Birth of the neutrino, from Pauli to the Reines-Cowan experiment

C. Jarlskog
Division of Mathematical Physics, LTH, Lund University
Box 118, S-22100 Lund, Sweden

Fifty years after the introduction of the neutrino hypothesis, Bruno Pontecorvo praised its inventor stating [1]:

> "It is difficult to find a case where the word "intuition" characterizes a human achievement better than in the case of the neutrino invention by Pauli".

The neutrino [a] hypothesis generated a huge amount of excitement in physics. Several hundred papers were written about the neutrino before its discovery in the Reines-Cowan experiment. My task here is to share some of that excitement with you.

1 Introduction

I would like to start by expressing my gratitude to the organizers for having invited me to give this talk. Indeed I am "Super Glad" to be here because of a very special reason. A few years ago I produced a book in honor of my supervisor Professor Gunnar Källén (1926-1968) [2]. Because I lacked the necessary experience, it took me about three years to produce the book. First I had to locate Källén's scholarly belongings, among them his scientific correspondence. Due to tragic events that took place after his death, the search took some time. Eventually, I found 18 boxes which had been deposited at the Manuscripts & Archives section of the Lund University's Central Library. To my great surprise, this "Källén Collection" contained about 160 letters exchanged between him and Pauli - almost all in German.

After Pauli's death in 1958 his widow Franziska (called Franka) collected his scientific belongings and donated them to CERN and not to ETH in Zürich, where Pauli had been a professor since 1928, i.e., for 30 years. He was first appointed in 1928 for 10 years. Afterwards, every ten years his position was reviewed by authorities and prolonged.

[a] This particle was named neutron by Pauli. The particle that we call neutron was discovered by Chadwick soon afterwards and the name neutrino (the little neutral particle) was suggested by Enrico Fermi.

Mrs Pauli asked Källén to send her the originals of her husband's letters. Källén wrote back that the letters were so precious to him that he just couldn't hand them over. Instead he sent her copies of the letters. For me it was a fantastic feeling to have Pauli's original letters in my hand and to read them. For the material available at CERN see the Pauli Archive [3].

The Källén-Pauli correspondence shows that Källén considered Pauli as his supervisor, his scientific father. Nobody had influenced him as much as Pauli. Källén had been sent to Zürich to attend Pauli's lectures during the summer of 1949. Pauli was mighty impressed by the young man and wanted him back. Afterwards, Pauli sometimes would refer to him as "my discovery". Their intensive scientific interaction continued until Pauli died in December 1958. For me it was a chocking revelation to discover, at an advanced age, that I was perhaps the only scientific granddaughter of Pauli! It is indeed a great honor for me to have been given this unique opportunity where I can pay tribute to Grandpa Pauli, with no exaggeration. I would, of course, never dare to call him by his first name. By the way, neither did Källén.

Pauli was a teenage prodigy. As a teenager he had already produced articles on general relativity, when this field was only a couple of years old. In preparing this talk I have benefited from consulting the "Pauli Collection" [4] which is a huge collection of his correspondence, including more than 3000 letters augmented by comments, discussions, time-lines, and references. This collection is a real jewel for those interested in the history of our science. The letters that I quote from are found in this Collection. Pauli wanted to know "everything" in theory, experiment and beyond.

2 "Cherchez la femme" - the "foremother" of the neutrino

One may ask how come Pauli got interested in the kind of physics that led him to his neutrino? In French there is a saying: "Cherchez la femme" which means look for the woman, in general assuming that behind every "crime" there is a woman who shares the responsibility. But in the case of neutrino, when we look for the woman, we find a very different kind of woman - a much respected female physicist of great integrity. A serious woman who devoted her life to science. The lady in question is **Lise Meitner** (1878-1968). She was 21 years older than Pauli and 47 years older than Källén. This large age difference could explain why I never heard Källén talk about her. Fortunately, I have communicated with a distinguished scientist who got to know her - Herwig Schopper, the Director General of CERN during the period 1981-1988. He had been a postdoctoral student of her in Stockholm [5].

In 1958 Pauli wrote a long letter, in a mixture of German and English, to Max Delbrück, who had been an assistant to Lise Meitner in Berlin, for about five years. In particle physics we have the Delbrück effect (scattering of light by light), invented by him to explain some measurements done by Meitner and Kösters. Delbrück's work is not found as an independent publication in the web of science because it is included as an addendum to the paper of the two experimentalists [6]. What Pauli and Delbrück did not know in 1958 is that Delbrück was to receive a Nobel Prize in 1969, not in Physics but in Physiology or Medicine, for "discoveries concerning the replication mechanism and the genetic structure of viruses". Inspired by Bohr he had changed his area of research!

Returning to Pauli's letter, he reminded Max Delbrück that Meitner's 80th birthday, on November 7, 1958 was approaching and that she would certainly be very happy to hear from him on this festive occasion. He also noted that the starting point of the concept of neutrino (which he called "my foolish child") was indeed Meitner's fight over the beta decay spectrum.

