Neutrinos: An insight into the discovery of the neutrino and the ongoing attempts to learn more

This document investigates the illusive neutrino and provides an insight into the particle, which has plagued physicists for over half a century—and yet still remains, a source of fascination and discovery.

> *"On reflecting a neutrino in a mirror, one sees nothing"*
> *Abdus Salam, 1957*

During the production of this document, I have endeavoured to provide an encompassing insight into the world of the neutrino, using as many sources as possible to provide an informative view for the intelligent reader. This includes a combination of texts from *Imperial College & Science Museum Libraries*[1], as well as resources from leading research facilities into particle physics, such as CERN[2]. Of main concern when researching areas of physics that are rapidly changing is the availability of up-to-date information. I myself have recently read many dated texts which refer to things such as the undiscovered top quark (*discovered in 1994*) or expectations from the construction of LEP at CERN (*completed in 1989—now approaching the end of the road with the LHC*[3] *planned to be the next step*). Therefore, many sources used here have been accessed via the Internet to ensure accuracy and reliability.

I have chosen to address this topic for several reasons—one of which is my interest and continually expanding understanding of particle physics. I also feel particularly honoured to have visited CHORUS[4] (*CERN Hybrid Oscillation Research Apparatus*) and NOMAD[5] (*Neutrino Oscillation Magnetic Detector*) at CERN—both of which are significant neutrino experiments.

Finally, I would add that writing this has provided me with a fascinating, if only 'tip of the iceberg', understanding of neutrinos.

John Kut

---

[1] http://www.lib.ic.ac.uk

[2] http://www.cern.ch – European Laboratory for Particle Physics

[3] http://wwwlhc01.cern.ch/

[4] http://choruswww.cern.ch

[5] http://nomadinfo.cern.ch

[6]

---

[6] From CERN http://choruswww.cern.ch/welcome.html – a graphic depicting a neutrino oscillation – the conversion of a muon neutrino (ν_μ) into a tau neutrino (ν_τ)

Preface

In this document I intend to provide an introduction to neutrinos—and essentially its properties, flavours and the experiments surrounding its existence, as well as some of the questions which still remain. I am forgoing the usual historical account and instead of providing names and dates, I am attempting to provoke the thought that originally struck the brilliant minds of the many involved. As neutrino research is deeply integrated into the field of particle physics, I shall endeavour to explain terminology and concepts for the inquisitive mind, where necessary—without getting overly concerned about other areas of particle physics[7] or the strenuous mathematics that would otherwise be involved.

The Neutrino

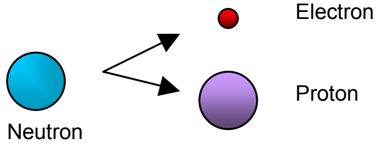
ν_e ν_μ ν_τ

"Not everyone would be willing to say that he believes in the existence of the neutrino, but it is safe to say there is hardly one of us who is not served better by the neutrino hypothesis as an aid in thinking about beta-decay"[8]

H. Richard Crane, 1948

The concept of a neutrino originates from problems whilst investigating beta decay. Unlike α-particles ($^{4}_{2}He^{2+}$) which have discrete energies, the β-particles ($^{0}_{-1}e^{-}$) emitted during decay have a continuous spectrum of energies from zero eV [9] onwards.

$n \rightarrow p + e^{-}$



β-decay was originally regarded as the decay of a neutron in an unstable nucleus into a proton and an electron which is released.

The problem with this concept is that the mass-energy[10] of the system after decay was less than that of before, and spin[11] was not conserved. Thus energy seems to have '*disappeared*'. Such a notion is a blatant violation our understanding of the conservation of energy[12] and assuming the law holds true, then the missing energy must be accountable for. Yet experiments using a calorimeter to measure all the energy evolved in β-decay as heat confirms the discrepancy[13]. The only possible way by which energy could 'escape' from such a closed measuring system would be by the emission of electromagnetic radiation such as gamma rays which could penetrate the apparatus—yet none are detected. The two options this dilemma provides us with, is to either discard the established conservation of energy[14] or contemplate the release of energy by means of a highly penetrative, yet effectively invisible medium.

The Neutrino.

---

[7] For further information of a general educational nature on particle physics, try http://durpdg.dur.ac.uk/lbl/cpep/adventure_home.html which provides a most informative and clear introduction to the subject.

[8] Spaceship Neutrino – Christine Sutton – Cambridge University Press – 0-521-36703-4

[9] Electronvolt. A unit of energy equal to the work done on an electron in moving it through a potential difference of one volt. It is used as a measure of particle energies although it is not an SI unit. $1eV = 1.602 \times 10^{-19}$ J

[10] According to Einstein's mass-energy relationship, every quantity of energy (E) has a mass (m), which is given by E/c^{2} where c is the speed of light. Therefore if mass is conserved, the law of conservation of energy must be of equally wide application.

[11] Beyond the scope of this document. See references on quantum mechanics for further information.

[12] A law stating that the total magnitude of a certain physical property of a system, such as its mass, energy, or charge, remains unchanged although there may be exchanges of that property between components of the system.

[13] A radioactive source emitting β-particles was placed into a container adequate to stop β particles penetrating. This container was immersed into a calorimeter and the total heat detected was equal to the mean energy of the β particles emitted. Therefore indicating that no other detectable energy carrying rays appeared to be emitted.

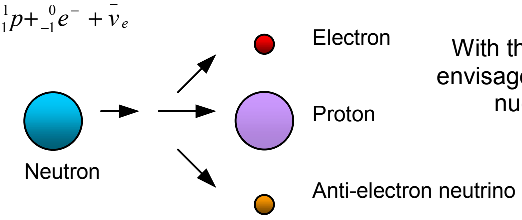
[14] And contemplate things such as perpetual motion!

