Enrico Fermi – The Complete Physicist

Amit Roy

Amit Roy is currently Raja Ramanna Fellow at Variable Energy Cyclotron Centre, Kolkata after spending more than two decades each at Tata Institute of Fundamental Research, Mumbai and Inter-University Accelerator Centre, New Delhi.

Enrico Fermi was a versatile physicist contributing in equal measure to theory and experiments. He is credited to be the 'Father of the Atomic Age' following his successful demonstration of sustained chain reaction in Chicago Pile-1. In this article, I have discussed his major experimental contributions that clearly demonstrate his simplicity of conception, meticulous attention to detail and directness of approach to the problem at hand.

History of science is replete with towering intellects that have influenced and shaped the direction of development of the field. Of these, some are known for their experimental discoveries while others for their theoretical breakthroughs. Only a few exceptional physicists have contributed in equal measure to both theory and experiment like Archimedes and Newton. Enrico Fermi was a physicist in the same mould and possibly the only one of this class in the 20th century. His seminal contributions to the statistical behaviour of particles, beta decay, transport problems and a brief account of his life have appeared in an earlier issue of *Resonance*[1].

[1] See *Resonance*, Vol.19, No.1, 2014.

Enrico Fermi is credited to be the 'Father of the Atomic Age' that ushered in the exploitation of nuclear energy both in its civil and military applications. He was honoured by the Nobel Prize "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons".

Keywords
Neutron-induced radioactivity, fission, chain reactiom, nucleon resonance.

In this article, I shall discuss his experimental activities, focussing on his three major adventures, each opening up new dimensions of research, viz., the neutron induced radioactivity work at Rome, the work on chain reaction and establishment of the first nuclear reactor at Chicago and finally the discovery of resonant excited state of the proton at Chicago. Each of these experiments bear the stamp of the master; simplicity of conception, meticulous attention to detail and directness of approach to the problem at hand.

Each of these experiments bear the stamp of Fermi; simplicity of conception, meticulous attention to detail and directness of approach to the problem at hand.

Neutron Induced Radioactivity

The neutron was discovered by James Chadwick at Cambridge in 1932 by bombarding beryllium with α-particles. In Paris, Irene Curie and Frederick Joliot had succeeded in observing radioactivity induced by α-particles in boron, magnesium and aluminium creating new radioactive elements. Till then, radioactivity was thought to be a natural property of certain heavy elements like uranium, thorium, radium, etc. Fermi was intrigued by these discoveries and wanted to pursue the study of artificial radioactivity. Till that time, apart from his thesis for which he did experimental work on X-rays (PhD was not awarded for theoretical physics in Italy at that time), his research work was all theoretical. He had already formulated the antisymmetric statistics that is known as Fermi–Dirac statistics and the theory of beta decay. Fermi decided to switch to experiments and chose neutrons over α-particles as projectiles for his quest of artificial radioactivity although the flux of neutrons available was lower than that of the α-particles. Neutrons were produced as a result of bombarding a Be target with α-particles from a radioactive source. He reasoned that the neutron being a neutral particle would be able to penetrate the nucleus without facing the Coulomb repulsion encountered by the positively charged α-particle. Thus his chances of producing new radioactive elements would be higher. This would be especially true for the case of heavy elements where the cross section for α-induced reactions would decrease exponentially (*Box* 1).

Fermi reasoned that the neutron being a neutral particle would be able to penetrate the nucleus without facing the Coulomb repulsion encountered by the positively charged α-particle.

Box 1. Flux of Neutrons

For a radon source (half-life ~ 3.824 days) of strength 800 mCi, the number of α-particles emitted is $\sim 3 \times 10^{10}$/sec.

Energy of these α-particles = 5.489 MeV. Neutrons are produced by bombarding Be with these α-particles,

$$\begin{aligned} \alpha + {}^{9}\mathrm{Be} \;\Rightarrow&\; {}^{12}\mathrm{C} + \mathrm{n} + 4.692\mathrm{MeV} \\ \Rightarrow&\; {}^{12}\mathrm{C}^{*} + \mathrm{n} + 0.29\mathrm{MeV}. \end{aligned}$$

$N_{\mathrm{n}}/N_{\alpha} \sim 2 \times 10^{-5}$, therefore $N_{\mathrm{n}} \sim 6 \times 10^{5}$/sec.

Neutrons do not have charge and hence do not lose energy in ionizing matter as α-particles do. Hence the thickness of the target which effectively contributes to the reaction is much larger. This fact alone gives a factor of the order of one hundred in favour of the neutrons.

The cross section for neutrons is a large fraction of the geometric cross section, while in the case of charged particles the cross section is strongly reduced by the 'Gamow factor = $\exp(-E_{\alpha}/V_{\mathrm{c}})$' representing the penetrability of the electrostatic potential barrier, where E_{α} is the energy of the α-particle and V_{c} is the Coulomb potential $= e^{2}Z_{1}Z_{2}/E$. This last factor reduces the cross section by a large amount for nuclei with high atomic numbers.

