond the bending magnet seen in the background. Figure 25 shows Darragh Nagle working on the hydrogen target.

Returning again to the notebook, we show page 18, dated October 5, 1951 in Fig. 26. Here we see how Fermi made a careful tally of all the material in the beam to take account of the energy loss in each. This is continued on page 19 (Fig. 27), that gives the effect of multiple scattering. On page 27 (Fig. 28), we show an absorption curve in aluminum taken by Fermi in a test for proton extraction in the 122 $\pi^-$ channel with all currents reversed. From the location at which he set the target, Fermi expected the proton energy to be 120 MeV and this was pretty close to what he found.

I show these samples of his work to emphasize how closely Fermi participated in the experiments. It wasn't that he felt he had to do it himself to be sure it was done right, but that he enjoyed making measurements so much that the rest of us always stood aside to let him do it.
Fig. 18: Fermi's signature on title page of one of the notebooks.
Fig. 19: Measurement of trajectory position as a function of wire current.
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<td>87.9</td>
</tr>
<tr>
<td></td>
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<td>111.2</td>
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</tr>
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</table>

Move wire 1" west at south end of channel

\[ 89.86 + 0.05 x_5 + 1.64 x_{55} \]

<table>
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<th>89.8</th>
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<td>89.7</td>
</tr>
</tbody>
</table>

\[ 86.07 + 1.31 x_5 + 1.53 x_{55} \]

Move wire 1" east at south end of channel

\[ 86.1 \]

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<th>-4</th>
<th>0</th>
<th>85.7</th>
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</thead>
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<td>0</td>
<td>1.1</td>
<td>86.6</td>
</tr>
<tr>
<td></td>
<td>1021</td>
<td>87.5</td>
<td>-2</td>
<td>0</td>
<td>85.7</td>
</tr>
<tr>
<td></td>
<td>1021</td>
<td>87.5</td>
<td>-9</td>
<td>0</td>
<td>85.7</td>
</tr>
</tbody>
</table>

Move wire 1" west at south end of channel

\[ 86.31 + 2.08 x_5 + 0.63 x_{55} \]

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<th>89.0</th>
<th>-9</th>
<th>0</th>
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<tr>
<td></td>
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<td>88.7</td>
<td>0</td>
<td>-5</td>
<td>85.6</td>
</tr>
<tr>
<td></td>
<td>1.036</td>
<td>90.0</td>
<td>0</td>
<td>1.2</td>
<td>86.9</td>
</tr>
</tbody>
</table>

**Fig. 20:** Tension/current measurements continued.
Fig. 21: Calibration of scale for determining tension.
$HR = 10 \, \text{g} \times \frac{\text{grams}}{\text{amps}}$

$\eta = \frac{HR}{470,000} = \frac{980 \times 10}{470,000} = \frac{9800 \text{amps}}{47.96}$

<table>
<thead>
<tr>
<th>Position of Source</th>
<th>$I$(magnet)</th>
<th>$x_x$</th>
<th>$x_55$</th>
<th>$\eta$</th>
<th>MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>700 amp</td>
<td>0</td>
<td>0</td>
<td>1.857</td>
<td>156.4</td>
</tr>
<tr>
<td>(1° west)</td>
<td>700</td>
<td>0</td>
<td>0</td>
<td>1.874*</td>
<td>158.5</td>
</tr>
<tr>
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<td>657</td>
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<td>0</td>
<td>1.769</td>
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</tr>
<tr>
<td>(1° east)</td>
<td>657</td>
<td>0</td>
<td>0</td>
<td>1.795*</td>
<td>148.8</td>
</tr>
<tr>
<td>0</td>
<td>600</td>
<td>0</td>
<td>0</td>
<td>1.665</td>
<td>132.8</td>
</tr>
</tbody>
</table>

* Cyclotron on

Note: There are magnetic parts in the scale that may have been affected.

Fig. 22: Formula for the momentum from tension/current.
Fig. 23: Design of liquid scintillation counter.

