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# Teaching the history of science in physics classrooms—the story of the neutrino

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**Abstract**

Because there is little connection between physics concepts and real life, most students find physics very difficult. In this frontline I have provided a timely link of the historical development using the basic story of neutrino physics and integrated this into introductory modern physics courses in high schools or in higher education. In this way an instructor may be able to build on students' curiosity in order to enhance the curriculum with some remarkable new physics. Using the history of science in the classroom shapes and improves students' views and knowledge of the nature of science and increase students' interest in physics.

One of the essential matters in physics education at the high school level and/or even at higher education is to understand the historical developments of any physical concept. The history of physics increases students' interest in physics, perceptions and positive attitude towards it as well having the potential to make connections between science, technology and culture that could help construct students' thoughts about science, scientists and scientific knowledge [1]. According to Stinnner, learning science and teaching context by providing relevant historical information is very important and gives us valuable experiences that could not be achieved by traditional instructions [2–5]. Using the history of science in the classroom shapes and improves students' views and knowledge of the nature of science (NoS) [6–10].

An instructor with an awareness of the history of physics would be able to relate students' alternative conceptions with interconnected ideas throughout the course to foster their learning and remedy any misconceptions [11]. The connection between students' and early scientists' preconceived ideas, examined by Seroglou *et al,* found that there is a strong connection between electricity and magnetism concepts [12].

Teixeira *et al* examined 152 published works from international journals related to the history of science and philosophy of science education [13]. Of the 152 works, they found only eleven studies that directly related to the use of history and philosophy in physics education. They also indicated that none of the works they examined included the effects of learning about the historical development of physics on epistemological beliefs. A basic chronology of key events in the history of modern experimental physics is an essential tool for the understanding of historian's contributions to developments in science. For example, according to Galili, Mach's textbook in mechanics and optics remains to be valuable and interesting teaching resources [14]. Atomic models of J J Thomson and Ernest Rutherford redefined how we look at the structure of the atom, and how to use these models to attempt to measure and eventually split the atom. Modern physicists have been capable of certifying essential and partial charges of subatomic particles that structure the atom, and how they directly result in the behavior observed by Millikan's oil drop experiments. It can be said that particle physics experiments described in *How Experiments End* are the direct ancestors of experiments currently being conducted at research institutions around the world.

There are a few studies that use the history of physics in the classroom to enhance learning [1, 15–23]. According to Henke and Höttecke, there are four types of teaching formats that teachers usually carryout in their classroom when using the history of physics as part of their lesson [24].

- Using historical research papers or related reports to read, analyse and discuss in the classroom [25–27].
- Using chronological anecdotes, short stories or interactive sketches (of their interest, cultural and epistemological) with accompanied conceptual, methodological and philosophical reflection in the classroom [17, 28–32].
- Performing a historical (thought) experiment or repeating the actual laboratory procedure to trace the development of scientific methods, concepts and theories [7, 33–38].
- Using combinations of the above strategies within the context of detailed historical case studies spanning multiple lessons [9, 39–41].

There are thousands of experiments records, both successes and failures in the technical papers and textbooks of the experimental physics discipline. But, in a search for a more definite explanation, it is often the role of the experimentalist to question existing information from free of experimental bias or error.

Here I suggest the integration of the basic story of neutrino physics into introductory modern physics courses in high school or higher education, providing a timely link of historical development. In this way an instructor may be able to build on students' curiosity in order to enhance the curriculum with some remarkable new physics. Because students make little connection between physics concepts and real life, most find physics very difficult. Changing this belief or thought is not easy, but teaching the history of science in related contents could improve students' attention or change their attitude positively toward physics and the nature of science, and link connections between science, technology and society as well. One of the goals of physics education is to make students aware that science is the progress of a collaborative study of many scientists and their studies, like subatomic studios in CERN and many other places around the world. We learned from the story of the neutrino that seeking a couple of neutrinos for the sake of science and curiosity takes patience with a lot of time and effort. As well as this many trials and errors could be faced and to overcome these we have to follow our dream and never give up, as Reines and Covan and Davis did. However, using the history of physics has some obstacles, for example, lack of teachers' knowledge about the history of science and time constraints in the classroom. Now let's look at the story of the neutrino and use this in the classroom as a teaching material to enhance student understanding of the history of basic physics concepts of beta decay. This material could be used in several ways depending on curriculum allowance, students' backgrounds and levels and/or teacher's capability of implementing the material. For example, when the teacher does all activities given on related links in the story, a question would arise about how to manage or pace time to fulfil curriculum requirements in the classroom. In this case the story could be used as a homework assignment. Therefore, I cannot give any specific practice for teachers to follow. One could find their right usage according to their experiences and their students' backgrounds related to the subject.