Fermi had attracted several talented experimenters around him at the University of Rome that included Emilio Segre, Eduardo Amaldi, Franco Rasetti, D'Agostino, and Bruno Pontecorvo. They got busy in doing the experiments with a very simple arrangement. First they needed a neutron source. Earlier experimenters produced neutrons using α-particles from either Po or Ra bombarding a Be target.

Fermi wanted to maximize the yield of the neutrons and for this he used the gaseous source, radon (a daughter product of radium), that could be thoroughly mixed with Be metal powder in a sealed glass tube. The material to be bombarded was kept as close as possible around the source. Materials that needed chemical treatment after bombardment were in the form of concentrated water solutions in a test tube. Since the neutrons were accompanied by γ-rays from the α-source as well

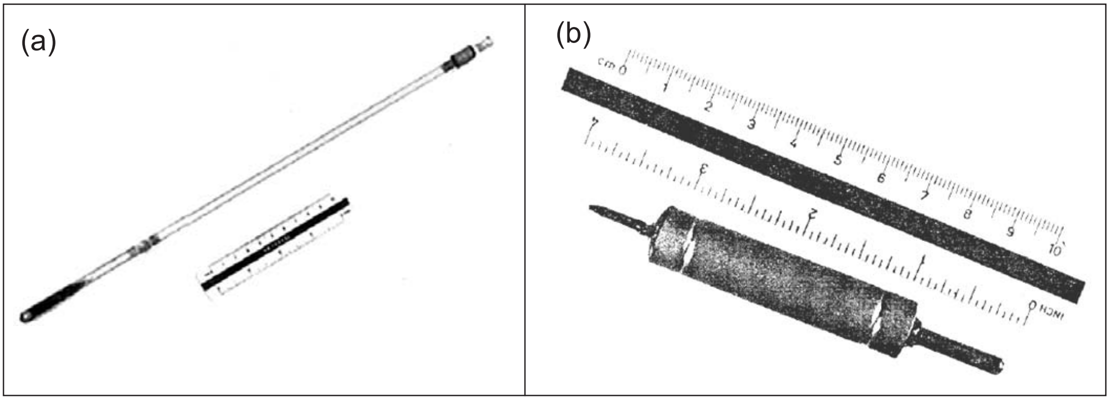

Figure 1a. Photograph of one of the radon α + Be sources used in Rome in 1934–1936. The long glass tube is used only for handling the source without having the hand of the operator exposed too heavily to the gamma radiation emitted by the decay products of Rn.

Figure 1b. One of the GM counters used in 1934 by Fermi's group. The Al wall was between 0.1–0.2 mm thick. The small cylinder was obtained by cutting the bottom of a box of medical tablets.

(Reprinted with permission from *Physics Reports*, Vol.111, Nos.1–4, 1984 pp.1–332. North-Holland, Amsterdam.)

as from the reaction on Be, the radioactivity induced in the sample was counted with a Geiger–Mueller counter at a location far away from the n-source. Photographs of a neutron source and a GM counter used in the experiments are shown in *Figures* 1a and 1b. The GM counters were made in their laboratory with the help of his colleague Rasetti. They also checked that the γ-rays from the α-source without any Be present had no effect on the samples. To maximize the counting efficiency, the activated samples were made in the form of cylinders fitted around the GM counter. Fermi and his collaborators bombarded elements in the order of increasing atomic number from hydrogen, followed by lithium, beryllium, boron, carbon, nitrogen and oxygen all with negative results. Fluorine was the first element in which they observed induced radioactivity with a half-life of $\sim$9 sec emitting high energy β-rays. Fermi's thoroughness is clear from the way they investigated nearly all the elements available with their chemical supplier in Rome, numbering about 60 starting with hydrogen and ending with uranium. They found induced radioactivity in about 40 of these and measured their half-lives.

Fermi's thoroughness is clear from the way they investigated nearly all the elements available with their chemical supplier in Rome.

When he replaced the Pb absorber by paraffin between the neutron source and the Ag sample, the activity increased appreciably.

They also measured the intensity of the radiation emitted as well as its absorption in Al screens of different thicknesses. By applying a magnetic field, they identified the emitted radiation to be electrons in most of the cases and accompanied by gamma radiation in some cases. In some elements evidence was found for alpha or proton emission. Even though the intensities of the activities produced were not measured with too high an accuracy, they could conclude that the production cross sections were close to the geometrical cross sections of the nuclei. This showed that a large percentage of the neutrons that hit the nucleus were effective in producing radioactivity.