If we consider such a particle as the solution to the β-decay problem, without experimental data[15] we can hypothesise various attributes for it. Firstly, that it must be more penetrating (*and thus less ionising*) than γ radiation—otherwise it would already have been detected by previous experiments. It must also be extremely small or virtually null, otherwise a large quantity of mass-energy would be lost due to its production and is unlikely to be charged—otherwise it would leave an ionised trail, which would have been detected. Since β-decay is a nuclear process, such a neutrino should be elemental, and thus can account for spin.

Since particles such as the photon can knock an electron out on an atom[16], and a neutron can knock protons out of a nucleus—it does not seem unreasonable to conceive that a neutrino would eventually interact with matter. Subatomic particles are generally detected through their impact on their environment. Electrically charged particles, such as protons and electrons, directly ionise matter through which they pass—in other words, they knock electrons from atoms via electromagnetic interactions. In some detectors, the particles leave trails of ions and electrons behind them, and these can be made visible, similar to ‘footprints in the snow’. However, neutral particles, such as neutrons and photons, do not leave ionised trails in matter. We have to resort to detecting them indirectly—and the same seems plausible for neutrinos.

> *“I am not much impressed by the neutrino theory. In an ordinary way I might say that I do not believe in neutrinos….Dare I say that experimental physicists will not have sufficient ingenuity to* <u>*make*</u> *neutrinos?”*
>
> *Arthur Eddington, 1939*

$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e^{-} + \bar{\nu}_{e}$



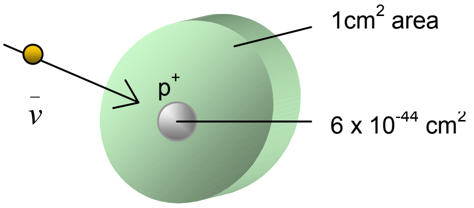
With the emergence of the neutrino theory, β-decay is envisaged as the decay of a neutron within an unstable nucleus producing a proton, electron and neutrino

So just how penetrating (*or not*) are neutrinos? An experiment was conducted whereby a solution of radium (*an β-emitter*) was place in front of a detector with thick lead in between[17]. The idea was that the resulting ionisation would be due to the particles that had been ‘slowed down’ and penetrated the lead shielding—neutrinos. But no ionisation was found beyond even the thickest lead. Yet this cannot be because neutrinos have been unable to pass through, else how are such neutrinos escaping from the previous calorimeter experiment? It suggests that neutrinos are indeed extremely penetrating. Early calculations indicated that neutrinos could travel approximately 300km before an ionisation occurs. Later estimates increased this to 31000km[18].

We now estimate that neutrinos could travel approximately 9.5×10^{18}*km* through lead before interacting with a single atom.

---

[15] Since this is a purely theoretical solution
[16] The Photoelectric effect
[17] The experiment was conducted by Pauli and Fermi around 1934
[18] From further experiments conducted at Holborn station of the London Underground by M.E. Nahmias



Behind one square centimetre of surface lies a proton. If one antineutrino of 2MeV is incident on this surface, the chance of it interacting with the proton is the same as its chance of striking an area of 6 x 10^{-44} square centimetres—a very slender chance indeed.[19]

So despite the fact that we have contemplated the solution to the β problem, are we any closer in that we cannot prove the neutrinos existence? Neutrinos are very difficult to detect because of their low probability of interacting with matter. Yet neutrinos are not rare particles. In nature, we believe them to be abundantly created in the centre of stars such as our sun, during the nuclear fusion reactions that produces electromagnetic radiation such as light and heat.

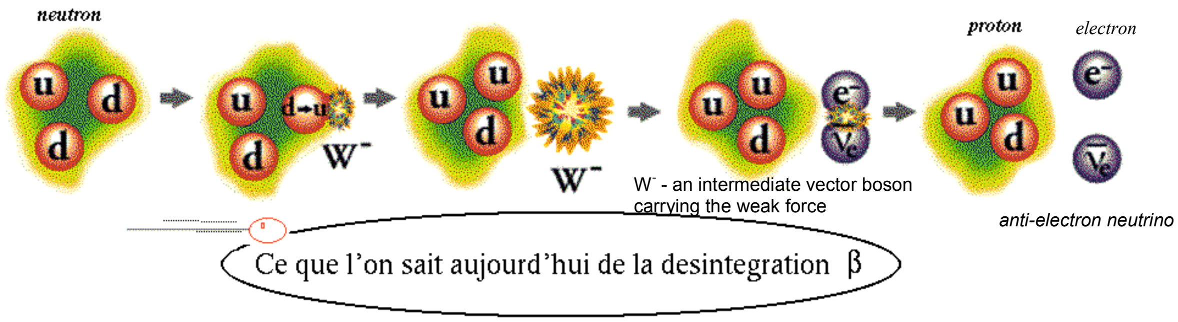
$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

The decay of a proton into a neutron, positron and a neutrino, allows for the fusion of a proton and neutron to form deuterium—as a small step in the overall solar fusion process.

In one second, the tip of our finger is crossed by a flux[20] of approximately one hundred billion solar neutrinos[21]--since, due to their effective zero mass[22] they travel at the speed of light. However, the chance that a neutrino could be directly detected by its interaction with any kind of instrument is virtually non existent. We infer that neutrinos must be incredibly small, much smaller than some of the smallest particles like protons and electrons, and even quarks[23]! But what of their mass?[24]

Beta Decay

E.g. $${}^3_1He \xrightarrow{\beta-decay} {}^3_2He + e^- + \bar{\nu}_e$$



W⁻ - an intermediate vector boson carrying the weak force

anti-electron neutrino

"What we know today about β-disintegration"[25]

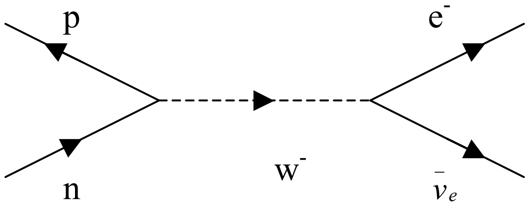
So that we can better understand the situation, let us consider β-decay. β-Decay, as in the example shown above, is the process by which an unstable atomic nucleus changes into a nucleus of the same mass number but with a different proton number. On the left we start with a neutron composed of one up and two down quarks – the elementary constituents of all matter[26].