Pauli had been very interested in what Meitner was doing in science as well as in her well-being. They were both raised in Vienna but had left Austria and gone to Germany for pursuit of science - Meitner as a researcher to Berlin where she was to stay for about 30 years (1907-1938) and

Pauli, first to Munich for doctoral studies and then to Göttingen, Copenhagen and Hamburg before ending up as a professor at ETH in Zürich. Both had acquired other citizenships later on, Pauli from USA (in January 1946) and from Switzerland (in 1949 - after facing tough challenges that took a long time) and Meitner became a German citizen, not by choice but due to annexation of Austria into Nazi Germany on 12 March 1938. This destroyed her scientific life - as a German citizen she was no longer protected from race laws imposed by the Nazis. She was forced to flee from Germany, which she did "illegally" under dramatic conditions in July 1938. She, who was one of the most prominent female physicists in the world, ended up in Sweden where there was no tradition to provide anyone (with the exception of very few) with adequate research facilities. It is said that in those days in Sweden, the university was essentially an extension of high school[7]. Being over 60 years old didn't help either. Nonetheless, she accepted her far more limited research facilities and kept doing research. I have read many of her popular writings, conference reports and of course letters which are mostly in German to gauge the extent of her well-being. I have found no trace of any bitterness in them. After becoming a Swedish citizen, she became, in 1951, the second female Swedish member of the Royal Swedish Academy of Sciences, in the history of the Academy - The first one had been elected in the 18th century![a].

After my talk in Paris a young Frenchman, interested in the history of physics, came up to me and asked me: did Meitner and Pauli have an affair? Perhaps he had got this idea because Pauli, who was living in Zürich, often visited Berlin where Meitner lived and worked.

Actually, it is true that Pauli often visited Berlin in those for the neutrino crucial years 1929 and 1930. It is quite possible that he dropped by Meitner to discuss with her. But his primary agenda was to meet his sweetheart Luise Margarethe Käthe Deppner[8]. They married in December 1929. The marriage, which was a disaster for Pauli as the couple's moral compasses pointed in opposite directions, ended up in less than a year in a bitter divorce that almost destroyed Pauli's life (as is evidenced by several of his letters). Fortunately, he was rescued by his second wife whom he married in 1934. They had a happy marriage and were planning to celebrate their silver anniversary in 1959, which sadly didn't happen as Pauli died on December 15, 1958. There can be no doubt that the 21 years older Meitner was not responsible for any of this.

Of course, Meitner did not come up with the neutrino hypothesis. Nonetheless, we owe it to her to have made Pauli aware of the β-decay problem. Once he got to know what was going on, he was hooked. He truly enjoyed the exciting scientific fight of the discrete versus continuous spectrum.

The famous Pauli letter, dated December 4, 1930 - the pre-birth certificate of neutrino - which was shown to you today by our first speaker, Professor Allan Franklin, was sent to Meitner. Geiger was a newly appointed professor in Tübingen where the meeting of what Pauli calls "radioactive Ladies and Gentleman" was taking place.

Actually, Pauli must have mentioned his idea somewhat earlier to his closest scientific friend Werner Heisenberg because in a letter to Pauli, dated 1 December 1930, Heisenberg notes that Pauli's neutrons will result in false statistics for certain nuclei.

In a letter to Franco Rasetti (1901-2001 who was one of so called Fermi's boys) on December 10, 1956, Pauli wrote:

> " ... Thanks due Miss Meitner, who still had a copy of the enclosed letter from December 4, 1930, I am today in the position to provide you with another document concerning the history of the neutrino. (I remembered the existence of this letter, but I did not know anymore the date and the exact content of it. Therefore, I recently wrote to Lise Meitner, which turned out to be successful.)

[a] I wish to thank Professor Anders Barany for providing me with this information.

> ...
> The ’radioactive group’ in Tübingen consisted essentially of Miss Meitner and Geiger. It was also Geiger who answered it. I do *not* have anymore a copy of his answer (which he wrote after consulting Miss Meitner, too, what he mentioned), but I remember with certainty the answer was positive regarding my idea. They (Geiger and Lise Meitner) found it well possible and even plausible. Miss Meitner remembered this, too.”

In spite of popularity and getting plenty of attention, the neutrino hypothesis was not accepted by everyone. This is, of course, to be expected. It is our duty as physicists to be skeptical and to demand evidence for a hypothesis before we accept it. Among those who rejected the neutrino were: Niels Bohr (1885-1962), Arnold Sommerfeld (1868-1951) and Arthur Eddington (1882-1944).

Sommerfeld was a highly respected physicist. As supervisor he was a rarity and adored by his disciples. He had a large number of students, among them four who ended up getting Nobel Prizes, three in physics - Werner Heisenberg (1901-1976) got the 1932 Prize, for the “creation of Quantum Mechanics”, Pauli the 1945 Prize for his “Exclusion Principle also called the Pauli Principle” and Hans Bethe (1906-2005), the 1967 Prize for “theory of nuclear reactions, especially his discoveries concerning the energy production in stars”. Sommerfeld’s fourth to be Nobel Laureate student was Peter Debye (1884-1966), who received the 1936 Prize in Chemistry. Scientists like Sommerfeld are indeed rare. A corresponding example, on the other side of the Atlantic Ocean, is Julian Schwinger (1918-1994).

