Helicity of the Neutrino

Determination of the Nature of Weak Interaction

Amit Roy

Measurement of the helicity of the neutrino was crucial in identifying the nature of weak interaction. The measurement is an example of great ingenuity in choosing, (i) the right nucleus with a specific type of decay, (ii) the technique of resonant fluorescence scattering for determining direction of neutrino and (iii) transmission through magnetised iron for measuring polarisation of γ-rays.

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In the field of art and sculpture, we sometimes come across a piece of work of rare beauty, which arrests our attention as soon as we focus our gaze on it. The experiment on the determination of helicity of the neutrino falls in a similar category among experiments in the field of modern physics. The experiments on the discovery of parity violation in 1957 [1] had established that the violation parity was maximal in beta decay and that the polarisation of the emitted electron was 100%. This implies that its helicity was -1.

The helicity of a particle is a measure of the angle (cosine) between the spin direction of the particle and its momentum direction. $\boldsymbol{H} = \sigma.\boldsymbol{p}$, where σ and $\boldsymbol{p}$ are unit vectors in the direction of the spin and the momentum, respectively. The spin direction of a particle of positive helicity is parallel to its momentum direction, and for that of negative helicity, the directions are opposite (*Box* 1). The net polarisation, i.e., the expectation value of the helicity $\langle \boldsymbol{H} \rangle$ is zero, if parity is conserved.

Keywords:
Helicity, neutrino, weak interaction, V–A theory, resonant fluorescence scattering.

Why was the measurement of helicity important? It was crucial to the determination of the nature of the interaction responsible for beta decay. The interactions respon-

Box 1. Helicity

Helicity for a particle is defined as the projection of the particle's spin along its direction of motion. For a massive particle, the sign of its helicity depends on the frame of reference and the value is given by $\langle H \rangle = \pm v/c$. For massless particles, the helicity is the same for all observers. For a photon, although its spin has a value of 1, there exist only two helicities corresponding to left and right circular polarization. The helicity of the neutrino (or antineutrino) emitted in a beta decay depends on the form of the beta interaction, since this interaction determines the $\beta - \nu$ angular correlation, i.e., the variation of intensity with the angle between the emitted beta and the neutrino.

sible for beta decay could be of five types: vector (V), axial vector (A), scalar (S), pseudoscalar (P) and tensor (T) [2]. Only experiment could help identify the correct interaction type(s) responsible. The antineutrino emitted along with the electron would have a helicity depending on the nature of the interaction. Thus, a determination of the helicity of the neutrino emitted in the beta decay would settle the issue (*Box* 2). How could this be achieved?

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A team of three scientists at Brookhaven National Laboratory, M Goldhaber, L Grodzins and A W Sunyar set about to rectify the situation. Wu *et al* [3] had shown in their experiment that the electrons from oriented ^{60}Co nuclei are preferentially emitted in the direction opposite to that of the ^{60}Co spin. The electrons are, thus, polarised opposite to their direction of motion. In other words, they have negative helicity. The method used for measuring the helicity of electrons is to scatter them off oriented electrons and measure the asymmetry of scattering. But this method will not work for neutrinos, since the neutrinos, having no charge, interact only weakly and the probability of interaction is too low. A completely new idea was needed. Goldhaber and his colleagues turned their attention to the decay of a particular radioactive nucleus ^{152}Eu, in which gamma rays are emitted following beta decay. This nucleus decays by electron capture, a process in which there are only two particles in the final state as opposed to the case of

Box 2. Allowed Transitions and Electron–Neutrino Angular Correlation

In beta decay, the selection rules for angular momentum (J), parity (π) and isospin (I) determine which transitions are favoured or allowed. The terms 'allowed' and 'forbidden' were given in the early days to broadly classify beta decay in nuclei according to the rates of decay or inversely to the decay lifetimes. For 'allowed' transitions, the change in angular momentum between initial and final states, $\Delta J = 0$ or 1, and the product of initial and final state parities should be positive, i.e., $\pi_{\rm i}.\pi_{\rm f} = +\,1$. 'Forbidden' transitions are further classified in sub-categories depending on whether they involve a parity change and/or a change of angular momentum of more than one unit.