---

[19] Diagram from Neutrinos – G.M.Lewis – Associated Book Publishers Limited – 0-85109-140-7
[20] The number of particles flow unit area of cross section in a beam of particles
[21] Sources vary on the exact number of neutrinos, particularly depending on the source since this cannot be accurately measured—however, it is nevertheless a large number.
[22] the answer to this question remains to be seen
[23] the smallest quark, the up quark, has a mass of approximately 5MeV
[24] all in good time – see later
[25] http://wwwlapp.in2p3.fr/~verkindt/neutrinos/neutimg/betadecay.gif – Particle Physics Laboratory at Annecy-le-Vieux – France – translated by John Kut
[26] See references to elementary particles

Protons and neutrons both belong to a class of particles known as hadrons[27] consisting of three quarks. When a neutron decays, a down quark is converted into an up quark through a weak interaction[28], causing the production of two expelled particles – the electron (*in this case moving at high velocity as β-radiation*[29]), and an anti-neutrino[30]. As you can see from the diagram, none of these particles existed prior to the decay. The diagram below[31] illustrates the aforementioned decay, but in a more formal fashion.

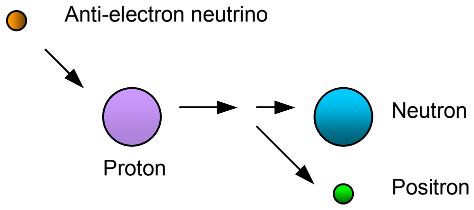
The arrows indicate the movement of particles before and after the decay. The central transfer particle illustrates the force carrier



The decay of a neutron – supposedly proceeding through the creation and subsequent annihilation of an intermediate vector boson W^-

Inverse Beta Decay

If our theoretical neutrino is produced in β-decay, is it not plausible that one could be absorbed in the reverse process? Can a nucleus capture a neutrino to form a new nucleus? Moreover, given that this is a reverse process, would it not emit a positive electron? A positron? Indeed, such a particle exists[32] and experiments have found that certain unstable nuclei have the ability to undergo this "inverse beta decay".



The collision of an anti-electron neutrino with a proton in the nucleus causes it to decay into a neutron and a positron that are expelled

$$^1_1p+\bar{\nu}_e \rightarrow {}^1_0n+{}^0_1e^+$$

Certainly, by performing such an experiment, one would be able to prove the existence of the neutrino—not directly, but by the results of its interaction. The production of a neutron and a positron. However, the overwhelming problem of the infrequency of neutrino interactions remains. This logically makes the chance of performing it void. So how could we get more neutrinos, and increase their chances of interaction? Let us consider known sources[33]:

- Solar neutrinos – created by the thermonuclear fusion inside stars, such as our sun – which is our primary source of neutrinos. The sun emits an estimated 2×10^{38} neutrinos s^{-1}
- Us - our bodies contain approximately 20mg of Potassium-40, which undergoes β-decay, emitting an estimated 4×10^{3} neutrinos s^{-1}.

---

[27] Any of a class of subatomic particles that interact by the strong interaction. The class includes protons, neutrons and pions. Hadrons are believed to have an internal structure consisting of quarks, and so they are not technically elemental.

[28] The weak interaction or weak force is one of four different types of interaction that can occur between bodies – the other three being the strong force, the electromagnetic force and gravity. All of these forces are thought to be conveyed by a carrier particle. In the case of the weak force, this is performed by intermediate vector bosons – W^+, W^- and Z^o.

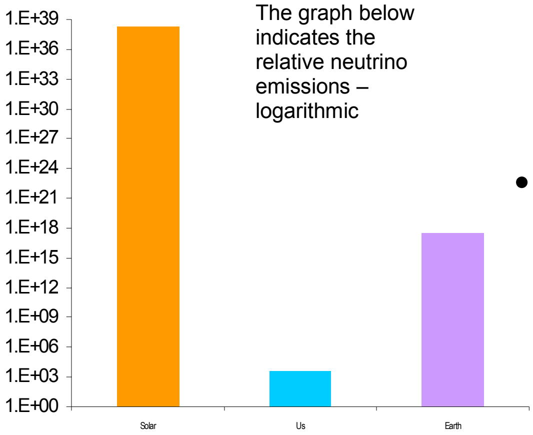
[29] β-radiation is formed by a stream of fast moving electrons

[30] Due to the convention of 'lepton conservation', an anti-neutrino is produced since the total lepton number before and after must remain the same.

[31] Neutrinos – G.M.Lewis – Associated Book Publishers Limited – 0-85109-140-7 © 1970

[32] Paul Dirac formulated the now famous equation universally know as the Dirac equation, which accounts for the existence of both electrons and positrons.

[33] Data extracted from "The Sources of Neutrinos" – http://wwwlapp.in2p3.fr/~verkindt/neutrinos/ansources.html – and is supported by data from http://choruswww.cern.ch/Public/textes/english/node1.html and http://windows.ivv.nasa.gov/sun/Solar_interior/Nuclear_Reactions/Neutrinos/neutrinos.html . Neutrino emission rates have been standardised for comparison as necessary.