## The story of the neutrino

Before starting the subject matter in class, the teacher might start with some activities related to understanding of the particles and interactions as described in [42, 43] in order to prepare students' background knowledge and to be ready for the neutrino concept. Then one would start the story of the neutrino.

*Our story begins with the discovery of the radiation from radioactive elements*

Actually, most of publications state that Henri Becquerel (see figure 1) accidentally discovered some unusual radiation coming from

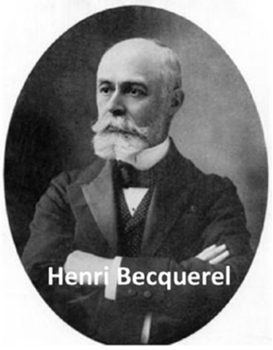

**Figure 1.** Henri Becquerel. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Henri_Becquerel.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

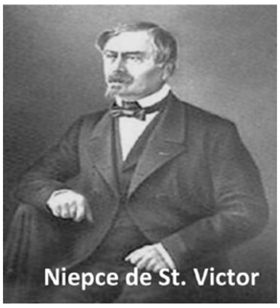

**Figure 2.** Niepce de St Victor. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Claude_F%C3%A9lix_Abel_Ni%C3%A9pce_de_Saint-Victor.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

uranium salts in 1896. However back in 1858, 38 years before Becquerel's report on the effect of uranium salts on a photographic plate, Niepce de St Victor (see figure 2) had discovered the radioactivity with deducing that heat contained in the uranium salt was responsible of the darkening of the plate. Moreover, de St Victor showed some pictures as the result of the photochemical reduction of the uranium salt to photographic plates at the Third Exhibition of the Société Française de Photographie in Paris in 1859 [44].

Then Marie and Pierre Curie (see figure 3) in 1898, identified radium and polonium and showed that radioactivity doesn't limit to uranium [45].

In 1899, Ernest Rutherford (see figure 4) showed that there are two different types of radiation and called them alpha and beta (actually Rutherford knew that the beta particle was indeed an electron, but he named it as beta, therefore, to this day when a radioactive atom breaks down and releases electrons the process is known as beta decay [46].

**Figure 3.** Pierre and Marie Curie. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Pierre_and_Marie_Curie.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

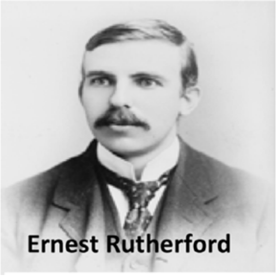

**Figure 4.** Ernest Rutherford. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Ernest_Rutherford_1908.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

In 1900, while French scientist Paul Villard was studying the radiation emitted by radium, he discovered a third type of radiation, and called it gamma radiation. Pierre and Marie Curie explained that beta radiation was indeed an electron emission in 1902. Then Rutherford revealed that an alpha particle was equivalent to a helium nuclei in 1904.

During the study of radioactivity there must be two important considerations. First, the law of conservation of momentum (before and after) must be the same ($\vec{P}_{\text{initial}} = \vec{P}_{\text{final}}$). Second, when the nucleus of an atom transforms into a new configuration, some fraction of the energy is released as gamma rays or as alpha or beta particles. The energy of the system must be equal before and

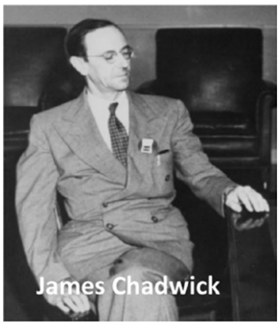

**Figure 5.** James Chadwick. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:James_Chadwick.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