Fig. 24: Author setting up liquid scintillation counters. The bending magnet is in the background.
Cross-Section Measurements

A typical geometry for a transmission measurement is sketched, in Fermi's hand on page 16, of the notebook (Fig. 29). The date from the preceding page (not shown) was October 3, 1951. Counters 1 and 2 were 1 in\(^2\) terphenyl crystals. Counters 3 and 4 were liquid scintillation counters. The liquid hydrogen target, 7 1/2 inches long, was inside a 10.6-inch long container and set in the space between counters 2 and 4, closer to counter 4. The basic measurement is the ratio of quadruple to double coincidences, with and without hydrogen. Gold foils were inserted when the hydrogen was removed to keep the multiple scattering of the beam the same. The liquid hydrogen was removed by pressure, its container remained in place. The 3/16-inch Pb sheet prevented proton recoils from reaching counter 3. A summary of the measurements taken with Martin "slow" circuits and not recorded in this notebook is given. The ratio of \((Q/D)\) taken without and with hydrogen is 1.0392 ± .0017, and the corresponding cross-section \(\sigma = (47 ± 2) \times 10^{-27} \text{ cm}^2\).

The measurement was repeated as recorded on the next page (Fig. 30) using "Slattery fast circuits." The ratio, inverse of the transmission, was 1.0464 ± .0033 and the cross-section calculated from \(\sigma = \ln T/x\) with \(x = 8.15 \times 10^{23}\) hydrogen nuclei per cm\(^2\) is given as \(\sigma = (56 ± 4) \times 10^{-27} \text{ cm}^2\). There were fewer accidentals with the Slattery circuits than with the Martin circuits. These measurements were done with \(\pi^-\) at 137 MeV. It is important to note that the effect was only 4% even though the cross-section was quite large, close to the geometric value.

Figure 31 shows page 24 of the notebook on which Fermi analyzed the data from a measurement of 175 MeV \(\pi^-\) on H, taken October 16, 1951. Background corrections are included explicitly, but none of the others. Again, the effect is 4.4% and the cross-section \(\sigma = (54.1 ± 3.9) \times 10^{-27} \text{ cm}^2\), about the same as at 137 MeV, so the cross-sections were leveling off.
Fig. 26: Energy losses in the beam.
<table>
<thead>
<tr>
<th>Material</th>
<th>Energy Loss $\Delta E$</th>
<th>Thickness</th>
<th>Multiple Scattering $M$</th>
<th>KeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$ Crystal</td>
<td>$5.4 \times 10^{-4}$</td>
<td>-14.0</td>
<td>2.40 $\times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>.005&quot; Al</td>
<td>.29</td>
<td>14.0</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>.005&quot; Cu</td>
<td>2.0</td>
<td>14.0</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>(19 cm H)</td>
<td>(2.2)</td>
<td>(13)</td>
<td>0 or 1.01 $\times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>.005&quot; Cu</td>
<td>2.0</td>
<td>14.0</td>
<td>.88</td>
<td></td>
</tr>
<tr>
<td>.005&quot; Al</td>
<td>.29</td>
<td>14.0</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 27:** Energy loss and multiple scattering in the beam.
Fig. 28: Absorption curve in aluminum.
Fig. 29: Sketch of arrangement for transmission measurements.
Fig. 30: Measurement of total cross section by transmission method, $\pi^-$ on H at 137 MeV.
Measurement of Oct 16 57

Scattering of $\pi^-$ on H

175 MeV channel in reverse (Energy in magnet 226 MeV)

Deflecting magnet set for about 33° deflection

10 min runs (Circuit in defl. magnet 21.75 min)


<table>
<thead>
<tr>
<th>Time (min)</th>
<th>D/10^10</th>
<th>Q/10^10</th>
<th>D/Q x 10°</th>
</tr>
</thead>
<tbody>
<tr>
<td>97.03/6</td>
<td>3.64-70</td>
<td>61.66-07</td>
<td>1.1896</td>
</tr>
<tr>
<td>77.20/10</td>
<td>81.20-52</td>
<td>66.94-08</td>
<td>1.3052</td>
</tr>
<tr>
<td>100.47/10</td>
<td>76.34-82</td>
<td>63.57-09</td>
<td>1.1879</td>
</tr>
<tr>
<td>81.10/10</td>
<td>74.38-68</td>
<td>61.58-07</td>
<td>1.1991</td>
</tr>
<tr>
<td>102.46/10</td>
<td>73.18-82</td>
<td>57.55-40</td>
<td>1.2172</td>
</tr>
<tr>
<td>106.49/10</td>
<td>74.11-85</td>
<td>61.25-09</td>
<td>1.1978</td>
</tr>
<tr>
<td>106.06/10</td>
<td>77.21-85</td>
<td>63.72-80</td>
<td>1.2003</td>
</tr>
<tr>
<td>123.02/10</td>
<td>83.37-92</td>
<td>69.50-11</td>
<td>1.1873</td>
</tr>
<tr>
<td>142.94/10</td>
<td>85.52-92</td>
<td>71.67-11</td>
<td>1.1822</td>
</tr>
</tbody>
</table>