The graph below indicates the relative neutrino emissions – logarithmic

- The earth – since the earth contains a variety of radioactive elements, some of which are slowly decaying by β-decay, it emits an estimated 3 x 10^{17} neutrinos s^{-1}.
- The big bang[34] – the “standard model” of the big bang predicts that, similar to the idea of photons and microwaves which have been left behind, a vast number of neutrinos remain – an estimated 300 neutrinos per cm^3 of space.[35]

However, it should be noted that these are not sources that can be obtained, used—and then removed when we no longer want them. These sources are all around us[36], and theoretically, neutrinos ‘passing by’ can come from anywhere. The sun, or the ends of the universe. In the same way, the neutrinos that our own bodies produce, travelling at the speed of light (*or close to*), could reach galaxies so far away that their mere existence is beyond our comprehension!

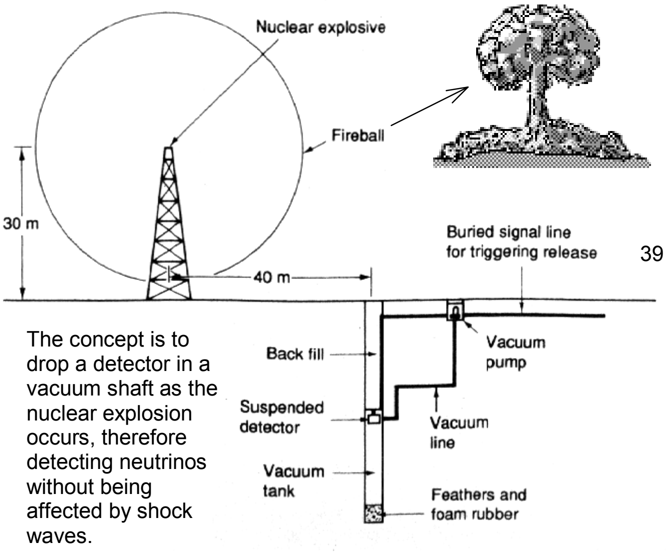
Recall that in original beta disintegration problem, the β-particles produced had a range of energies. Likewise, the neutrinos evolved from different sources have different energies[37]. Despite the seemingly abundant availability of ‘natural’ neutrinos, they are quite low in energy—in particular neutrinos from the big bang. Analogous to the way in which a speeding car is more likely to collide than a prudent driver is, it does not seem unreasonable to believe that neutrinos with greater energies are more likely to interact with matter than their less energetic counterparts. So how does one go about obtaining them? Presumably from an ‘artificial’ source.

Nuclear reactions.

One possible way to provide a short-burst of high-energy neutrinos is the use of a nuclear bomb[38]

The detonation of a nuclear bomb would produce billions of high-energy neutrinos due to the fission reaction—with a much higher probability of causing inverse beta decay

However, there are some obvious logistical problems. The idea that such a sensitive device could be operated within close proximity to the most violent explosion known to man, being one of them

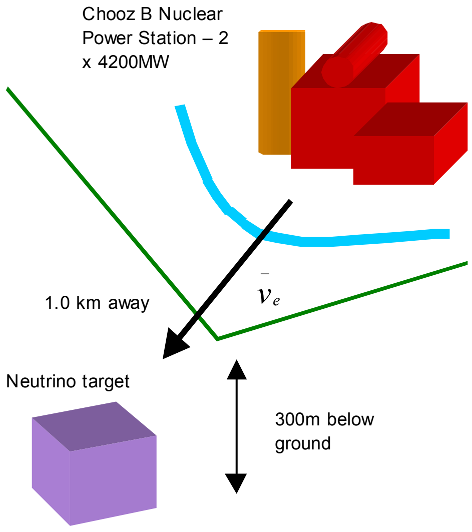


[39]

The concept is to drop a detector in a vacuum shaft as the nuclear explosion occurs, therefore detecting neutrinos without being affected by shock waves.

---

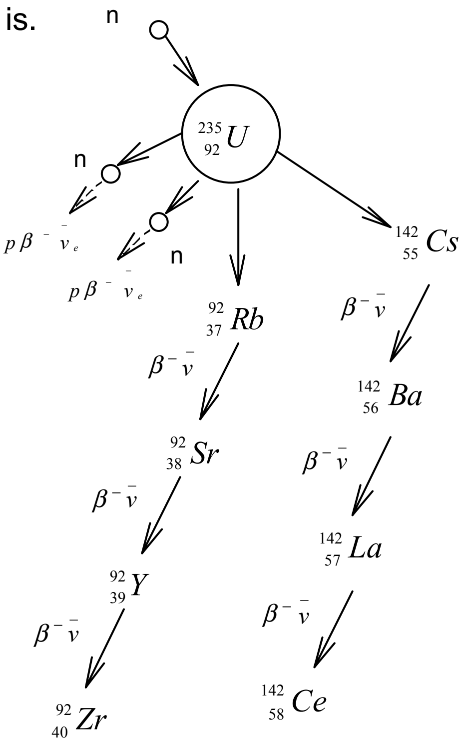
[34] As in the big-bang theory of the creation of the universe
[35] The significance of this will be discussed later on in the document
[36] and even are us!
[37] Measured in eV - electronvolts
[38] This was the very first plan for detecting neutrinos, designed by Fred Reines and Clyde Cowan, which planned to intercept some of the many billions of neutrinos emitted in the explosion of a nuclear bomb. Obviously, this plan never went ahead. Diagram imported from Neutrinos Galore – What is a neutrino?
[39] Fireball Diagram from Microsoft Encarta 1997 - ©Microsoft Corporation 1993-1995. All Rights Reserved.



[40] Chooz Underground Neutrino Laboratory – Ardennes, France

Although in some ways a possibility, it would be nicer to have a source of neutrinos that come from a more contained and continuous source. Indeed, if neutrinos are the small highly penetrable virtually massless particles they pledge to be, we should, in theory, be able to obtain high-energy versions from a commonplace nuclear reactor.

So it is.