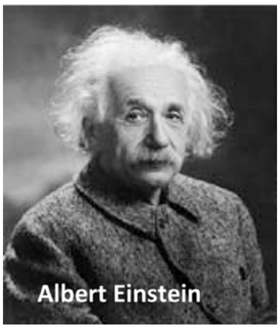

**Figure 6.** Albert Einstein. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Albert_Einstein_1947.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

after radioactive decay. The law of conservation of energy is $E_{\text{initial}} = E_{\text{final}}$. In alpha and gamma decays, it was not complex to balance the energy accounts, but that was not the case with beta decay [47]. During beta decay, a nucleus seems to release a single particle, an electron. In 1914, the British physicist James Chadwick (see figure 5) found that there was a problem with the energy of the electron. The energy of the electron was not always the same; sometimes the electron appeared to have very little energy, while at another instances, it came with a lot. How could that be? If the electron emitted in beta decay is obeying energy conservation, it should have the same energy every time.

Even applying Einstein's (see figure 6) energy equation ($E = mc^2$) to the beta decay phenomenon, it didn't account for all the missing energy and the momentum conservation either.

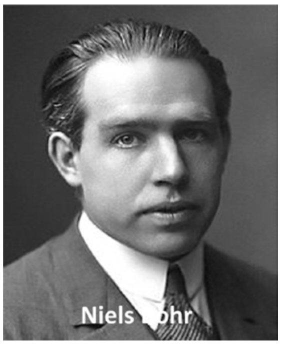

**Figure 7.** Niels Bohr. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Niels_Bohr.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

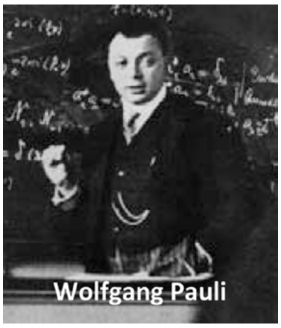

**Figure 8.** Wolfgang Pauli. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Wolfgang_Pauli_young.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

At this stage, to emphasise the importance of energy conservation it can be explained in relation to the missing energy mystery experiment as described in [48] and ask the student questions related energy and momentum conservation. For example:

- In your own words, what is the conservation of energy and momentum?
- Why they are so important in physics?
- What is the connection between momentum and subatomic particles?

The problem with beta decay was so insistent and severe that even Niels Bohr (see figure 7), the founder of quantum physics, considered giving up on the principle of energy conservation completely. So, Austrian physicist Wolfgang Pauli (see figure 8) and many others

**Figure 9.** Enrico Fermi. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Enrico_Fermi_1943-49.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

**Figure 10.** Hans Bethe. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Hans_Bethe.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

were suspicious of his suggestion, and therefore they did defend energy conservation. At that time, physicists knew of only three elementary particles, namely they were the proton, electron, and photon, but Pauli came to a brave resolution to account for this missing energy with a hypothetical ghostly particle that might be escaping from the scene of beta decay. He assumed that such a probable particle would be neutral and have to be lighter than an electron. Pauli wanted to share his idea with a group of top European physicists in Germany in December of 1930. Because Pauli wasn't able to attend the meeting in person, he had a mate read out the famous letter (starting with 'Dear Radioactive Ladies and Gentlemen') to a scientific committee [49].

For the first time, the next summer Pauli travelled to several cities across the United States to give lectures and conferences to publicly declare his proposed particle. Meanwhile, in 1932, the English physicist James Chadwick discovered a previously unknown neutral particle, nearly the same mass as the proton, in the atomic nucleus. Because Chadwick called his particle the neutron, the same word that Pauli had used previously to describe his hypothetical particle, Fermi (see figure 9) introduced a new term for the latter; the neutrino—Italian for 'little neutral one'—and physicists started to use this new term [50].

After meeting with Pauli and thinking about the mystery of beta decay, in 1933, finally Fermi was able to express a clear mathematical description of beta decay within the context of quantum mechanics. According to his theory the nucleus of the atoms consisted of hefty particles (protons and neutrons) and during beta decay a neutron morphs into a proton, which remains in the nucleus, while an electron is released along with a neutrino, as Pauli had suggested ($n^0 \rightarrow p^+ + e^- + \overline{\nu}$). Fermi made it clear that the neutrino did not exist in in the nucleus to begin with, but was created during beta decay. He compared the results of experimental data with his theoretical calculations, and concluded that 'the rest mass of the neutrino is either zero or in any case very small with respect to the mass of the electron' [51].