In 1930’s the skeptics could rightly ask: where was the neutrino hiding in the atom before getting out? Also, introducing a new particle was a highly unusual act. Rutherford had suggested the existence of the “neutron” though one was not clear about what kind of a particle it was. Was it a bound state of a proton and an electron? Then it would have been a boson which was not OK, as far as Pauli was concerned. Before 1930, except for Einstein’s photon, there existed only one single what we now call elementary particle and that was the electron, discovered in 1897. The proton had also been discovered, around 1919, but as we learned much later, the proton is *not* an elementary particle but a bag of quarks and gluons, even though we kept calling it elementary for many years.

Bohr and Eddington will now enter into our discussions to voice their opposition to the neutrino hypothesis.

3 Fight with Bohr over energy crisis

According to people who had known Pauli personally, among them his assistant Victor Weisskopf, he had a sharp tongue but was never vicious. On the contrary, he was kind but provocative in order to ignite discussions to achieve a better understanding. He was excited about and enjoyed an honest scientific fight. Moreover, Pauli was very sure of himself. Weisskopf used to tell that once he had made a rather serious error in a calculation, whereupon he went to Pauli and said that he wanted to quit physics. Pauli had replied don’t worry. Everybody makes mistakes. And then pointing at himself he had added “Ich Nicht” (literally translated not me, meaning I never make errors).

Pauli and Bohr were fond of each other. It seems that “everybody” loved Bohr. In my humble opinion, this could have been due to Bohr’s unusual brain-power and generosity. Pauli was often in Copenhagen visiting Bohr and had an extensive correspondence with him. But nothing stopped him from criticizing his dear friend. In March 1929 he sends a postcard to Bohr, informing him that he is looking forward to participating in the Copenhagen Conference (to be held soon, in the beginning of April) and asks Bohr (literal translation from German):

> What is the current status of clarification of your new thoughts? Do you intend to continue with maltreatment of the poor energy law?

Figure 1 – Pauli and Bohr in Lund (1954). Picture taken by Erik Gustafson

On July 1, 1929, Bohr sends him a short note on β-decay spectrum, and informs Pauli that he has produced it, after having thought about the issue for a long time. He asks for Pauli's opinion. Pauli's verdict is harsh. On July 17 he responds:

> You yourself write that the purpose of the note is to emphasize how meager a basis we have for a theoretical treatment of the problem of β-decay.
>
> Here I have to raise the question of whether with such lack of knowledge one can at all justify publishing a note. In any case, let the note rest for a long time. And let the stars shine in peace. [in other words, don't publish.]

What was this all about and what did it have to do with neutrino?

The β-decay looked like a process in which the energy was not conserved because one measured a transition of the type $A \to B+\beta$ where A and B are the initial and final nuclei and β is an electron or a positron. The energies and the momenta did not balance. It was then natural to question the law of conservation of energy and momentum. Actually Bohr, together with Kramers and Slater, had such a theory. They had been seeking a unified wave-particle description of radiation - Maxwell's wave and Einstein's particle. More specifically, their purpose was

"to connect the discontinuous effects occurring in atoms with the continuous radiation field in a somewhat different manner from what is usually done" [9].

This so called BKS paper, with the title "The Quantum Theory of Radiation" is rather strange and difficult to read because, in spite of being almost 20 pages long, it contains only one single (and completely trivial) equation, the familiar "Einstein-Bohr" equation $h\nu = E_1 - E_2$, informing us of the energy of the photon emitted through a transition between levels 1 and 2. In this article except for this equation everything is said in words! But words lack precision! The upshot of the paper is that conservation laws for energy and momentum are only valid statistically. The BKS theory was tested later on and was rejected by experiments.

A second reason why neutrinos were relevant had to do with the energy production in stars. In 1967, Hans Bethe (1906-2005; born in Strasbourg) received the 1967 Nobel Prize in Physics for

> "his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars".

Bethe starts his Nobel Lecture "Energy production in stars" with the sentence

> "From time immemorial people must have been curious to know what keeps the sun shining".

Then he presents a few historical facts, among them the work by Eddington:

> "Eddington, in the 1920's, investigated very thoroughly the interior constitution of the sun and other stars, and was much concerned about the sources of stellar energy. His favorite hypothesis was the complete annihilation of matter, changing nuclei and electrons into radiation".

Actually, the only known particles at the time being electron and proton, the only possibility was then the electron capture, $e + p \rightarrow \mathit{radiation}$, which is terribly forbidden by what was discovered later.

There is a story about Hans Bethe which I believe I heard from Viki Weisskopf: Bethe's fiancée/wife Rose once walking with him marveled at the beauty of the shinning stars. Bethe turned to her and said: Rose do you realize that you are walking with the only man on earth who knows why they are shinning.

The bottom line is that the hypothesis of non-conservation of energy and momentum was not as crazy then as it sounds to us now.