Fermi wanted quantitatively more accurate numbers on the cross sections and assigned this task to Amaldi and Pontecorvo. He wanted to standardise the conditions for irradiation so that reproducible results were obtained. For this purpose he chose the element Ag in which the activity with 2.3 min half-life was produced. They found that the activation depended on the surrounding material. The sample of Ag irradiated on a wooden table was more active than that irradiated on a marble table. They decided to interpose different materials between the source and the samples, changing their relative positions. Fermi learned of the results and wanted to make the measurement himself. When he replaced the Pb absorber by paraffin between the neutron source and the Ag sample, the activity increased appreciably (>50 %). Fermi correctly interpreted the increase as being caused by neutrons which were slowed down by elastic collisions with protons in paraffin. The same afternoon, they repeated the experiment with the source and Ag target dipped in the pool of water in the fountain in the garden of the institute and verified that the increased activity was due to slowing down of neutrons by hydrogen in water.

They realized that with the higher cross sections for slow neutrons, production of artificial radioactivity for other applications, especially in medicine was a distinct possibility.

They realized that with the higher cross sections for slow neutrons, production of artificial radioactivity for other applications, especially in medicine was a distinct possibility and a patent was filed. The activities induced by slow neutrons were also measured systematically for a large number of elements from hydrogen to uranium. These experiments led to the identification of the existence of absorption bands; i.e., many nuclides for which neutrons with kinetic energy falling in some characteristic bands of target nuclei are resonantly absorbed.

Fermi's interpretation of neutron-induced artificial radioactivity was correct for all the elements except in the case of uranium.

This work provided impetus to the development of the compound nuclear model by Niels Bohr and co-workers (*Box* 2) and was an important contribution to the understanding of nuclear reactions.

Fermi investigated the dependence of the cross sections on neutron velocity and deduced that it followed the $1/v$ law. He found that a paraffin sphere of about 10 cm radius was enough to thermalize the neutrons and a larger amount of paraffin was not necessary. Fermi also worked out the theory of neutron diffusion and the motion of neutrons in hydrogenous media, which he later applied to his work on the nuclear reactor.

Fermi's interpretation of neutron-induced artificial radioactivity was correct for all the elements except in the case of uranium, in which activities with four different half-lives were identified. For all lighter elements, he

Box 2. Neutron Resonances and Compound Nucleus

The mechanism of neutron capture by a nucleus was not at all clear. The time for a neutron to cross the nuclear diameter is $\sim 10^{-21}$ sec. This is the time the neutron spends for a direct capture. If one calculates the probability of emission of a γ-ray during this time it would be much smaller than what was observed. Bohr postulated that the energy deposited in the nucleus gets shared between all the nucleons through a large number of collisions which results in a long lifetime for the compound nucleus. The energy is emitted through a statistical process after a much longer time $\sim 10^{-16}$ sec and the cross section for such a process could be much larger. Neutrons could be resonantly absorbed if their energy plus the binding energy matched that of an energy level in the compound nucleus.

had correctly interpreted the activity to be the result of neutron capture to produce a heavier isotope of the element bombarded that would usually beta decay resulting in the element with the next higher atomic number. He cautiously extended the same mechanism for the activities to be due to production of a heavier isotope of U that beta decays to produce the element with atomic number 93. Following the results of Fermi's group, others, notably among them, I Curie and F Joliot in Paris and L Meitner, O Hahn and F Strassmann in Berlin repeated the same experiments on U and observed similar activities as reported by Fermi's group. However, Curie and Joliot while trying to chemically separate the activities found that some of the activity had the chemical behaviour similar to lanthanum but did not identify it conclusively. Hahn and Strassmann (by then Meitner had left Germany because of the loss of her position due to Nazi politics) following more detailed chemical separation came to the conclusion that at least one of the activities produced was certainly an isotope of barium, an element with atomic number close to half of uranium. This indicated a hitherto unknown phenomenon taking place in neutron bombardment of U Meitner and Frisch interpreted these results to be due to splitting of the nucleus and termed the process 'fission'. It is quite surprising that Fermi and his group did not pursue the work on U any further, although a German scientist, Ida Noddack had suggested the possibility of elements of much smaller atomic number being produced on neutron bombardment of U (*Box* 3).

Box 3. Fermi and Fission

The citation of the Nobel award to Fermi mentions his demonstrations of the existence of new radioactive elements. This probably referred to the transuranic elements that were thought to be produced by neutrons bombarding on uranium. By the time Fermi gave the Nobel Lecture in December 1938, Hahn and Strassmann had confirmed that neutron bombardment of uranium resulted in much smaller nuclei like Ba and not transuranic elements, although their results were not published till January 1939. However, among

Box 3 continued

Box 3 continued

the fission products there was also one component of the activities with half-life of 23 min, and this activity was later identified to belong to an element with atomic number 93. Fermi always felt bad about the mistake in interpreting the uranium data. Jay Orear in the book *Enrico Fermi: The Master Scientist* writing about T D Lee says that when he came to Chicago to enrol as a graduate student, Fermi showed him the blueprints of the Institute of Nuclear Studies then under construction. In the blueprint was a figure of a man standing by the front door. Fermi pointed out to the man and said to Lee, "That is the man who made the great mistake".