For Fermi transitions, $\Delta J = |J_{\rm i} - J_{\rm f}| = 0$, $S = 0$ (S denoting the resultant spin of electron and neutrino. In this case, electron and neutrino spins are anti-parallel.). For Gamow–Teller (GT) transitions, $\Delta J = 0, \pm 1$; $S = 1$ (electron and neutrino spins are parallel). Thus, if we have a transition between spins $J_{\rm i} = J_{\rm f} = 0$, it would be pure Fermi type and $\Delta J = 1$ transitions are pure Gamow–Teller type. $\Delta J = 0$ and $J_{\rm i} \neq 0$ transit are mixtures of Fermi and Gamow–Teller types.

The electron–neutrino angular correlation, which gives the probability of emission of an electron of energy E and momentum p and an antineutrino with a definite angle, θ between their moment is governed by the type of interaction responsible for the beta decay. It can be written in the form,

$$P(E,\theta) = C[1 + a\boldsymbol{p}\cos\theta/E],$$

where the value of C depends on the electron energy and momentum and the antineutrino momentum and a correction factor due to the Coulomb field of the nucleus. The value of a depends on the strengths, g, of the type of interaction responsible for the beta decay, i.e., scalar (S), pseudoscalar (P), vector (V), axial vector (A) and tensor (T).

For a pure Fermi type of decay, $a_{\rm F} = ({g_{\rm V}}^2 - {g_{\rm S}}^2)/({g_{\rm V}}^2 + {g_{\rm S}}^2)$;

In case of only vector type, the value of $a_{\rm F}$ is +1 and $\boldsymbol{H}_e = -$ve, $\boldsymbol{H}_\nu = +$ve; for scalar type, the value of $a_{\rm F}$ is -1 and $\boldsymbol{H}_e = -$ve, $\boldsymbol{H}_\nu = -$ve.

For a pure GT type of decay, $a_{\rm GT} = ({g_{\rm T}}^2 - {g_{\rm A}}^2)/3({g_{\rm T}}^2 + {g_{\rm A}}^2)$.

In case of only tensor, the value of $a_{\rm GT}$; is $+1/3$ and $\boldsymbol{H}_e = -$ve, $\boldsymbol{H}_\nu = -$ve; for only axial vector, the value of $a_{\rm GT}$ is $-1/3$ and $\boldsymbol{H}_e = -$ve, $\boldsymbol{H}_\nu = +$ve.

Pseudoscalar interactions occurs only for forbidden type decay, the value of $a_{\rm P}$ is -1 and $\boldsymbol{H}_e = -$ve, $\boldsymbol{H}_\nu = +$ve.

beta decay, where three particles particles are present in the final state. Following Goldhaber, let us consider the decay of a parent nucleus A with spin $J_{\rm A} = 0$ to an excited state B* with spin $J_{\mathrm{B}^*} = 1$ of nucleus B, through capture of an electron from the atomic s-state. Let this excited state, B* decay to the ground state of daughter nucleus B with spin $J_{\mathrm{B}} = 0$ through gamma emission. The whole process can be represented by

$$e_{\mathrm{k}}(1/2) + \mathrm{A}(0) \rightarrow \mathrm{B}^*(1) + \nu(1/2) \rightarrow \mathrm{B}(0) + \gamma(1) + \nu(1/2),$$

where the spin values are indicated in the brackets. Now, we work out the consequence of conservation of angular and linear momentum in the whole process of decay. The nucleus B* must recoil with momentum equal and opposite to that of the neutrino. So a measurement of the direction of recoil of nucleus B* determines the neutrino momentum direction. As the sum of the initial spins of e_{k} and A equals 1/2, we can deduce from conservation of angular momentum that the spin of B* would be in a direction opposite to that of the neutrino. Therefore, the nucleus B* has the same-handedness as the neutrino and the helicity of the neutrino can be determined through a measurement of the helicity of the recoiling nucleus. The polarised recoiling nucleus B* decays by emitting a γ-ray to the ground state of B with spin zero, hence a γ-ray emitted opposite to the direction of the neutrino direction will have the same helicity as that of the neutrino, i.e., $H_\gamma = H_\nu$. This is shown in *Figure* 1.