In addition, Fermi's theory recommended a new essential force of nature, what we now call the weak force, which drives the subatomic world. Two of the four known forces are gravity and electromagnetism that act over large distances, and we are generally familiar with them in our daily experience.

Fermi submitted his 'tentative' theory of beta decay to *Nature* in 1934. The journal's editors were not impressed and rejected his manuscript claiming that 'it contained speculations too remote from reality to be of interest to the reader'. Fermi then submitted his paper to Italian and German publications [52].

Two German physicists, Hans Bethe (see figure 10) and Rudolf Peierls, considered an interesting likelihood. As a neutrino is released in beta decay, could one be absorbed in a reverse process, the same way that photons are emitted and absorbed by atoms? They found that the chances of a neutrino being absorbed by an atom are little. The two theorists concluded in writing a brief note to *Nature* that there was 'no practically possible way' of detecting the neutrino [53].

**Figure 11.** Bruno Pontecorvo. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Bruno_Pontecorvo_1950s3.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

Nuclear fission, during the bursts, produced unstable nuclei that decayed after, freeing astounding numbers of these particles. Because of the higher flux of neutrinos, experimentally the greater the possibility that some would record in a detector. One of Fermi's Italian colleagues, Bruno Pontecorvo (see figure 11), however, firmly assumed that physicists should be able to detect neutrinos with the right experimental setup. The probabilities of a particular neutrino interacting with a detector were extremely small, but Pontecorvo believed that if there were many trillions of particles reaching a detector every second, it should be possible to capture a few. The first step toward this aim was to detect an abundant source of neutrinos. He recognised that even a very big amount of radium would not release enough neutrinos through beta decay to detect them. According to Fermi's theory, Pontecorvo recognised that two things should happen when a neutrino hits an atomic nucleus. The first one is that the neutrino should pick up a negative charge and turns into an electron. And the second one is that the nucleus should gain a positive charge to balance out the system [54].

In 1953, American physicists, Frederick Reines (see figure 12) and Clyde Cowan (see figure 13) built a cylindrical tank holding 300 ℓ (80 gallons) of scintillator liquid, observed by ninety photomultiplier tubes spotting the inside walls. The tank was surrounded by thick covers of paraffin, borax, and lead to shield from gamma rays and the other background 'noise' coming from the reactor or outside the other sources.

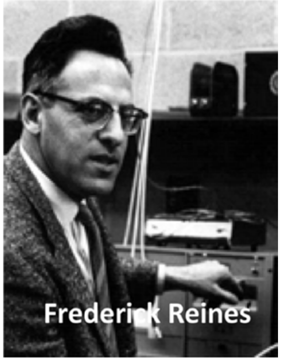

**Figure 12.** Frederick Reines. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Frederick_Reines.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

**Figure 13.** Clyde Cowan. This image has been obtained by the author from the Wikimedia website (https://commons.wikimedia.org/wiki/File:Clyde_Cowan.jpg), where it is stated to have been released into the public domain. It is included within this article on that basis.

Reines and Cowan recorded the first clues of a signal within months. The detections were not as precise as they had expected, however, their detector recorded events even when the reactor was closed. This was a big problem. Then, they decided to try again with a more sensitive redesigned experiment at the more powerful newly finished reactor at the Savannah River Site in South Carolina to distinguish true neutrino events from fake signals caused by cosmic ray particles by equipping the experiment with multiple scintillator tanks. They completed the new device which weighed in at some ten tons in late 1955. Their apparatus was shielded from neutrons produced by the reactor and from cosmic rays and located in a basement below the nuclear reactor. They noted hundreds of hours of data with the reactor turned on and off for comparison over five months. The device recorded five times as many pairs of sparkles separated by a few microseconds when the reactor was on than when it was off. After extensive tests and checks by the summer of 1956, the group was assured that they had absolutely identified neutrinos [55].

Capturing the ghostly particles provided us with a satisfactory solution to the mystery of beta decay and helped us to preserve the law of energy conservation confirming the theoretical predictions made by Pauli and Fermi.