Sustained Chain Reaction

Fermi started the second phase of his scientific career in USA, which was as remarkable as the first phase in Italy. Very soon, after he joined Columbia University as a professor, news of the fission phenomenon reached him and his colleagues through a visit of Niels Bohr. He lost no time in devising experiments to verify the phenomenon. It was apparent to everyone studying fission that it held the potential of releasing a tremendous amount of energy and they looked for means to have a sustained way of this energy release. The idea of a chain reaction was already patented by Leo Szilard in 1934 soon after the discovery of neutron and he was looking for a nucleus to multiply neutrons. Two conditions were required to be met for sustaining a chain reaction. First, it was essential that more than one neutron is released in the fission process initiated by the capture of a neutron and second was that the neutrons generated are able to interact with other U nuclei and do not escape or get absorbed by other elements present. A uranium nucleus has many more neutrons than protons from stability considerations. The fission products having much lower atomic numbers require relatively lower neutron numbers to be stable and one way to reduce the n-number was through beta decay or emitting neutrons. This was realized by many including Fermi and they all got busy to determine the excess neutrons emitted in the fission process.

The idea of a chain reaction was already patented by Leo Szilard in 1934 soon after the discovery of neutron.

Fermi decided to test this in a geometry with a large amount of U to estimate the neutron production and absorption by U with his student H L Anderson and Szilard.

In France, Joliot and his co-workers were the first to show that more than one neutron was generated in the fission of uranium. Fermi's colleagues, L Szilard and W Zinn at Columbia also measured the number of neutrons emitted in fission and came up with the number of about two per fission. Fermi decided to test this in a geometry with a large amount of U to estimate the neutron production and absorption by U with his student H L Anderson and Szilard.

Several other technical questions had to be answered before establishing a chain reaction.

Several other technical questions had to be answered before establishing a chain reaction. Since the fissioning isotope was the rare ^{235}U with only 0.7% natural abundance, the majority of the neutrons would interact with ^{238}U and would not contribute to the fission process. Since the processes for the enrichment of ^{235}U had not been developed and would be costly as well as time consuming, Fermi decided to use the available natural uranium as it gave him the advantage of starting immediately without waiting for the enrichment of the ^{235}U isotope. It was necessary to determine precisely the rates of neutron capture by the two isotopes. Initial experiments showed that the capture rate for slow neutrons would be less for ^{238}U, and hence a method had to be found to slow the neutrons down from energies at which they were emitted in the fission process without losing them.

They took a cylindrical tank of 90 cm diameter and 90 cm high and filled it with 540 litres of 10% $MnSO_4$ solution as shown in *Figure* 2. The n-induced activity

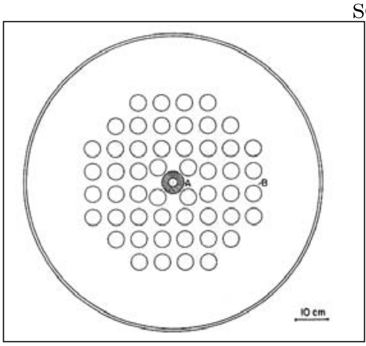

Figure 2. Horizontal section through the center of a cylindrical tank, which is filled with 540 liters of 10% MnS_{O4} solution. A: Photo-neutron source composed of 2.3g of radium and 250g of beryllium. B: One of 52 cylindrical cans 5 cm in diameter and 60 cm in height, which are either empty or filled with uranium oxide.

(Reprinted with permission from H L Anderson, E Fermi and Leo Szilard, *Physical Review*, Vol 56, 284, 1939. © 1939 by the American Physical Society.)

of Mn (half-life of ∼2.6 hrs) was used as a measure of the number of neutrons. 52 cylindrical cans of 5 cm diameter and 60 cm in height were arranged near the centre of the tank and some were left empty and others filled with uranium oxide (U_3O_8). A total of 200 kg uranium oxide was used, sufficient to give an average over a geometric distribution and to ensure a high probability of interaction of neutrons with U. The tank design also took care to ensure that most of the generated neutrons would get absorbed in the tank. From their measurements they found that at least 1.5 neutrons were effectively produced per fission induced by an incident neutron. Fermi also measured the velocity of neutrons using apparatus that was designed by him, consisting of two sets of rotating disks with slots and mechanical shutters. These developments were forerunners of the future generation of neutron spectrometers.

Fermi decided to use the available natural uranium as it gave him the advantage of starting immediately without waiting for the enrichment of the ^{235}U isotope.