4 Celebrating Lise Meitner and on Bohr-Pauli Friendship

From Pauli's attacks on Bohr one may get the idea that Pauli was too harsh on Bohr as well as impolite but neither of them saw it that way, as is evidenced by their correspondence.

Early in October 1958, the distinguished female physicist Chien Shiung Wu (1912-1997) (often called Madam Wu) wrote to Pauli that Frisch (nephew of Lise Meitner) had informed her that "Miss Meitner, Otto Hahn and von Laue were going to be 80 years soon" and a festschrift was being prepared for them and that Frisch had asked her to contribute a paper on the history of β-decay. She wrote:

> "Since Miss Meitner has contributed so much in straightening out the complications of the β-decay phenomena in the early period of perplexity, I am going to write a story to emphasize her contribution. However, the central figure of β-decay is the elusive particle which you created more than twenty year ago. I wonder if you would be so kind as to write down a few lines to tell me what led you to this neutrino hypothesis? ..."

Pauli replied promptly, in a long letter with plenty of information, that he had already produced such an article about this matter, in German [b], and had sent a copy to Meitner as "a kind of

[b] The English translation of this article, called "Wolfgang Pauli, On the earlier and more recent history of the neutrino" has been reproduced in Ref. [10]. Pauli recounts the history as well as explains the physics.

birthday present for her". He then gave a list of the historical events, starting with Chadwick's paper of 1914, followed by the disagreement between C. D. Ellis, who had obtained continuous spectrum and Meitner who didn't agree with him, because the apparatus used by Ellis could not see photons. Pauli added:

> "Our good Lise said about the result of it [meaning Ellis and Wooster [11]]
>
> "I don't believe that I shall make this experiment much better" and she did it actually with a much better apparatus. L. Meitner and W. Orthmann, Zeitschrift für Physik 60, 143, 1930. I still think this paper was her experimental master piece: *the result was the same as the one of Ellis and Wooster*.
>
> But besides it, Lise Meitner had a new important result to announce in the same paper: Ellis had guessed that some continuous γ-ray spectrum could save the energy law, because such a spectrum would not be absorbed in the calorimeter. But, independent of the heat measurement, Meitner showed with help of particular counters that such a continuous γ-spectrum does not exist. ..."

In the above long letter Pauli also explained to Wu that Bohr had been his "great opponent", while Enrico Fermi had sided with him. Moreover he wrote:

> "Soon after the Solvay meeting [c] Fermi published his theory and independently F. Perrin published the correct statistical weight factor of the states and also concluded, that the neutrino rest mass must be small or zero."

Wu, in her next letter to Pauli, informed him that she in her article had put the developments in chronological order, according to the outline provided to her by him. She added:

> "I omitted to mention the opposition role played by Niels Bohr because I do not want to remind him of this incident".

Pauli replied:

> "That you leave Bohr's opposition role to me, is perhaps quite good. It is not the same, if I say it than if you say it. Of course, I treated this in my article at length. Bohr and I were accustomed to this kind of struggles in all friendship: sometimes he was right and sometimes I."

Pauli's last letter to Wu is dated just ten days before his death. He was asking for her advice on what he could do to diminish a conflict between three physicists.

5 Triumphant reception thanks to Fermi, Bethe and others

Pauli talked about the "silly child" of his, whom he actually loved, at several places in the summer of 1931 (Pasadena, Michigan, Princeton, ...). And most importantly at a congress in Rome organized by the great Enrico Fermi in October 1931, i.e., less than a year after his famous letter to "radioactive ladies and gentlemen. Fermi learned about Pauli's particle (which he renamed neutrino) and became very enthusiastic about it.

By 1933, more particles had been added to the family of known "elementary " particles: the neutron (which no longer is considered to be elementary) by Chadwick and positron by Anderson [see the Nobel lecture of Chadwick 1935 and that of Anderson in 1936]. Anderson was also a co-discoverer of the muon in 1936. This discovery was not recognized by Nobel Prize. After all,

[c] The 7th Solvay Conference: Nuclear Physics at the Crossroads, 22-29 October 1933.

Anderson had already been "knighted". The discoveries of the neutron and the positron were prerequisite for understanding what was going on in beta decay. By the way, the positron was also confirmed by Irène Curie (1897-1956) and her husband Frédéric Joliot (1900-1958). Years later Carl D. Anderson noted that the discovery of positron would have been extremely easy if he had known some theory. By that he meant that he could have sent a beam of light through, for example, lead and study the electron-positron pair production. This would have not taken more than one afternoon!

Fermi combined the neutrino hypothesis and the existence of new particles to formulate a superb theory for beta decay which had an enormous impact [12]. When I was a doctoral student in 1960's we were using Fermi's theory, local and relativistic, in a somewhat generalized form to take into account parity violation. At low energies it worked beautifully but one knew that it was doomed to fail at high energies. Of course knowing that a theory eventually must be modified doesn't mean that you can't use it in domains where it works. Newtonian mechanics and Einstein's general relativity are other examples of fantastic "doomed" theories. In short Fermi gave the neutrino hypothesis credibility. This was to start a "global neutrino fever".