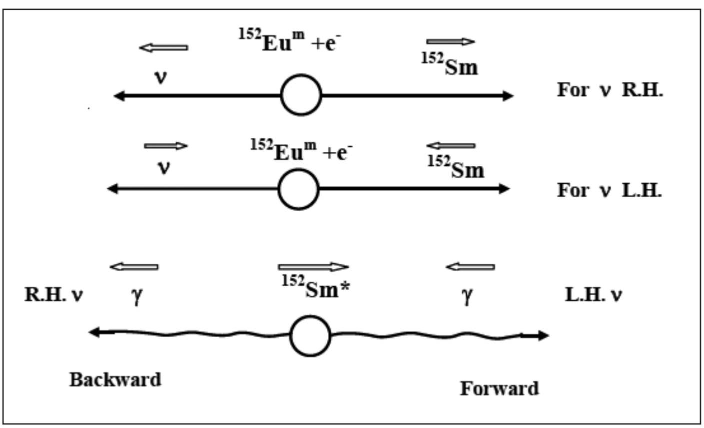

Figure 1. The relation between the directions of the emission of the γ-ray and the recoiling nucleus for different signs of neutrino helicity. The solid arrows show the direction of motion and the hollow arrows show the spin direction.

In general, the circular polarisation of the γ-ray is proportional to the cosine of the angle between its momentum and that of the recoiling nucleus, B*.

Thus, the measurement of neutrino helicity requires picking out the γ-rays emitted in the direction of recoil and then measuring their circular polarisation. The conditions for successfully carrying out such an experiment rested on finding a suitable radioactive nucleus decaying by electron capture to an excited state of a nucleus having spin 1. All these conditions were met by the radioactive nucleus ^{152}Eu$^{\mathrm{m}}$. The isomeric state with spin, parity 0^- has a reasonably long lifetime of 9.3 hrs and decays by K-electron capture to an excited state at 961 keV in the nucleus ^{152}Sm (spin, parity = 1^-). The excited state in ^{152}Sm decays to the 0^+ ground state through the emission of a γ-ray. It is interesting to note that at that time, the decay scheme of the nucleus ^{152}Sm was probably known only to the Brookhaven team. The energies of the excited state, determined by Grodzins are shown in *Figure* 2 [5].

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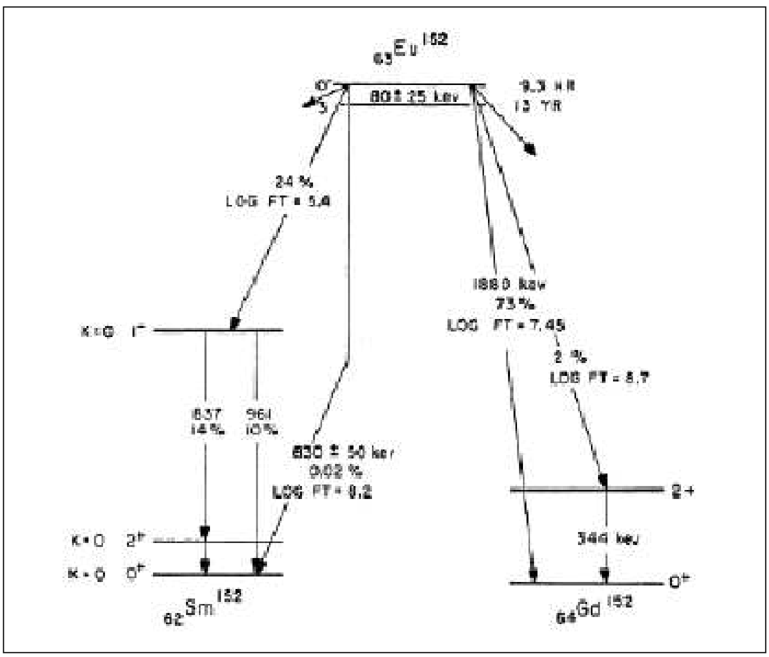

Figure 2. The decay scheme of the isotope, ^{152}Eu with a half-life of 9.3 hours. It decays via emission of an electron to ^{152}Gd (75%) and by electron capture to ^{152}Sm (24%). Following electron capture, the nucleus emits the γ-rays of energies 837 and 961 keV.