Fred Reines and Clyde Cowan were not the only scientists that chase neutrinos in the early 1950s. Raymond Davis was one of them. Davis first set up his apparatus to attempt neutrino hunting, a 3800 ℓ (1000 gallon) tank of dry-cleaning fluid (or carbon tetrachloride) next to a modest nuclear reactor of Brookhaven. He also recognised that neutrinos rarely interacted with matter. Hoping that would allow enough time for a few reactions to occur, so he waited several weeks. Then he measured the amount of argon that accumulated in the tank. However, the results were disappointing because there was no extra argon beyond what cosmic ray collisions could account for. It means that there was no sign of neutrinos. In 1955, building a bigger version of his apparatus next to the much more powerful reactor at the Savannah River Site in South Carolina, the same place where Reines and Cowan conducted their experiment, Davis tried again but found nothing. On the other hand, Reines and Cowan had confirmed these particles by the following year. But Davis turned his attention to chasing neutrinos produced inside the Sun rather than those formed in nuclear reactors in late 1959 [56].

This time he took his experiment to Barberton limestone mine in Ohio to get rid of background noise from cosmic rays that might intervene in the neutrino signal. He assumed from this apparatus to record several neutrinos coming from the Sun each day. But when Davis examined the results, he was again disappointed by not finding any sign of the mysterious particles from the Sun.

After two years of gathering data at the Homestake mine (see figure 14), Davis declared the first results of his experiment at a meeting at Caltech in 1968. He claimed to detect solar neutrinos, but there was a problem that there was only about one-third as many neutrinos as Bahcall's model calculations predicted. Bahcall feared that Davis's results meant his solar model was wrong.

**Figure 14.** Homestake Mine. Image reproduced with permission from https://bnl.gov/bnlweb/raydavis/images/hires/1-390-66.jpg (courtesy of Brookhaven National Laboratory).

**Figure 15.** Kamiokande. Image reproduced with permission from http://sk.icrr.u-tokyo.ac.jp/sk/detector/image-e.html.

The discrepancy between theory and data raised suspicions not only about Bahcall's model, but also about the reliability of Davis's research. Many scientists were unconvinced that Davis had detected solar neutrinos at all. Unfortunately, none of these developments, nor gathering of years more data, changed the results [56].

To get convincing results we had to wait till the summer of 1989 for the announcement of the Kamiokande team (see figure 15). Their independent measurements from Davis did not only confirm that neutrinos came from the direction of the Sun but also found a discrepancy in the particle number predicted by Bahcall's model confirming that the energy spectrum of the received neutrinos agreed with his calculations. Thus, it seemed that Davis and Bahcall were both right, and the solar neutrino shortfall was existed.

Over a half century ago, Bruno Pontecorvo had two essential intuitions that hold the keys to unravelling the solar neutrino mystery. His first vision was that there were more than one variety of neutrinos. While examining the decay of an unstable particle termed a muon, which belongs to the lepton family and is negatively charged, along with the electron and the neutrino, he came to this conclusion. Pontecorvo suggested that the muon and electron each had a distinct variety of neutrino associated with it. His second insight was that neutrinos could be changeable. The laws of quantum mechanics could allowed neutrinos to morph, or ‘oscillate’, between its types, but this could happen only if they had some mass. According to him, the neutrino’s mass might be tiny, but it could not be zero. He also knew that nuclear reactions in the Sun created only one flavour of neutrinos—electron neutrinos—as Davis’s experiment discovered. Soon after Davis’s first report related to a discrepancy of solar neutrinos in 1968, Pontecorvo and his Russian colleague Vladimir Gribov suggested that neutrino oscillation among flavours on their way from the Sun could account for the shortfall. As odd as the theory might sound, their recommendation presented a simple and sophisticated justification for the missing solar neutrinos by turning two-thirds of the electron neutrinos created in the Sun into other varieties during their long trip, and thus escaping from detection [57].

Particles in quantum mechanics can also be described in terms of waves. As a neutrino travels through space, the waves linked with the three flavours spread at different rates. The waves associate with each other along the way, therefore at different points in space you could get a different combination of flavours. Occasionally you would taste typically caramel, while at other times lemon or cherry would dominate. Thus, a neutrino that was born as an electron neutrino could become a tau neutrino after some distance. That’s why, as Pontecorvo and Gribov recommended, neutrinos could morph between flavours as they travel from the Sun to the Earth.