Average $1.19624 \pm 0.00340$

$\sigma = (54.1 \pm 3.9)$

$R = \frac{1.19624}{1.1465} = 1.04507 \pm 0.0087$

$\sigma = 0.04806 \pm 0.0037$

$\sigma = (54.1 \pm 3.9)$

Average $1.14465 \pm 0.00160$

Data for BG corrections

\[
\frac{S_1}{\text{cm}^2} = 12.84, \quad \frac{S_2}{\text{cm}^2} = 13.77, \quad \frac{D_{34}}{\text{cm}^2} = 4.46, \quad \frac{BG}{\text{cm}^2} = \frac{10^{10} (D_{34} - 977)}{1377 - 1377} \cdot \frac{BG_{34}}{\text{cm}^2}
\]

\[
\frac{BG_{34}}{\text{cm}^2} = \frac{(S_1 - D_{34}) (S_2 - D_{34})}{60} \cdot \frac{BG_{34}}{\text{cm}^2}
\]

\[
= \frac{(1322 - 70)(1347 - 76)}{60} \cdot \frac{BG_{34}}{\text{cm}^2} = 0.0887
\]

Fig. 31: $\pi^-$ on H cross section at 175 MeV.
Cross Section for $\pi^+$

The $\pi^+$ measurements are given in another notebook that Fermi labeled Vol IV, December, 15, 1951--. The back page of this notebook has an index, written in Fermi's hand that is reproduced in Fig. 32. The portions that I want to present here are the 122 MeV $\pi^+$ measurements on liquid hydrogen, pages 32 to 36, and the 145 MeV $\pi^+$ measurements, also on hydrogen, pages 49 to 53. The arrangement was sketched by Fermi on page 32 on December, 21, 1951 (Fig. 33). In this case aluminum was used to compensate for the effect of multiple scattering in the liquid hydrogen and a calculation of the proper position for the hydrogen target is shown. Fermi noted the photomultiplier high voltage settings and the cable lengths. The measurements begin on page 33 (Fig. 34) and continue through page 35 (Figs. 35, 36). The sequence is ABBA: $H_{in}, H_{out}, H_{out}, H_{in}$, repeated three times. The first measurement started at 11:38 AM. At 12:38 the handwriting changes from Fermi's to mine. At 13:40 it's Fermi's handwriting again until the end of the measurement at 15:16. It was clear from the first sequence of four measurements that something unusual was going on. There was a 7% effect and this was so much greater than anything we had seen before that it left Fermi shaking his head in wonder. The $\pi^-$ values had been large, but they had leveled off close to the geometrical value. Here we were finding a $\pi^+$ cross-section that was substantially larger still. According to my recollection I had received, on that day, a preprint from Keith Brueckner in which he showed that the $\pi^+/\pi^-$ ratio could be explained in terms of a nucleon isobar with spin 3/2 and isotopic spin 3/2. Fermi expressed skepticism at first. It seemed like a wild guess. But I could read from the graphs that Brueckner was predicting a cross-section of 88 mb. Our value was coming out to be 83 mb. It was pretty close, and the agreement would be even better after corrections. At this point Fermi reached for the paper and asked to be excused. He returned a short time later with a broad grin on his face. He announced, with evident satisfaction, that the cross-sections

\begin{center}
\begin{tabular}{ll}
122 $\pi^-$ & $\sigma(D) - \sigma(H)$ \\
122 $\pi^+$ & $\sigma(H)$ \\
122 $\pi^+$ & $\sigma(H)$ with Be block \\
122 $\pi^+$ & Al abs. curve with Be block \\
145 $\pi^\pm$ & Gen. data + target position \\
145 $\pi^+$ & $\sigma(D) - \sigma(H)$ \\
145 $\pi^+$ & $\sigma(H)$ \\
145 $\pi^-$ & $\sigma(H)$ \\
145 $\pi^\pm$ & Absorption curves in Al \\
\end{tabular}
\end{center}

14 - 31  32 - 36  38 - 40  41  42 - 43  45 - 46  47 - 48  49 - 53  54 - 55  57 - 58

Fig. 32: Index to one of Fermi's notebooks.
Fig. 33: Arrangement for measurement of cross section of 122 MeV \( p^+ \) on liquid hydrogen.
Fig. 34: Measurement of 122 MeV Tl\(^+\) on liquid H.
Table showing measurements at 122 MeV continued.