An instance of the fission process. It shows neutrons and two chains of neutron-rich radioactive products, decaying successively by beta-decay and anti-electron neutrino emission. In each chain, bound neutrons turn into bound protons, successively, until finally a stable nucleus is reached.

Notice from the neutrino detector diagram (above) that such experiments need only take place nearby a nuclear power plant, and that there is no direct link – hence, no sort of special pipeline is needed for the neutrinos. Logically there is no need for one, and in my opinion, this is the beauty of such an experiment. The neutrinos produced will travel in every direction, to all ‘corners of the universe’. Clearly the closer you are, the greater the probability of detecting a neutrino. However small distances (*in terms of kilometres*) should make no significance difference, and such proximity can give way to more practical needs[41]—in particular the need to avoid elevated radiation levels. So too, can any concern of having a several metre thick lead wall affect your results[42]. Truly, the penetrating power of neutrinos is remarkable[43].

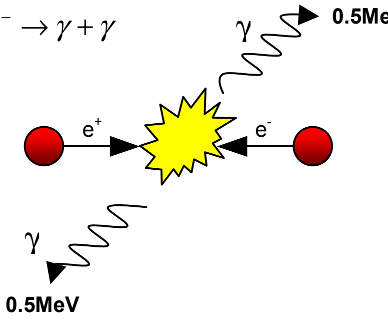
Nevertheless, the problems do not end here. The neutron emitted along with the positron in inverse beta-decay, like any free neutron, is an elusive beast to capture[44]. It effectively *staggers* through a material like a ‘drunk in a crowd’, colliding with one nucleus first, and then another, loosing energy on each occurrence—until it is finally absorbed. Since we can only show that a neutrino has caused inverse β-decay by the products formed, one has no option but to prove that both a neutron and a positron existed consequently.

---

[40] The diagram has been constructed from the aerial view of the site – The Chooz experiment, France. http://duphy4.physics.drexel.edu/chooz_pub/
[41] Land costs, available space, construction difficulties etc.
[42] It is fortunate for humans that we are not affected by neutrino bombardment, as we do not currently know of any method for controlling exposure.
[43] Estimates indicate that the total number of neutrinos produced per second by all the nuclear power stations collectively exceeds the natural neutrino production of our planet. – http://wwwlapp.in2p3.fr/~verkindt/neutrinos/ansources.html
[44] Further references can be found concerning the neutrons discovery by Chadwick – and the appreciable difficulty in doing so.

Consider carefully, the adsorption of a neutron by a nucleus. The neutron in question is still quite energetically active, and so in an attempt to form a new stable nucleus, this extra energy must be released—not surprisingly, by the emission of a gamma ray photon. The positron should also emit gamma rays, for a different reason. A matter anti-matter reaction.

$$e^{+} + e^{-} \rightarrow \gamma + \gamma$$

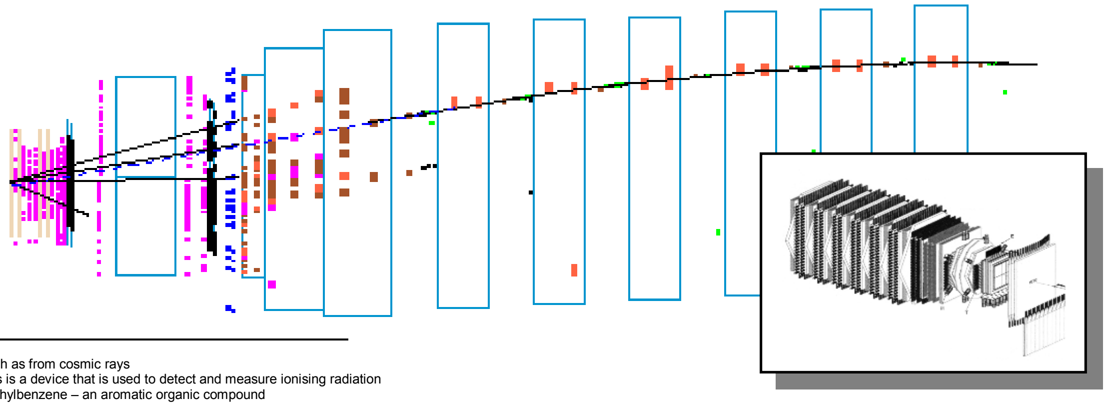


The annihilation process of matter and anti-matter produces a 100% conversion of mass to energy, released as gamma radiation – the total energy released being determinable by E=mc^2

Based on the rest mass of an electron of 9.109 x 10^{-31} kg, we can deduce that the minimum energy released is: E=mc^2, where c= 2.998 x 10^8 ms^{-1} ∴E = 2(9.109 x 10^{-31}) x (2.998 x 10^8)^2 = 1.64 x 10^{-13} J ≡ 1023397eV ≈ **1MeV**

Clearly, we can detect the γ-radiation produced by a neutrino interaction. However, neutrino interactions are not the only particles that could cause a γ-ray photon to be released from a material. There exists a multitude of charged particles hurtling around us, which must be differentiated—a form of background noise, if you will[45]. One also has to eliminate background radiation, but this is not a complicated task. The crucial factor for detection is the neutron's 'drunken walk' between its birth and capture. This takes a characteristic average time, analogous to the characteristic length of time between a drunk leaving a pub and falling over in the street!

Yet, fine detection of the γ-rays emitted is not easy. Even sensitive Geiger-Müller counters[46] could not provide a practical method for displaying the origin, track, destination and time of the rays. What's really needed is visual method—scintillation. Using certain toluene[47] based liquids with a scintillating chemical added, small flashes of light are produced almost immediately after a charged particle has passed through and ionised some of the atoms. Since gamma rays can induce ionisation indirectly, scintillations would also mark the death of any positrons annihilating in it. Such material can therefore be both the target, providing protons for inverse beta-decay reactions, and the detector. These light pulses can be detected by photomultipliers that are used to generate the appropriate information on computer systems[48].