Having made the above remarks, I would like to point out that one the first scientists who applauded the arrival of neutrino was Francis Perrin (1901-1992), the son of the the 1926 Nobel Laureate Jean Perrin who received the Prize for his work on Brownian motion. Francis Perrin published two papers in the French Academy's journal Comptes Rendus [13]. Perrin argued that it is would be natural to have a massless neutrino because it would be simpler to emit such a photon-like object. He pointed out how this assumption can be tested by measuring the shape of the beta-decay spectrum near the end point. Fermi in his monumental paper of 1934 on beta-decay [12] refers to Perrin's work.

Another interesting early paper on neutrino was published by Hans Bethe and Rudolf Peierls [14] in 1934. They noted that Irène Curie and Frédéric Joliot had observed decays where instead of an electron a positron was emitted, in other words β^+-decays. They concluded that

> "this supports the hypothesis that the electron/positron and neutrino are created in these processes as one can scarcely assume the existence of the positive electrons in the nucleus".

Bethe and Peierls estimated the penetrating power of the neutrino to be 10^{16} km and concluded that "there is no practically possible way of observing the neutrino".

The "super-physicist" Bethe, together with a colleague, Bacher, published in 1936, a 148 pages long review article on nuclear physics. In this review, 20 pages were devoted to neutrino [15]. Bethe had a very broad spectrum of knowledge in physics, was meticulous as well as excellent in doing computations. The article goes through a large number of issues and finds that:

> "there is a considerable evidence for the neutrino hypothesis. Unfortunately, all this evidence is indirect; and more unfortunately, there seems at present to be no way of getting any direct evidence. ... There is only *one* process which neutrinos can *certainly* cause. That is the inverse β-process, consisting of the capture of a neutrino by a nucleus together with the emission of an electron (or positron). This process is, however, so extremely rare that a neutrino has to go, in the average, through 10^{16} km of solid matter before it causes such a process. The present methods of detection must be improved at least by 10^{13} in sensitivity before such a process could be detected."

The properties of the neutrino, as found by these authors are:

- No charge

- Very small mass, probably zero, at least small compared to electron mass
- Spin 1/2
- Fermi statistics
- Magnetic moment less than 1/7000 Bohr magnetons, if any[d]
- No detectable effects in free state.

This reminds one of the famous saying: nothing is impossible, the impossible just takes longer time. It is true that nobody has ever seen a neutrino but we have seen processes induced by neutrinos. Of course, all along we have need theory to "connect the dots", such as conservation law of energy and momentum that Bohr wanted us to abandon.

6 Neutrino theory of light

From the very beginning, neutrinos fascinated theorists. Some advocated that light is in fact a bound state of neutrinos. To us this sounds absurd - how do you get the neutrinos to stick to each other and where does the binding energy come from? But such speculations were taken seriously by some distinguished mathematical physicists of that time.

A famous nobleman who strongly supported the neutrino theory of light was Louis, duc de Broglie (1892-1987). He had received the 1929 Nobel Prize in Physics for "his discovery of the wave nature of electrons". His work had inspired Schrödinger to put forward his wave mechanics. de Broglie was fascinated by and lyrical about light. He published a rather large number of papers on this matter, some of which can be found in Ref.[16]

In 1937 he published a popular book "Matière et Lumière (Matter and Light) which was translated into English in 1939, with a second edition in 1946.[17]

de Broglie's book is lovely. It is poetic and makes one dream. But it is not scientific. For example, being excited about the discovery of the neutron and positron, he writes:

> " No doubt it is on such lines that we shall gather the data needed to understand the character of the photon. The theory of light, then has a long and striking history; and a fine career lies before it."

At times one wonders what he is talking about.

The neutrino theory of light was an excellent framework for those who were strong in mathematics and field theory and who wished to publish many papers. Among those who did so were Pascual Jordan (1902-1980), a close collaborator of Heisenberg, and Ralph de Laer Kronig (1905-1995) whose work on dispersion relations (done together with Kramers) had been very important for Heisenberg's formulation of his "matrix quantum mechanics". Each of these excellent mathematical physicists had a series of articles on the neutrino theory of light. These articles are all available on the web of science. All these authors mention Bohr and the problem of the energy non-conservation.

In the beginning Pauli had found the idea that light is made up of a neutrinos-antineutrino pair very attractive. Who wouldn't? To see his baby be promoted to the highest level of creation - building block of light - must feel great. He expresses his satisfaction in a letter to Joliot, dated 26 January 1934. However, after a closer examination, he soon finds that the theory doesn't make sense. There is no way to get the two members of the pair to move in the same direction. Pauli turns against such approaches and labels them as "Quatsch" (rubbish).

[d] This result is based on the underground measurement by Nahmias, discussed further down in this article.