<table>
<thead>
<tr>
<th>Time</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
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<td>330</td>
<td>360</td>
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<td>31.5</td>
<td>320</td>
<td>330</td>
<td>340</td>
<td>350</td>
<td>360</td>
<td>370</td>
</tr>
<tr>
<td>33.6</td>
<td>340</td>
<td>350</td>
<td>360</td>
<td>370</td>
<td>380</td>
<td>390</td>
</tr>
<tr>
<td>35.1</td>
<td>360</td>
<td>370</td>
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<td>390</td>
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<td>410</td>
</tr>
<tr>
<td>35.9</td>
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<td>380</td>
<td>390</td>
<td>400</td>
<td>410</td>
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<td>390</td>
<td>400</td>
<td>410</td>
<td>420</td>
<td>430</td>
<td>440</td>
</tr>
<tr>
<td>36.2</td>
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<td>410</td>
<td>420</td>
<td>430</td>
<td>440</td>
<td>450</td>
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</table>

Fig. 35: Measurement at 122 MeV continued.
Fig. 36: Measurement at 122 MeV continued.
would be in the ratio 9:2:1 for the reactions in which the final states were $\pi^+$, $\pi^0$, and $\pi^-$, respectively. The isotopic spin $3/2$ interaction was very strong.

To see how firmly Fermi had taken hold of the idea that this might be a resonance, I looked up the notebooks he used when he worked in his office. These show that on December 24, 1951, he had written on page 91 (Fig. 37) the charge states corresponding to total isotopic spin $3/2$ and $1/2$ using the appropriate Clebsch-Gordon coefficients. On the next page (Fig. 38) he wrote the wave function of the incident plane wave for scattering due to a virtual $p^+\pi^-$ state. On page 93 (Fig. 39) is a derivation of the cross section, in the Breit-Wigner form, for scattering from such a resonant state. The next page, 94 (Fig. 40), is dated December 25, 1951. Fermi had written the expressions that take into account both the isotopic spin and the ordinary spin. The next page, 95 (Fig. 41) carries the heading, "Assuming scattering due to a single level resonance of a state $I = 3/2, J = 3/2$." On this page the phase shift is introduced and the theory is developed further on the next (Fig. 42) and succeeding pages (not shown) to include the $\pi^-p$ scattering.

![Fig. 37: Pion-proton states for isotopic spin 3/2 and 1/2.](image)
The entries in the notebook were interrupted after December 26, 1951 until January 3, 1952 because on December 27, we had a new run on the cyclotron and we set up to do the $\pi^+$ scattering at the next and highest energy, 145 MeV. These were recorded in the lab notebook starting on page 49 (Fig. 43) that shows the geometry used. The measurements of transmission are given on pages 50, 51, and 52 (Figs. 44, 45, and 46, respectively). We now had an unprecedented 11% effect and a cross section that continued to rise in accordance with Brueckner's predictions. After corrections, the cross section at 136 $\pm$ 6 MeV turned out to be $(152 \pm 14) \times 10^{-27}$ cm$^2$, about 3 times the geometric value. The cross section was as large as it could be; Fortune was smiling at us.

All the values of the total cross section for $\pi^+$ and $\pi^-$ in hydrogen were published in a series of Letters to the Editor of the Physical Review in the March 1, 1952 issue. They are shown on a plot on the single page on which the positive pion results were reported. The values included the corrections for accidentals, geometry, pion decay in flight, electron and muon contamination of the beam, and
proton recoil. The plot also included the measurements made at Brookhaven and Columbia. The page is reproduced in Fig. 47.