[49]

---

[45] Such as from cosmic rays

[46] This is a device that is used to detect and measure ionising radiation

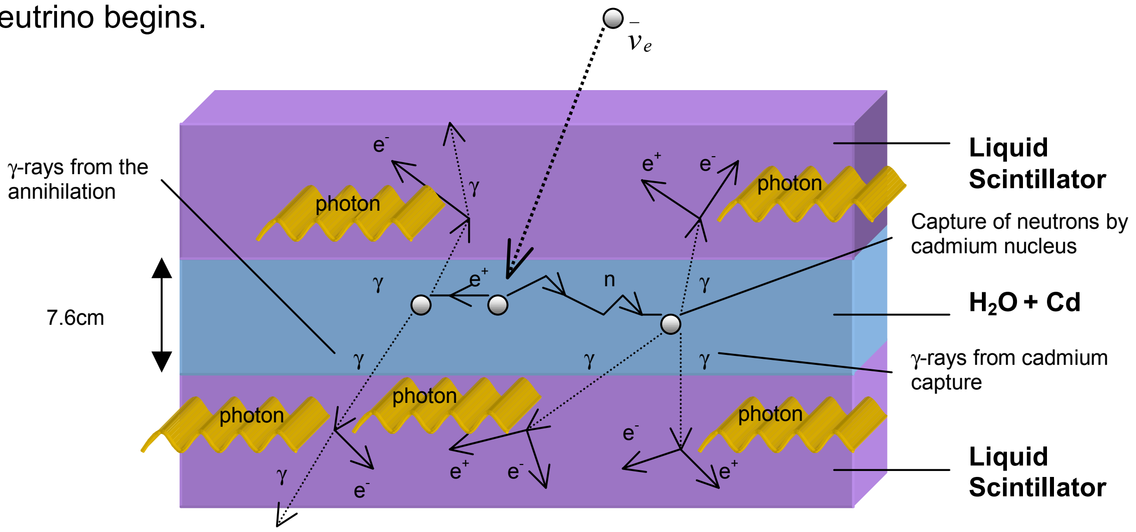
[47] methylbenzene – an aromatic organic compound

[48] In certain materials such as deuterium, the interaction of neutrinos directly causes the production of flashes of blue light, know as Cerenkov Radiation, and is not the same as scintillations produced as a result of ionisation. Cerenkov Radiation is electromagnetic radiation, emitted by a beam of high-energy charged particles passing through a transparent medium at a speed greater than the speed of light in that medium.

[49] A computer constructed detection from the CHORUS experiment. http://choruswww.cern.ch/Public/first_evt.html - here we see a cross section of the detector and particle traces. [right] – a model of the detector can be seen.

So the two characteristic bursts of light during inverse beta-decay in the scintillator are closely related in time: the flash due to the neutron must follow the one due to the positron by a regular time delay – a delay that we should be able to determine from our knowledge of the way neutrons interact with matter.[50]

For neutrons emitted in inverse beta-decay, travelling through liquid scintillator, the delay is approximately five microseconds (5µs)—thereby allowing us to ignore any other irrelevant scintillations. So the detection of the neutrino begins.



[51]

This method of neutrino detection uses a three-step process: first a proton in the water would absorb a neutrino, and produce a neutron and a positron—then almost immediately, the positron would annihilate with an electron, emitting two back-to-back γ-rays which could be detected in the adjacent layers of the scintillator. Then some 5µs later after the annihilation γ-rays had emerged, the neutron would be captured by a Cd nucleus, which would then emit some more γ-rays.

“We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta-decay of protons. Observed cross-section agrees well with expected six times ten to minus forty-four square centimetres.”

Reines and Cowan, 1956

Neutrinos and Mass

We are certain that neutrinos exist. However, many issues remain to be clarified. So far, reference to the mass of the neutrino has been that of “near massless” and “null”. So just how massless is it? The original concept and a variety of theoretical work suggests that the neutrino has no mass—and like the photon, travels at the speed of light. If the neutrino’s mass is indeed exactly zero, one cannot prove this experimentally. A possible measurement of the neutrinos mass could be obtained by measuring the difference between the available energy in a β-decay to the mass difference between the initial and final nuclei, and the highest energy of β-radiation—the resulting difference being the energy spent in the neutrinos mass, based on the mass-energy equation. However, in practice this direct method is confronted with experimental errors that, despite being small, can only suggest what its mass may be less than.

---

[50] Attempts to derive this are beyond the scope of this document

[51] Diagram constructed in Microsoft Word ’97 WordArt using schematics from Neutrinos – G.M.Lewis – Page 70 and Spaceship Neutrino – Christine Sutton – Page 42

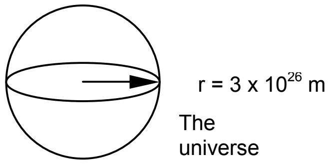
Early experimental work suggested a neutrinos mass was less than 60eV—approximately 1 x 10^{-34} kg. Today, from ongoing experiments, we believe it to be less than 3.9eV—6.9 x 10^{-36} kg.[52]

Currently statements either for or against a neutrino mass cannot be substantiated. Nevertheless, what is the significance? Since so many neutrinos are travelling throughout the universe and none tend to affect us, why should we care about particles that have a mass some 240 million times smaller than a proton? —Especially since so many people remain blissfully unaware of them.

Consider that in our current theory of the beginnings of our universe, there was a big bang—a singular point from which time and space was created—continuously expanding outwards. We believe that the universe is still expanding, but will it do so forever? If the total mass of the universe is sufficiently large, the attractive gravitational forces between the celestial bodies could attract them towards each other sufficiently so that the universe begins to contract again. Some theorise the big crunch, the collapse of the universe back to the same singular point. So what is the mass of the universe? Astronomers are currently unable to account for what is believed to be the whole mass of the universe from all visible matter—and a large part is thought to be "dark matter"[53]—a constituent of which are neutrinos.