Theoretical thoughts alone weren’t enough to persuade physicists that Pontecorvo had been true about neutrino oscillations. Luckily, the Super-K detector (updated version of the Kamiokande detector (see figure 16)) in Japan was capable of distinguishing between two neutrino types. While an electron neutrino hitting the water would yield a vague circle of light, on the other hand, a muon neutrino would leave a sharp ring. After observing both types for nearly two years, the Super-K team informed that they discovered roughly equal numbers of each, on the contrary they expecting twice as many of the muon variety, which was a surprising result. Their reason for this was that half the muon neutrinos could morph into the third type, tau neutrinos, which Super-K may perhaps not detect easily.

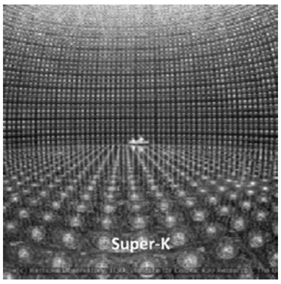

**Figure 16.** Super-K. Image reproduced with permission from http://sk.icrr.u-tokyo.ac.jp/sk/detector/image-e.html.

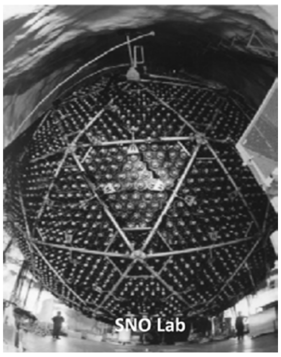

**Figure 17.** SNO Lab. Image reproduced with permission from http://snolab.ca/content/sno-detector.

Thanks to researchers from Kamiokande and SNO-Lab (see figure 17) for discovering to solve the problem of the missing solar neutrinos that Ray Davis and John Bahcall battled with for decades. Neutrino chasers have also determined that neutrinos do have a mass—this is the first clear-cut confirmation of physics beside the standard model—and that they transform between the three flavours during their journey. Using the more sensitive experiments, researchers started to determine the odd properties of these chameleon-like particles. By providing priceless tools for cosmology and astrophysics, the process of neutrino hunting opened new frontiers to fundamental physics [58].

Scientists believe that most elementary particles have corresponding antimatter twins with opposite charge and spin. Possessing a strange property, neutrinos appeared to be identical to their antineutrinos. This mystery might play an important role in the cosmic riddle. Since neutrinos and antineutrinos have no charge, the only way to differentiate them is by their spins (neutrinos spin left while antineutrinos spin right). Even though there is variation in the spin, both could interact with matter the exact same way. If it is true, and the two types of particle were entirely identical, this could help out to explain how matter came to predominate over antimatter in the early universe.

Latest developments imply that the neutrinos must have a mass smaller than a billionth of a hydrogen atom. Scientists thus assume that neutrinos make up less than 20% of the dark matter in our universe, and that the rest has to be in some yet known mysterious form. Scientists also expect that the '*stuff*' of the universe consists of 5% ordinary matter, 27% exotic dark matter and about 68% dark energy [59].

To represent the existence of new radioactive elements associated with the discovery of nuclear reactions accomplished by slow neutrons, Fermi received a Nobel Prize in 1938 while Pauli discovers the exclusion principle, he was awarded the prize in 1945. However, The Nobel Prize for the discovery of the neutrino wasn't rewarded until 1995, almost thirty years after detecting them by Reines and Cowan. By that time, Cowan had passed on, and because Nobel prizes cannot be awarded posthumously only Reines was alive to receive the prize. Then second and third Nobel Prizes were also awarded related to neutrino studies in 2002 (Davis won a sharing prize by detecting solar neutrinos) and 2015 (for finding oscillations among different flavors of neutrinos).

At this stage, the evidence can be collected to make inferences about a hidden object in a sealed box to learn to critically raise questions for a thorough investigation and formulate and test hypotheses as described in [60]. Then, to summarise and go over the document, the following questions could be asked:

- What did you learn from the story of the neutrino?
- In the earlier explanation of beta decay it appeared that momentum and energy were not conserved. Who faced and solved this problem?
- Why it is so difficult to detect neutrinos?
- Could you explain why Davis and Reines and Cowan's work for detecting neutrinos was so important?
- If you were a scientist what would you do when you fail to get expected results from your experiment?

## Acknowledgments

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