The measurements allowed Fermi and Szilard to plan out a 'reactor pile' for testing the feasibility of a sustained chain reaction. Fermi had realised that deuteron was the best nucleus for slowing down and thermalizing neutrons. Protons, although most effective in reducing the energy of neutrons through collisions, would also absorb a good fraction of the slow neutrons. However, the natural abundance of deuteron is only ∼0.01% and the process of purification of heavy water from normal water would be very costly. Szilard suggested the use of carbon (graphite) to be the moderator for neutrons. Fermi knew that carbon has a low cross section for absorption of neutrons and agreed to the suggestion. It is also a reasonably light element available in large quantities in pure and elemental form.

The measurements allowed Fermi and Szilard to plan out a 'reactor pile' for testing the feasibility of a sustained chain reaction.

To be doubly sure, Fermi decided to build a small 'atomic pile' as a stack of pure graphite bricks surrounding a neutron source to experimentally determine the effect of graphite on neutron activity, absorption, re-emission and fission. Next he added uranium by rebuilding the

To be doubly sure, Fermi decided to build a small 'atomic pile' as a stack of pure graphite bricks surrounding a neutron source.

From these early experiments and calculations Fermi could establish that instead of a uniform distribution of U in graphite, a lattice containing either layers or blocks of graphite and U in a certain ratio reduced the probability of neutron absorption by ^{238}U.

graphite brick stack with some of the bricks loaded with U. From these early experiments and calculations, Fermi could establish that instead of a uniform distribution of U in graphite, a lattice containing either layers or blocks of graphite and U in a certain ratio reduced the probability of neutron absorption by ^{238}U. He extended his work on neutron diffusion done in Rome for developing the theory of neutron diffusion in a pile that is known as the Fermi Age Theory and is of great importance to the design of a reactor.

The difference between his experimental pile at Columbia and a controlled chain reaction pile was that the size had to be large enough to contain the neutrons escaping from the surface of his experimental pile. He also established that impurities present in either graphite or uranium were able to absorb neutrons and some of them, even in small amounts, were enough to kill the chain reaction. To gather the required amount of graphite and uranium of the required purity needed a large-scale effort. This happened with the establishment of the Manhattan Project and Fermi shifted his work on chain reaction to the University of Chicago in 1942. A large industrial effort was mounted to produce the required amounts of pure graphite and uranium for the project.

To gather the required amount of graphite and uranium of the required purity needed a large-scale effort.

The reactor named Chicago Pile (CP1), assembled in an unused squash court at University of Chicago, consisted of alternate layers of graphite and uranium in the predetermined ratio. Cadmium having a very large cross section for absorption of neutrons was chosen to control the reaction. Cd strips attached to wooden rods were embedded in the lattice to act as control rods. In addition, the pile was provided with two safety rods and one automatic control rod, all operated by electric motors. As a precaution, it was decided to enclose the pile in a balloon cloth bag which could be evacuated to remove the neutron-capturing air. Eventually, the bag was left open since the progress of neutron multiplication as the pile grew showed that criticality could be obtained even in the presence of air. Along with Fermi there was a highly talented group of scientists and engineers, notable among them, E Wigner, L Szilard, W Zinn, and H L Anderson, who worked round the clock in two 12-hour shifts. It is a testimony to Fermi's careful and detailed work on experimental piles and his understanding of the details of the behaviour of neutrons that the assembly of the reactor pile CP1 proceeded exactly according to the plans laid out by him. A series of measurements were made as the pile was assembled to ensure that critical assembly was not reached inadvertently without taking proper precautions. The neutron count rates were constantly monitored to check the multiplication properties of the pile so that the critical point could be determined before it was reached. The assembly was completed with all the control rods in place and on the morning of Dec 2, 1942, with all the co-workers assembled, Fermi asked his co-workers to remove the Cd control rods one by one and kept monitoring the neutron counts, quickly making calculations to check whether the reaction was proceeding as predicted.

The assembly was completed with all the control rods in place in December 1942.

Fermi's calm and confident nature was amply demonstrated by an incident at a crucial time in the experiment. With the neutron count rate climbing up, the experiment got unexpectedly interrupted before noon as one of the safety rods slammed in. It was soon realised that the set point was kept too low, but instead of continuing, Fermi ordered a break for lunch. In the afternoon after the set point was corrected, the experiment resumed and the last control rod was withdrawn to the exact extent asked for by Fermi. The neutron counts kept on increasing without levelling off indicating the occurrence of a sustained chain reaction. After allowing the chain reaction to run for about half an hour, Fermi had the control rods put back in, stopping the chain reaction. This established that not only the fission chain

Fermi's calm and confident nature was amply demonstrated by an incident at a crucial time in the experiment.

After this momentous event, Fermi was drawn into the war effort towards building of the atomic bomb.

reaction was sustainable but could also be controlled, opening up the possibility of building reactors for energy generation.

After this momentous event, Fermi was drawn into the war effort towards building of the atomic bomb in the Manhattan Project. He had set up the next reactor pile at the Argonne site near Chicago and made extensive measurements with his group on different aspects of reactor design. He discovered that the element plutonium (Pu) had a high rate of spontaneous fission and measured its interaction properties with neutrons. This led to the setting up of a reactor at Hanford exclusively for Pu production and the design of a Pu bomb.