Therefore, the difference between neutrinos of zero mass and negligible mass, can make a profanely profound difference to the total mass of the universe—given their plentiful nature. Let us perform a rough calculation to determine more mathematically the significance:

Assume the universe expanded from a single point evenly in all directions to form a sphere, with r = 3.0 x 10^{26}. [54] ∴



∴ The volume of the universe ≈ $\frac{4}{3}\pi r^3 \therefore \frac{4}{3}\pi(3.0\text{x}10^{26})^3$

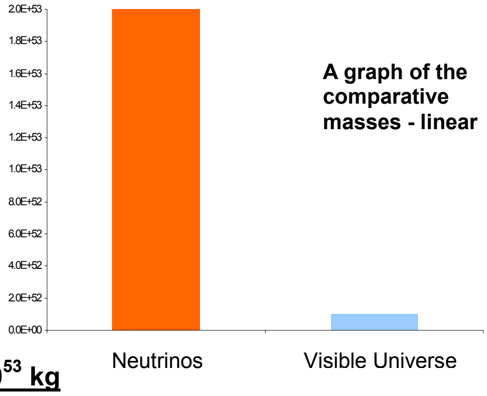
∴ ≈ 1.1 x 10^{80} m^3 ∴ 1.1 x 10^{86} cm^3

∴ Earlier data suggested that there are approximately 300 neutrinos per cm^3 of space from the big bang alone – assuming an even 'spread'

∴ There are (*very roughly*): 1.1 x 10^{86} cm^3 x 300 ≈ > **3.4 x 10^{88} neutrinos in the universe**

∴If each neutrino has a mass of approx. 6.9 x 10^{-36} kg, then the total mass of neutrinos in the universe would be:

6.9 x 10^{-36} kg x 3.4 x 10^{88} ≈ **2 x 10^{53} kg**


A graph of the comparative masses - linear

Note that the total mass of the observable universe ≈ **1 x 10^{52} kg** [55]

Even as a very crude estimate of the collective mass of neutrinos in the universe, we can most certainly see a fine line between no mass and a mass

---

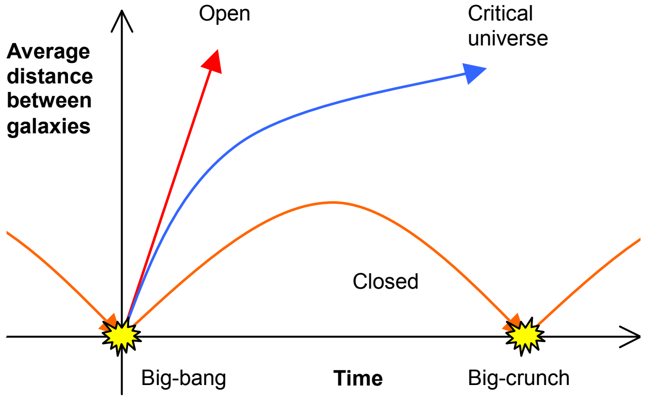
[52] Data refers to electron neutrinos - http://neutrino.pc.helsinki.fi/neutrino/

[53] The mass of matter in the universe that cannot be observed by direct observations of its emitted or absorbed electromagnetic radiation. There are a number of astrophysical observations that suggest that the actual mass of the universe is much greater than that estimated by observations using optical telescopes, radio telescopes, etc. It is thought that there is a considerable amount of *dark matter* (or *hidden matter*) causing this discrepancy.

[54] Source: Revised Nuffield Advanced Science Book of Data – Table1.7 – Length, Speed, Time, Mass: Some useful values

[55] Source: Revised Nuffield Advanced Science Book of Data – Table1.7 – Length, Speed, Time, Mass: Some useful values

which is 20 times greater than the observable universe! [56] So one can appreciate that this question of mass could decide the fate of our universe[57].



The Past and the future. The possibilities for the fate of the universe

Neutrino Oscillations

So far we have only referred to one particular type of neutrino—electron neutrinos (ν_e), the type involved in β-decay. However, we now appreciate that there are three types of neutrino—electron neutrinos (ν_e), muon neutrinos (ν_μ) and tau neutrinos (ν_τ), and their anti-particles ($\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$). These particles are all classified as leptons—and are closely affiliated with electron (e^-), the muon (μ), and the tau (τ) (*and their anti-particles*). The electron, muon and tau all have increasing mass and are relatives of each other. The same similarity emerges with the neutrinos—as the maximum experimental measurement of their mass increases too. m < 3.9eV for the electron neutrino, m < 170 keV for the muon neutrino and m < 18.2 MeV for the tau neutrino. So what does this all mean? To a certain extent, it would indicate that they have a mass that gradually increases—especially since in some grand unified theories they are predicted to have a nonzero mass[58]. Variations among classifications of this type are referred to as flavours[59]. Referring back to our earlier sources of neutrinos, we found that the sun was our primary source of energetic neutrinos[60]. The sun performs nuclear fusion at a typically constant rate, and from our understanding of it, we should be able to predict the average number of neutrinos one could expect to receive from it on a daily basis. Indeed, many experiments around the world are counting the number[61]—but all the data gathered reveals a slight problem. The expected electron neutrino flux from the sun is approximately double the experimental number found. Since experimentalists are certain that their apparatus is counting all the solar electron neutrinos received, and that their accuracy is high—it leaves us with two choices. Either our understanding of neutrino emissions from the sun is wrong, or quite simply we are not receiving the numbers we should do. Enter the theory of neutrino oscillations—and mass.