7 Other theoretical neutrino-induced paths from 1930's

In 1935, Maria Goeppert-Mayer (1908-1972), Nobel Laureate in 1963 for her work on nuclear physics, followed a suggestion by Eugen Wigner and computed the rate of the ordinary double-beta decay, with 4 light particles in the final state [18]. A few years later, in 1939, Wendel Furry (1907-1984) realized that the rate of decay should be much larger if the neutrino is its own antiparticle (Majorana neutrinos). They can then annihilate in the intermediate state and the rate could be much larger for these neutrinoless double beta decays [19]. Furry writes:

> " We have seen that the phenomenon of double beta-disintegration is one for which there is a decided difference between the results of the Majorana theory and those of the older theory of the neutrino. According to the older theory it seemed certain that double beta-disintegration could never be capable of observation Because of its extremely minute probability, but the Majorana theory indicates that this is by no means necessarily the case ..."

Thus Goeppert-Mayer and Furry started two new waves in particle physics which we are still following with much interest, including at this Conference.

8 The neutrino mass

Fermi's seminal article on weak interactions, first published in German and then translated into English and published in Nuovo Cimento [12], describes how one can extract the neutrino mass from the end-point spectrum of β-decay. This method was also discussed by Perrin [13]. This topic was further discussed, for example in 1935, by Henderson [20] who studied the Thorium β-decay spectrum and concluded that the mass of neutrino must be much less than that of the electron. Afterwards, there were a number of reports on this topic. It is interesting to know that a measurement in 1949, by G. C. Hanna and B. Pontecorvo, of the beta-spectrum of tritium could exclude the mass range above 500 eV (or 1 keV) [21]. The experiment was not the only one, there were several others as well. I assume that this will be discussed by other speakers during this conference.

For me personally, the issue of neutrino mass brings vivid memories of the very first international conference that I attended, "Topical Conference on Weak interactions", CERN, Geneva, 14-17 January, 1969. The Conference was chaired by John Bell (who later on became very famous because of his inequalities) and its Proceedings were published as a CERN "Yellow Report", CERN 69-7. The participation in this Conference was by invitation and my supervisor, Källén, had been invited but in the meanwhile he had been killed in a plane crash in October 1968. The organizers accepted me as his replacement, in spite of the fact that I was just a doctoral student. Several participants, including John Bell, contacted me during the Conference asking me about Källén.

The most spectacular paper presented at the Conference had the title "Reduced experimental upper limit on the electron-neutrino restmass". The speaker Karl-Erik Bergkvist (1930-1996) had performed a one man experiment, measuring the energy spectrum of the electrons near the end point in tritium decay. He had found [22] that:

> "We therefore feel safe to claim that our experiment shows (90 % confidence) that $m_\nu c^2 < 60\ eV$."

This was already a factor of ten to twenty below the Hanna-Pontecorvo upper limit and also substantially better than the lowest upper limit by Langer and Moffat [23], which according to a re-analysis by Bergkvist and others, was around 400 eV. Indeed, the amount of progress in this field has been tremendous. We are now talking about much smaller mass limits, especially as obtained from cosmology and neutrino oscillations. Particle Data Group regularly updates the material and gives us the latest results.

9 The first underground neutrino experiment

Pauli wrote to Patrick Blackett (who was considered to be a "giant" in physics) a letter, dated April 1933, which contained:

> "Dear Blackett!
>
> Your and Occhialini's paper about the positive electron is very interesting and the existence of the positive electron is very supported now by the paper of Meitner and Phillipp in Naturwissenschaften. ...
>
> Further the paper of Sargent with the sharp upper limits of the energies in the β-spectra suggested to me again my old idea, that at every β-disintegration even a neutrino could be emitted and could save the conservation-law of energy (and momentum). ...
>
> What think the experimental physicists of the Cavendish laboratory it now about those possibilities? Besides, I don't believe on the Dirac-"holes", even if the positive electron exist."

What this letter implies is that Pauli, in data obtained by Sargent, sees evidence for his neutrino hypothesis and against Bohr's non-conservation of energy. [e]

The first underground neutrino experiment was, suggested by Blackett and performed by Maurice Nahmias [24]. The work was reported by Blackett in December 1934 and published in 1935, The experiment was done at the underground station Holborn in London, the depth corresponding to 60 meters water equivalent. A radioactive source collectively called radium (actually including isotopes of lead and bismuth [25]) was placed between two Geiger-Müller detectors. Nahmias used the calculations by Bethe [26] to estimate the expected number of neutrinos crossing per minute. The point was that, if the neutrino has a sufficiently large magnetic moment it could produce observable effect. It is appropriate to relate what the great master Bethe had to say about this experiment. In section 39 of the Bethe-Bacher review article one finds [15]:

> "We know for certain that the neutrino has no charge, because the charge of the electron alone accounts for the change of the charge of the radioactive nucleus in P-emission (increase by one unit). The absence of charge precludes any strong ionization due to neutrinos. However, it is theoretically quite conceivable that the neutrino might have a magnetic moment associated with its spin. The ionization due to such a magnetic moment has been calculated (B14) and was found to be about 100n' [should read $100n^2$] ions per km path in air, n being the magnetic moment expressed in Bohr magnetons. Nahmias (N1) has searched for ionization produced by neutrinos, using strong radioactive sources shielded by large amounts (about 1 meter) of Pb in order to absorb e-, P- and y-rays [meaning γ-rays] and leave only the neutrinos. No ionization was found larger than the fluctuations of the ionization due to cosmic rays, in spite of the latter's intensity having been cut down by performing the experiment in an underground railway of London. The evaluation shows that neutrinos cannot form more than 1 ion in about 500,000 km path in air, which means