The US army wanted to present him with an instrument of his choice for research for his contributions to the US war effort.

The project culminated in the test of the first atomic bomb on 16 July, 1945 at Alamogordo, New Mexico and the dropping of a uranium bomb on Hiroshima on 6 August, 1945 and a plutonium bomb on Nagasaki on 9 August, 1945.

Varied Physics Interests at Chicago

After the war, Fermi moved to the University of Chicago in 1946 and the US army wanted to present him with an instrument of his choice for research for his contributions to the US war effort. Fermi chose to have a cyclotron to continue his investigations into nuclear interactions. The US Naval office decided to build a 450 MeV synchrocyclotron for his use.

Nine remarkable papers came out of this research during 1946–47 and opened the area of neutron physics.

While working on the reactors, Fermi became interested to exploit the intense neutron flux from a reactor for experiments. On coming to Chicago, he and his collaborator Leona Marshall utilized the CP-3 reactor at Argonne site for experiments. Nine remarkable papers came out of this research during 1946–47 and opened the area of neutron physics. These were on neutron diffraction by crystals, determination of magnetic properties, showing the importance of neutron scattering for determination of solid state properties. Many of the techniques like velocity measurement of slow neutrons, pulsing of neutrons, total reflection of neutrons, etc., were devised by him. He also made an attempt to detect the interaction between neutrons and electrons to probe the structure of the neutron.

Around that time, some exciting results from the study of cosmic rays caught Fermi's attention. This was the result reported by a group in Rome that negative mesotrons (old name for mesons, first discovered by Anderson and Neddermeyer in 1937) when brought to rest in carbon did not appreciably get absorbed by carbon nuclei, as would be expected if they were the mesons postulated by H Yukawa in 1935. Instead they were decaying in about 10^{-6} sec into an electron and possibly a neutral particle. This meson was later identified to be the mu-meson or 'muon', a name coined by Fermi. The meson responsible for nuclear strong interaction predicted by Yukawa was discovered in 1947 by C F Powell and collaborators at Bristol and is termed as the 'pion'. B Rossi and M Sands had looked into the stopping of muons in carbon but found that the number of decays observed were less than the expected number.

J Steinberger had just then joined as a PhD student and was looking for a thesis topic in theoretical physics. Fermi suggested to him to look into this anomalous result of stopping of muons in carbon. Steinberger reasoned that this may be due to the decay electrons having an energy lower than expected in a two-body decay of the muon. Fermi urged him to do the measurements and by the summer of 1948, Steinberger measured the electron energy distribution in muon decay and found it to be a continuum. This clearly showed that the muon undergoes a three-body decay, probably into an electron and two neutral particles. The determined rate of three-body decay could be understood using the concept of a universal weak interaction, a generalization of the Fermi

The determined rate of three-body decay could be understood using the concept of a universal weak interaction, a generalization of the Fermi theory of beta decay.

Fermi contributed in many ways to the construction of the cyclotron at Chicago.

theory of beta decay. Till that time the only weak interaction mediating reaction known was beta decay. It was Bruno Pontecorvo, another student of Fermi from his time in Rome, who pointed out the equivalence of the nuclear capture rates of negative muon and of electrons, if allowance is made for the difference in size of their atomic orbits. Steinberger went on later to establish the existence of two neutrinos along with L Lederman and M Schwartz, for which they were awarded the Nobel Prize in 1988.

Fermi contributed in many ways to the construction of the cyclotron at Chicago. He calculated the orbits of the pions from the production point (target) to the experimental area using the MANIAC electronic computer at Los Alamos. He helped in the setting up of the beam lines, assembling scintillation counters and even wiring some of the electronic circuits. He designed and built an electric cart (called Fermi Trolley and shown in *Figure* 3) in which a Be target for production of mesons would be mounted. The cart would be moved along the rim of the magnet using the field of the main cyclotron magnet as the stator of the cart's motor. This very conveniently eliminated the need to provide a series of targets that would need to be moved across the vacuum barrier in and out of the beam for working at different energies. He also devised a simple way to measure the intensity of the internal beam by measuring the increase in temperature of the target using a thermocouple.

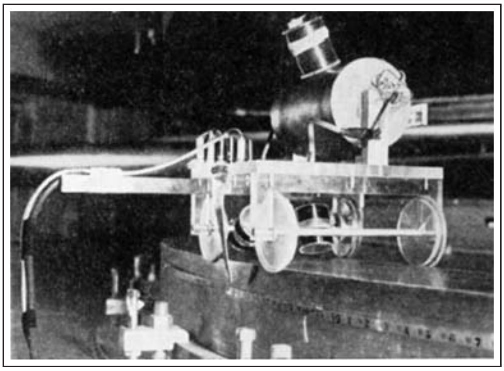

Figure 3. Trolley built for carrying target in the synchrocyclotron at University of Chicago by Enrico Fermi. (Reprinted with permission from H L Anderson, *Reviews of Modern Physics*, Vol.27, 269,1955. © (1939) by the American Physical Society).