---

[56] The calculations performed here are based on several simple approximations. It is not the values themselves that are important, but instead their relative sizes and hence the aim here is to highlight rather than to calculate the issue. The method of calculation used is based on a basic logic, and there may be much evidence to flaw the approach taken. Since to date we only know the upper limit for the neutrino mass, the collective neutrino mass in the universe can therefore be somewhere between zero and 2×10^{53} kg

[57] Diagram created from the information available at http://astrosun.tn.cornell.edu/courses/astro201/open_closed.htm

[58] GUT's are theories that attempt to unite the strong, weak and electromagnetic interactions into a single theory. TOE's (Theories of everything) go further in that they attempt to unite gravity too. Further reading: Superstrings – Davies and Brown – Cambridge University Press Canto Series

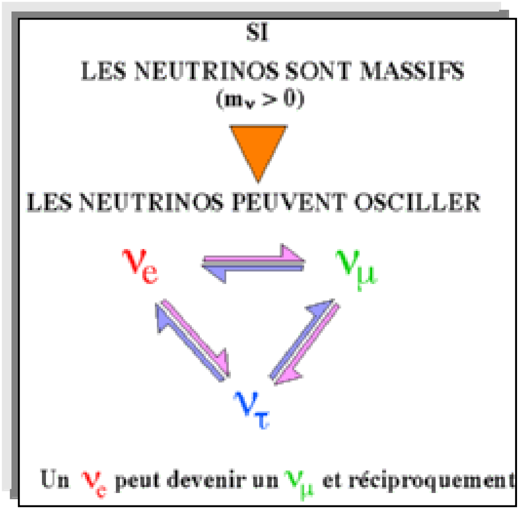
[59] especially with reference to quarks

[60] 0 – 20 MeV

[61] Visit http://wwwlapp.in2p3.fr/~verkindt/neutrinos/anexp.html for a list of examples

We appreciate that there are three flavours of neutrinos. We believed that only electron neutrinos are emitted from the sun—and that neutrinos are massless. Since experiments for solar neutrinos could only detect the electron flavour, it is not possible that other types are emitted instead? In theory, no. Muon and tau neutrinos are usually associated with the presence of the muon and tau particles, and they are unlikely to be present in the sun. So, what if neutrinos were changing from one flavour to another on their way to earth? Electron neutrinos converting into muon or even tau neutrinos. This seems quite plausible, but there is a problem with it. Massless particles as we understand it, cannot change into another type—so if we are to accept neutrino oscillations, so too must we accept a non-zero neutrino mass. This is the solar neutrino problem[62].

[63]



If neutrinos have a mass ($m_v > 0$)

Neutrino oscillations could occur

A ν_e could become a ν_μ and vice-versa

“By the grace of the AEC, BNL, God, Green and Hayworth (Alphabetical order) we should see neutrinos.”

Leon Lederman, 1960

“We do not know … [if] neutrinos are massive or massless. We do not know if the potentially massive neutrinos are Majorana or Dirac, and we do not know if these neutrinos can oscillate among flavours… In short, there is a great deal we do not know about neutrinos.”

Jeremy Bernstein, 1984

---

[62] A proposed experiment is to aim a neutrino beam from CERN in Geneva, Switzerland to the Italian Laboratory of Gran Sasso, at a distance of approximately 1000km to study neutrino oscillations. Are any taking place?

[63] From http://wwwlapp.in2p3.fr/~verkindt/neutrinos/neutimg/poscill.gif . Translated by John Kut

Bibliography

1. The Neutrino – CERN Hybrid Oscillation Research Apparatus Information – http://choruswww.cern.ch/Public/textes/english/node1.html
2. Revised Nuffield Advanced Science Book of Data – Longman – ISBN 0-582-35448-X
3. Physics Classical and Modern Second International Edition – Frederick J. Keller / W. Edward Gettys / Malcolm J. Skove – ISBN 0-07-112674-0
4. Spaceship Neutrino – Christine Sutton – Cambridge University Press – ISBN 0-521-36703-4
5. The Sudbury Neutrino Observatory – http://snodaq.phy.queensu.ca/SNO/sno.html
6. LAPP – History of Neutrinos – http://wwwlapp.in2p3.fr/~verkindt/neutrinos/aneut.html
7. ANTARES at Oxford – http://webnt.physics.ox.ac.uk/Neutrino/antareschat.htm
8. Neutrinos – G. M. Lewis – The Wykeham Science Series – Associated Book Publisher Limited – ISBN 0-85109-140-7
9. The Forces of Nature – Second Edition – P.C.W Davies – Cambridge University Press – ISBN 0-521-31392-9
10. The Particle Explosion – Frank Close / Michael Martin / Christine Sutton – Oxford University Press – ISBN 0-19-851965-6
11. FHEP Neutrino Experiments Page – http://www.physics.usyd.edu.au/hienergy/neutrino_experiments.html
12. Oxford Dictionary of Physics – New Edition – Oxford University Press – ISBN 0-19-280030-2
13. Oxford Dictionary of Chemistry – New Edition – Oxford University Press – ISBN 0-19-280031-0
14. Neutrino Oscillation Magnetic Detector – http://nomadinfo.cern.ch
15. Microsoft Encarta 1997 - ©Microsoft Corporation 1993-1995. All Rights Reserved. http://www.microsoft.com
16. The Chooz Experiment France – http://durphy4.physics.drexel.edu/chooz_pub/
17. Neutrino History - http://windows.ivv.nasa.gov/sun/Solar_interior/Nuclear_Reactions/Neutrinos/neutrino_history.html
18. The Neutrino Oscillation Industry - http://www.hep.anl.gov/ndk/hypertext/nu_Industry.html
19. The Ultimate Neutrino Page - http://neutrino.pc.helsinki.fi/neutrino/

CERN — European Laboratory for Particle Physics

20. http://www.cern.ch

Word Count: approximately 3300 words *(excluding footnotes, bibliography and cover text).*
Approximately 3800 words *(excluding footnotes)*

Saturday, 18 April 1998