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Direct determination of the direction of neutrino emission is extremely difficult due to the very low interaction probability of the neutrino. Goldhaber and colleagues chose the ingenious method of resonant scattering of the 961 keV γ-ray to determine the neutrino direction. The circular polarisation of the γ-ray was analysed by transmission through fully magnetised iron.

Let us consider these two techniques in some detail. Resonant fluorescence is a process where the radiation emitted by one atom excites the same transition in another atom. Resonance fluorescence of optical transitions can be readily observed by using a decay from a level, E_0, to supply radiation which will excite the same level in another atom. The transition has to involve two states that differ by an energy of E_0. Such a technique is usually not possible for high energy γ-rays, where recoil of the nuclei during both emission and absorption would reduce the γ-ray energy so much that absorption would no longer be possible. The energy lost by recoil of a nucleus of mass M during emission and absorption is $\Delta E = {E_0}^2\ /(2Mc^2)$, neglecting higher order terms in recoil velocity. For γ-ray transitions in nuclei ($E_0 \sim$ hundreds of keV), this energy lost due to recoil is in general much greater than the level width, Γ. Resonant scattering will only take place if extra energy equal to the energy lost by recoil is supplied to the emitted γ-ray. For low energy γ-rays, this may be done by the Doppler shift from thermal motion or from a spinning wheel or from the motion of the diaphragm of a speaker as in the case of the Mössbauer effect (*Box* 3, [5]). For high energy γ-rays the required speed of a wheel would be too large.

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Goldhaber and colleagues used the recoil from the emission of neutrinos in the case of decay of ^{152}Sm, to compensate for the loss due to the recoil of the nucleus while emitting and absorbing the γ-ray. The emission of a neutrino causes the nucleus to recoil and if the de-excitation

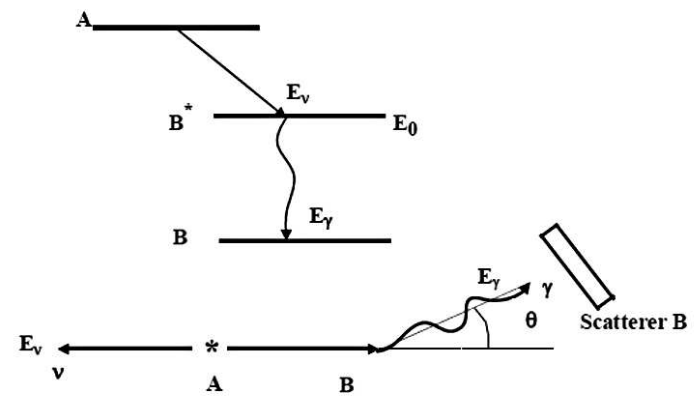
Box 3. Mössbauer Effect

This effect was discovered by R L Mössbauer in 1958 when he observed nuclei absorbing γ-rays without any energy loss to nuclear recoil. This happens when the nucleus is embedded in a crystal and the entire crystal takes up the recoil. This is truly a quantum effect. Since the crystal mass is very much larger than that of a single nucleus, the energy lost to recoil is very small. If the energy loss is less than half of the natural linewidth of the γ-ray, then recoil-free resonant absorption takes place. The natural linewidth of γ-rays are in the range of 10-5 eV, hence observation of this effect allows us to compare very precisely the energies of two atomic nuclei. Small shifts of energies due to temperature, magnetic impurities, chemical environment in materials, etc. can be measured using the Mössbauer effect easily in a laboratory with modest means and it has become a precise and routine tool in most laboratories across the world.