[e] Bernice Weldon Sargent (1906-1993), from Canada, was a doctoral student at the Cavendish laboratory, supervised by Rutherford and C. D. Ellis when he made this remarkable discovery, published in B. W. Sargent, Proceedings of the Royal Society 139 (1933) 659.
It is truly amazing that neither Sargent himself, nor anyone else at Cavendish understood or commented on the significance of these results. Only Pauli, a theorist, understood.

that their magnetic moment, if any, must be smaller than 1/7000 Bohr magneton [f]. It seems therefore probable that the neutrino does not have any magnetic moment at all. This makes it futile to search for ionization produced by neutrinos.

Therefore the only hope of getting more direct evidence for the neutrino is from the radioactive decay itself. The recoil of the product nucleus, which can be observed in principle, will decide definitely between the hypothesis of non-conservation of energy and the neutrino hypothesis."

A few years ago a reporter, standing outside the Holborn tube station, was asking people passing by if they were aware of the fact that the station had been the site of such a scientific experiment. Nobody knew. A woman familiar with the underground system in London had a simple explanation for why the result had been negative. She said:

"I have to be honest - I loathe Holborn Tube station. I have to go there quite often. It's always packed as it's a major interchange node between two of the deepest and busiest lines and it's a hike to get between platforms. Just the thought of it gives me jeebies. If I was a neutrino I wouldn't stop there either."

10 Disastrous events that followed

Why was neutrino not discovered earlier and in Europe where the action had been? The culprit, was no doubt the rise of the Nazis to power (1933) and introduction of race laws which threatened the very existence of a large fraction of the front-rank scientists in Europe. Many fled but some didn't make it. Let us just take a look at the main neutrino-actors in this article:

• Pauli, in spite of living in the neutral Switzerland, emigrated in 1940 to Princeton, USA. One had no guarantee that Switzerland would not be invaded in due time. Eventually, he returned to Europe and resumed his work in Zürich.

• Meitner (1878-1968), in order to save her life, made a dangerous, illegal and dramatic flee in 1938 from Berlin via Copenhagen to Stockholm.

• Fermi (1901-1954) fled in 1938 from Rome via Stockholm to USA.

In the case of Fermi he had been approached by a member of the Royal Swedish Academy of Sciences at a meeting in 1938 and had been told that he was being considered, among other candidates, for the Nobel Prize. He had then asked Fermi if he would rather wait, the reason being that Italians were not allowed to receive Nobel-money at that time and reckoning that the situation may change in a near future. Fermi had replied that he didn't want to wait. He came to Stockholm, with his wife Laura, received the 1938 Nobel Prize, as well as the Nobel money. Afterwards the couple fled directly to USA.

• Bethe (1906-2005), who had been recently employed at the University of Tübingen, was fired and ended up in 1935 in USA. He was a faculty member of the Cornell University for 70 years (1935-2005).

• Peierls (1907-1995) fled in 1933 to United Kingdom. He was knighted in 1968.

The list of all those who had to leave is painfully long!

11 Reines-Cowan experiment

I was asked to take you from the neutrino hypothesis to Reines-Cowan experiment. We have now reached our destination.

[f] This value is later quoted by Bethe and Bacher in their 1936 review article. [15]

In June 1956, Pauli was participating in a conference in Geneva, organized by CERN. This 1956 CERN Symposium attracted about 250 participants from outside, among them at least 18 past or future Nobel Laureates. At least, because the participants from CERN are not listed [27]. The most exciting news of this Symposium was announced by Pauli, who informed the participants that he had just received a telegram from Fred Reines and Clyde Cowan informing him that:

> "We are happy to inform you that we have definitely detected neutrinos ..."

Pauli added:

> "I make this announcement because otherwise everybody would ask me separately".

His reply to Reines and Cowan was:

> "Thanks for message. Everything comes to him who knows how to wait".

Copies of these telegrams are also exhibited about four decades later in Reines Nobel Lecture. This shows that Reines must have been very pleased, not only with his work but also with the great master's appreciation of it. Reines and Cowan published a series of papers, from early 1950's on, giving details of how they intended to go about to discover the neutrino. When this discovery was awarded a Nobel Prize in 1995, the recipient was Reines. Cowan had already passed away. Reines came to Stockholm and was present at the Prize Ceremony. His Nobel Lecture, which was delivered by a colleague, gives an account of the discovery. Reines was not well. During the rehearsal he turned to me and said "we know each other, don't we?". I said yes, we do. Then he said: "we like each other, don't we?" I replied yes, we do. However, I was puzzled by his question because I had assumed all along that everybody liked him. He was always kind and friendly, when I met him at conferences or at CERN, and loved to talk about his neutrinos. However, he insisted in calling me Carla. I didn't know why and never asked him or corrected him.