In the period 1947–51, while the cyclotron was getting ready, a major component of Fermi's research was theoretical. He worked on a mechanism of acceleration of cosmic rays and the origin of cosmic rays invoking a major role for the galactic magnetic field. He wrote a paper with C N Yang on 'Are mesons elementary particles?', where the idea of the mesons to be a bound state of 'nucleon–antinucleon' pair was suggested hinting for the first time to a possible sub-structure of the meson.

Even at this stage Fermi contributed as much if not more of the labour and sweat in the experiments as his junior colleagues and students.

High Energy Pion–Nucleon Scattering

Once the synchrocyclotron at Chicago became operational, Fermi returned to experiments. Experiments using big machines like cyclotrons were beyond the pale of individual researchers and Fermi had his team of collaborators that included H L Anderson, D H Nagle and graduate students G B Yodh, R Martin and M Glickmann. Even at this stage Fermi contributed as much if not more of the labour and sweat in the experiments as his junior colleagues and students and would be involved in all aspects of the experiments.

They measured the transmission of pions through a hydrogen target using a very simple arrangement as shown in *Figure* 4. The pion beam passed through two $1'' \times 1''$ scintillators, then the hydrogen target followed by two larger $4'' \times 4''$ scintillators. Double coincidence between the scintillators 1 and 2 identified the incoming pion and

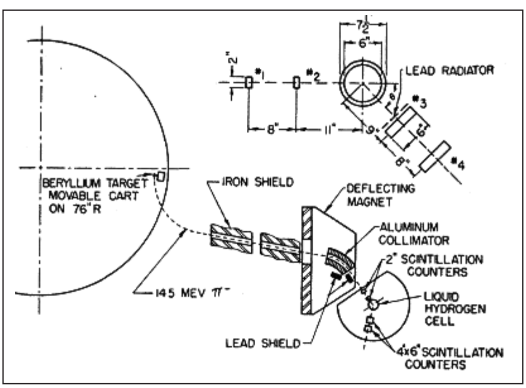

Figure 4. General arrangement for the pion–nucleon scattering experiments. In the inset the details of the scattering geometry are given. (Reprinted with permission from H L Anderson, E Fermi, R Martin, and D E Nagle, *Physical Review*, Vol 91,156, 1953. © 1939 by the American Physical Society.)

Fermi in his cautious way would not claim the case for resonance proven, till he had completed the detailed analysis of the angular distributions in terms of the 'phase shifts'.

the scintillators 3 and 4 detected the transmitted pions. They found that at low energies, the cross section was proportional to E^2, typical of a p-wave interaction, with the value increasing significantly at energies corresponding to one unit of angular momentum. This was as expected if the pion was a pseudoscalar particle. Secondly, the π^-p cross section levelled off with increasing energy around the geometrical value of $\sigma = \pi(h/mc)^2 \sim 67$ mb, consistent with the pion Compton wavelength and also confirming that the interaction was short ranged as predicted by Yukawa.

The third feature was the totally unexpected result that the π^+p cross section was much larger than the π^-p cross section. Since the π^-p reaction could proceed through three channels, viz., elastic, charge exchange and radiative capture while the π^+p reaction can proceed only through one channel (i.e., elastic), the π^-p reaction was expected to have a larger cross section. This anomaly was resolved with K Brueckner's calculation on pion–nucleon scattering, where he showed that the scattering should proceed through a resonant state near 180 MeV with isotopic spin 3/2 and spin 3/2 as a consequence of charge independence of nuclear interaction. Fermi and collaborators pursued the measurement and established that the π^+p cross section indeed went through a broad maximum. They also measured the angular distribution of the scattered particles. Fermi in his cautious way would not claim the case for resonance proven, till he had completed the detailed analysis of the angular distributions in terms of the 'phase shifts' (*Box* 4). The calculations were performed with N Metropolis using the MANIAC computer. From the analysis, two possible solutions emerged and the correct solution was settled only after Fermi's death in 1954, which confirmed the resonant nature of the excited state of the nucleon. This was the first experimental evidence of an excited state of the nucleon, later termed the Δ-resonance.

This was the first experimental evidence of an excited state of the nucleon, later termed the D-resonance.

Box 4. Phase Shifts and Resonance

The pion comes in three forms: π^+, π^- and π^0. As a consequence of charge independence, isospin is conserved in strong interactions. The pions have isospin (T) one and are the members of an isospin triplet with the third component $T_3 = +1, -1$ and 0. The proton and neutron are members of an isospin doublet with value $T = 1/2$ and $T_3 = +1/2$, $-1/2$.