by γ-ray occurs before the nucleus slows down, the γ-energy will be Doppler shifted. If E_ν be the energy carried by the neutrino, then the resonance condition is $E_\nu \cos\theta = E_0$, where E_0 is the energy of the level involved in γ-emission and resonant excitation and θ is the direction of emission. When $E_\nu = E_0$, it is precisely the 'forward' γ-rays, emitted in the direction of the recoiling nucleus, which are able to excite the state in ^{152}Sm, and are therefore automatically selected by the resonance scattering. For the 961 keV level in ^{152}Sm, the mean lifetime was determined to be $(3.5 \pm 1) \times 10^{-14}$ sec, much shorter than the stopping time of the recoiling nuclei even in a solid source and hence the γ-ray would be emitted by the nucleus in flight before any appreciable change in the recoil momentum.

In the case considered here, $E_\nu = 890 \pm 5$ keV and $E_0 = 961$ keV. Therefore, the expected polarisation of the γ-ray would be less than 100%. *Figure* 3 shows the relationships without considering thermal effects. If the finite level width and the $\cos\theta$ dependence of the circular polarisation are taken into account ignoring thermal motion and capture in L and M shells, the expected polarisation is calculated to be 84%.

Now all that remained was to determine the sense of polarisation of the γ-rays. This was easily achieved by



$$E_\gamma = E_0 (1 + (E_\nu/Mc^2 \cos\theta) - E_0^2/(2Mc^2)$$

$$E_\gamma' = E_0 (1 + (E_\nu/Mc^2 \cos\theta) - E_0^2/(Mc^2)$$

For resonance, $E_\gamma' = E_0$

$$\therefore \quad E_\nu \cos\theta = E_0$$

Figure 3. Relationship between the energy of the γ-ray and the recoil direction of the nucleus for the observation of resonance absorption. E_ν is the energy of neutrino emitted by nucleus A, E_γ is the energy of γ-ray emitted by the resultant nucleus B, after β-decay and E_γ' is the excitation energy available for the second nucleus (scatterer B), after subtraction of its recoil energy. The expressions are obtained using the principles of energy and momentum conservation and neglecting higher order terms in recoil velocity.

letting the γ-rays pass through fully magnetised iron. The electron spins in the iron would be aligned in the direction of the magnetic field. An electron in the iron with spin opposite to that of the photon can absorb the unit of angular momentum by spin-flip; if the spin is parallel to the photon it cannot. Hence, for γ-rays emitted in the same direction as the magnetic field, the transmission of the iron is greater for left-handed γ-rays than that for right-handed ones. The advantage of the transmission method lies in the fact that the energy of the transmitted γ-ray is the same as the incident ray. The disadvantage of the method is that the circular polarisation efficiency is poor and the intensity of transmission is small.

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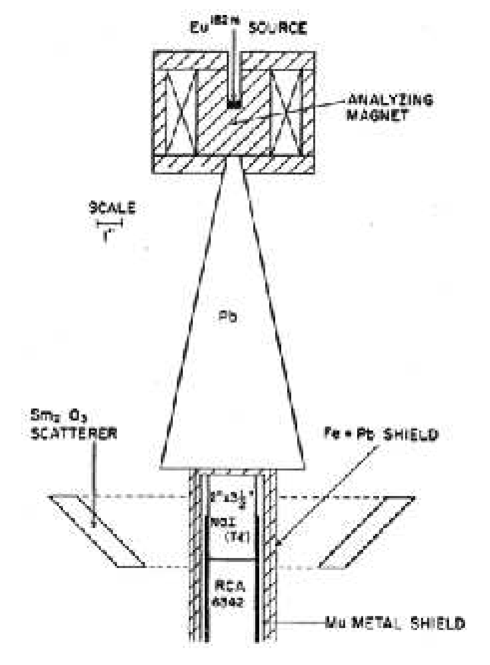
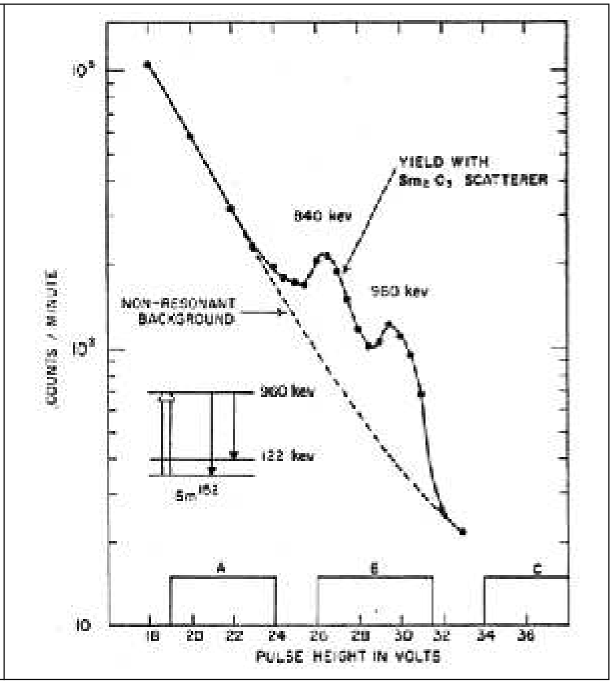
Goldhaber and collaborators used $^{152}Eu^{m}$ source prepared by neutron capture in a reactor and then placed it in the centre of an electromagnet whose field could be reversed (*Figure* 4). The γ-rays were made to traverse about 6.4 cm of fully magnetised iron, i.e., about 3 mean