In concluding this talk, I would like to emphasize that, already in the early neutrino years, many papers were written about the neutrino and neutrino-related subjects. It is sad that it is impossible to do justice to all those researchers in this field who have produced great results.

References

1. Bruno Pontecorvo, "Fifty years of neutrino physics: a few episodes", published in the Proceedings of the International conference on Neutrino Physics and Astrophysics (June 1980 at Erice, Italy), edited by E. Fiorini
2. Cecilia Jarlskog (Editor), "Portrait of Gunnar Källén: A Physics Shooting Star and Poet of Early Quantum Field Theory", Springer 2014
3. Biography of Pauli (1900-1958), CERN scientific Information Service (scientific & historical archives)
4. "Pauli Collection", "Wolfgang Pauli, Wissenschaftlicher Briefwechsel", main editor Karl von Meyenn
5. Herwig Schopper *in* Special publication of Humboldt University "Lise Meitner", November 2014, page 22 (in German)
6. M. Delbrück, Z. Phys. 84 (1933) 144 (addendum to the paper L. Meitner and H. Kösters, *ibid* pages 137-144)
7. Festschrift dedicated to Professor Carl Olof Gudmund Borelius, on the occasion of his 65th anniversary, 18 April 1954

8. Charles Enz, “No time to be brief - A scientific Biography of Wolfgang Pauli”, Oxford Univ. Press 2002
9. N. Bohr, H. A. Kramers and J. C. Slater, “The quantum theory of radiation”, Phil. Mag. 47 (1924) 785
10. “Neutrino Physics”, edited by Klaus Winter, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, Cambridge University Press 1991
11. C. D. Ellis and W. A. Wooster, “The average energy of disintegration of Radium E”, Proc. Roy. Soc. A117 (1927) 109
12. E. Fermi, “Versuch einer theorie der β-strahlen”, Z. Phys. 88 (1934) 161, in German; “Tentativo di una teoria dei raggi β”, Nuovo Cimento 11 (1934) 1, in Italian; Fred L. Wilson, “Fermi’s Theory of Beta Decay”, American Journal of Physics 36, 1150 (1968), English translation of the paper published in Zeitschrift für Physik
13. Francis Perrin, “Possibilité d’émission de particules neutres de masse intrinsèque nulle dans la désintégration β”, Comptes Rendus 197 (1933) 1625; “La dissymétrie des spectres β positifs et négatifs, et la masse intrinsèque du neutrino ou ergon”, *ibid* 198 (1934) 2086
14. H. A. Bethe and R. Peierls, “The neutrino”, Nature, 133 (1934) 532
15. H. A. Bethe and R. F. Bacher, “Nuclear Physics. A: Stationary States of Nuclei”, Rev. Mod. Phys. 8 (1936) 82
16. L. de Broglie, “Sur une analogie entre l’électron de Dirac et l’onde électromagnétique”, Comptes Rendus 195 (1932) 536; “Remarques sur le moment magnétique et le moment de rotation de l’électron”, *ibid* 195 (1932) 577; “Sur le champ électromagnétique de l’onde lumineuse”, *ibid* 195 (1932) 862; “Sur la densité d’énergie dans la théorie de la lumière”, *ibid* 197 (1933) 1377; “Sur la nature du photon”, *ibid* 198 (1934) 135; “L’équation d’onde du photon”, *ibid* 199 (1934) 445; “Sur l’expression de la densité dans la nouvelle théorie du photon”, *ibid* 199 (1934) 1165
17. L. de Broglie, “Matter and Light”, Dover Publications (1946)
18. M. Goeppert-Mayer, “Double beta disintegration”, Phys. Rev. 48 (1935) 512
19. W. H. Furry, “On transition probabilities in double beta disintegration”, Phys. Rev. 56 (1939) 1184
20. W. J. Henderson, “The mass of the neutrino”, Proc. of the Cambridge Philosophical Society, 31 (1935) 285
21. G. C. Hanna and B. Pontecorvo, “The β spectrum of ^{3}H”, Phys. Rev. 75 (1949) 983
22. Karl-Erik Bergkvist, Proc. of “Topical Conference on Weak interactions”, CERN, Geneva; CERN Report 69-7 (1969) 91
23. L. M. Langer and R. J. D. Moffat, “The beta-spectrum of tritium and the mass of the neutrino”, Phys. Rev. 88 (1952) 689
24. M. E. Nahmias, “An attempt to detect the neutrino”, Proc. of the Cambridge Philosophical Society, 31 (1935) 99
25. Earl K. Hyde, Isadore Perlman and Glenn T. Seaborg, “The Nuclear properties of the Heavy Elements”, Prentice-Hall, Inc. (1964)
26. H. A. Bethe, “Ionization power of a neutrino with magnetic moment”, Proc. of the Cambridge Philosophical Society, 31 (1935) 108
27. Proc. of CERN Symposium on High Energy Accelerators and Pion Physics (CERN 56-26, edited by A. Citron et al.)