A key statement in this paper is the one that reads, "We might point out in this connection that the experimental results obtained to date are also compatible with the more general assumption that in the energy interval in question the dominant interaction responsible for the scattering is through one or more intermediate states of isotopic spin 3/2, regardless of spin. On this assumption, one finds that the ratio for the three processes should be (9:2:1), a set of values that is compatible with the experimental observations. It is more difficult, at present to say anything specific as to the nature of the intermediate state or states. If there were one state of spin 3/2, the angular distribution for all three processes should be of the type 1 + 3 cos^2 θ. If the dominant effect were due to a state of spin 1/2, the angular distribution should be isotropic. If a state of higher spin or a mixture of several spin states were involved, more complicated angular distribution would be expected." It turned out that Brueckner had made the correct choice and it was the
Fig. 40: Expressions in which both isotopic spin and ordinary spin are included.

state with spin 3/2, now known as the $\Lambda_{33}$, that was dominant. However, demonstration that this was the case required measurements of the angular distribution and their analysis by the phase shift method. We quickly learned about Clebsch-Gordan coefficients and phase shift analysis, and set about doing the measurements of angular distribution, forthwith.

Figure 48, taken from the preprint Brueckner had sent me, shows the fit he obtained for the $\pi^-$ cross sections. Before his paper appeared in print, Brueckner added the fit to the $\pi^+$ cross sections we had reported at the Rochester Conference on Meson Physics, held in Chicago, January 11 to 12, 1952. The overall fit shown in Fig. 49 was remarkably good. The trend of the experimental data favored the 3:1 ratio expected for a pure isotopic spin interaction even more closely than in Brueckner's calculations.
Fig. 41: Scattering from a single level resonance of a state \( I = \frac{3}{2}, J = \frac{3}{2}, \ell = 1 \).

Phase Shift Calculations

We carried out so many angular distribution measurements in the next six months that Fermi began to think that the phase shift problem might best be handled with a computer. We had already published a short report giving the phase shifts we had calculated by hand. A more complete report was published the following year. During this period, Fermi liked to spend the summer in Los Alamos. This time, in the Summer of 1952 he could have an electronic computer at his disposal. The computer was the MANIAC, built at Los Alamos by Nicholas Metropolis, a close friend, who stood ready to guide his efforts. It was typical of Fermi to learn how the computer worked in sufficient detail to be able to operate it himself. Many of Fermis' notes and letters of this period have been preserved by Metropolis, to whom I'm indebted for the ones I show you now.

Figure 50 is a sample page from Fermi's Los Alamos notes. It is a description of a program he had designated A-7-2-5, having to do with fitting the data and finding the coefficients and cross sections for the angular distribution measurements.
Fig. 42: Scattering of $\pi^-$ as well as $\pi^+$. Figure 51 refers to the operation of this code. Figure 52 displays the phase shift formulas adapted for computer calculation. Fig. 53 is a flow diagram drawn by Fermi. Figure 54 is a sample of a program he wrote.

It became a straightforward matter to find the phase shifts that gave a good fit to the data with an electronic computer like the MANIAC. It took only five minutes once the program was in place. The trouble was that the computer found several sets of phase shifts. The phase shifts showed a plausible behavior at low energies. However, as these were followed to higher energies, among the set of phase shifts that seemed to fit the data best, the phase shift $a_{33}$, corresponding to the $I = 3/2, J = 3/2$ state reached a maximum and turned down again without going through 90°. This was unexpected and indicated the need for further work. Fermi’s reaction is shown in a letter to Metropolis, dated April 9, 1953 (Fig. 55). The problem was that the computer, given the freedom to manipulate six phase shifts without restraint, was able to find combinations that gave good fits to the data but with a non-resonant $a_{33}$. In the meanwhile, Hans Bethe, also a regular summer visitor to Los Alamos, interested himself in the problem and, working with deHoffman, Metropolis, and Adler, added plausible physical constraints that led the MANIAC to a solution that showed a resonant behavior for $a_{33}$. Two of the Chicago graduate students took
Fig. 43: Arrangement for 145 MeV π⁺ on liquid H.
Fig. 44: Transmission of 145 MeV π⁺ on liquid H.
<table>
<thead>
<tr>
<th>Hour</th>
<th>25.8</th>
<th>29.8</th>
<th>33.75</th>
<th>37.8</th>
<th>49.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al in</td>
<td>31.6</td>
<td>33.5</td>
<td>37.1</td>
<td>40.5</td>
<td>44.3</td>
</tr>
</tbody>
</table>

**Fig. 45:** Transmission measurement at 145 MeV continued.
Fig. 46: Transmission measurement at 145 MeV continued.