For π^-, the reaction can proceed in one of three ways:

$$\pi^- + \mathrm{p} \rightarrow \quad \pi^- + \mathrm{p} \quad \text{(elastic scattering)}, \tag{i}$$
$$\pi^- + \mathrm{p} \rightarrow \quad \pi_0 + \mathrm{n} \quad \text{(charge exchange scattering)}, \tag{ii}$$
$$\pi^- + \mathrm{p} \rightarrow \quad \gamma + \mathrm{n} \quad \text{(radiative capture)}, \tag{iii}$$

whereas for π^+ there exists only one channel,

$$\pi^+ + \mathrm{p} \rightarrow \pi^+ + \mathrm{p} \quad \text{(elastic scattering)}. \tag{iv}$$

If we use the principle of isospin conservation and the rules of addition of isospin (same as that of angular momentum), the ratio of cross sections at low pion energies for the reactions is σ_{iv}: σ_{i} : σ_{ii} = 9:1:2, as was verified in the experiment.

The angular distribution can be written as

$$\mathrm{d}\sigma/\mathrm{d}\Omega = |f(\theta)|^2 \,,$$

$f(\theta)$ can be expanded in terms of partial waves as

$$f(\theta) = \Sigma_{t=0}^{\infty}(2l+1)f_l(k)P_l(\cos\theta),$$

where $P_l(\cos\theta)$ are the Legendre polynomials and k is the wave number.

$f_l(k) = \frac{\exp^{2i\delta_l(k)}-1}{2ik}$ with $\delta_l(k)$ being the phase shifts.

At low energies we can expect s- as well as p-waves to be important and neglect higher partial waves. Taking spin zero for the pion leads to three angular momentum states, $s_{1/2}$, $p_{1/2}$ and $p_{3/2}$. There can be two isotopic spin states T= 1/2 and T=3/2; so in all there can be six different states. So six phase shifts could be determined from the angular distribution. At resonance the phase shift would change by 180°. The phase shift corresponding to spin = 3/2 and isotopic spin = 3/2 was found to change through 180° in case of π^+p scattering around 200 MeV.

This was the first clue that the proton had an internal structure. A flurry of activities in this field followed leading to the discovery of many more excited states of the nucleon and eventually to the understanding of the structure of the nucleon in terms of quarks. Further

The spin-orbit coupling term is the same term that Fermi suggested to Maria G Mayer as possibly playing a role in nuclear structure.

experiments were conducted on the measurement of polarization in pion–nucleon scattering. Fermi had shown theoretically that elastic nucleon scattering could produce large polarization utilizing a real plus imaginary nuclear potential and a spin-orbit coupling term. This is the same term that he suggested to Maria G Mayer as possibly playing a role in nuclear structure. Maria Mayer followed the lead and developed the shell model for which she won the Nobel Prize in Physics. He also worked on the problem of multiplicity of pions produced in high energy proton–nucleus collisions, which he could explain using statistical arguments.

During this period of intense experimental work, in which he participated equally with his colleagues, Fermi continued his theoretical interests in other areas of physics. He continued to work at Los Alamos on neutronics (study of characteristics and distribution of neutrons in a reactor) with S Ulam and J Von Neumann and helped in development of the 'Monte Carlo' method of numerical simulations using the ENIAC and later MANIAC computers. He even designed an analog mechanical computer that was nicknamed 'Fermiac'. In the summer of 1953, Fermi collaborated with J Pasta and S Ulam on a computer experiment on the behaviour of systems composed of a large number of identical objects like molecules or mass points to check on the equipartition of energy among all mass points, obtaining a surprisingly negative result.

He collaborated with S Chandrasekhar in the fall of 1952 on astrophysical problems related to magnetohydrodynamics and origin of cosmic rays that led to two papers titled 'Magnetic fields in spiral galaxy arms' and 'Problems of gravitational stability in the presence of a magnetic field'. His last paper shortly before his terminal hospitalization in 1954 was on 'Galactic magnetic fields and the origin of cosmic radiation'.

He even designed an analog mechanical computer that was nicknamed 'Fermiac'.

It is difficult to believe that one man could achieve in a relatively short life span of 53 years as much as Enrico Fermi did. One of the greatest tributes paid to Fermi was by Hans Bethe (another Nobel Laureate and early associate of Fermi), who said, "He may have been one of the last physicists who knew almost all of physics and used it in his research".

Address for Correspondence
Amit Roy
Variable Energy Cyclotron Centre
1/AF Bidhan Nagar
Kolkata 700 064, India
Email:
amitroy1948@gmail.com

Suggested Reading

[1] **Laura Fermi, *Atoms in the Family – My Life with Enrico Fermi*, University of Chicago Press, Chicago, 1954.**

[2] **Emilio Segre, *Enrico Fermi, Physicist*, University of Chicago Press, 1970.**

[3] **Jay Orear, *Enrico Fermi*: *The Master Scientist*, The Internet – First University Press, 2004.**