free paths (mfp) for analysis of the circular polarisation. The γ-rays were resonantly scattered by about 1700 g of Sm_2O_3 in the form of a ring, placed around a 51mm diameter, 89 mm long cylindrical NaI(Tl) scintillation detector. A lead scatterer containing an equivalent number of electrons could replace the Sm_2O_3 scatterer as a check on resonant scattering. The detector was shielded from the direct γ-rays from the source by about 30 cm of lead. The scattered γ-ray spectrum was recorded by reversing the magnetic field every three minutes and the cycle of field reversals was such that decay corrections were negligible. The experimental set-up employed by them is schematically shown in *Figure* 4. A typical spectrum recorded by them is shown in *Figure* 5. The whole set of measurements was repeated nine times, each time with a source of 50 mCi strength. The quantity δ, which is the normalized difference between counts with magnetic fields reversed, is defined as,

$$\delta = 2(N_- - N_+)/(N_- + N_+),$$

Figure 4 (left). Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays.
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Figure 5(right). Resonant scattering distribution from a scatterer of ~1850 g of Sm_2O_3.
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Thus, they concluded that the neutrino emitted in K-capture has negative helicity and therefore, the beta decay of the proton proceeds via the axial vector (A) and vector (V) modes of interaction.

where N_+ and N_- are the number of γ-rays counted with magnetic field in directions up and down respectively

If we assume the circular polarisation of the γ-ray to be 100%, the expected value of δ for the γ-rays travelling through magnetised iron 3mfp long, would be only about 2.1%. This shows that the task of Goldhaber and his collaborators was far from simple. They had to be sure that no interfering instrumental effects were present and the error of their measurement had to be much lower than 2%. To do this, they undertook the following procedure.

The γ-ray spectrum was divided into three regions A, B and C as indicated in *Figure* 5. The sum of counts observed under the two peaks at 837 and 961 keV in region B was taken as a measure of resonant excitation. The low energy region A represents Compton scattering in the detector and the region C was taken as a measure of the background. In all the runs, they found no significant effect of magnetic field on the count rate in region A. The count rate in region B decayed with the decay rate of $^{152}\mathrm{Eu}^{\mathrm{m}}$, i.e., 9.3 hrs. Neither decay nor any significant change with magnetic field was found for counts in region C.

Since magnetic fields can alter the gain of the photomultipliers, which would change the counts recorded under the peaks, the gain of the amplifier was monitored by observing the position of the γ-ray emitted by a $^{137}\mathrm{Cs}$ source placed next to the detector. Several dummy runs by replacing the Sm_2O_3 by a lead scatterer were taken. No effect of the magnetic field was observed within the accuracy of the measurement in this case. The $^{152}\mathrm{Eu}^{\mathrm{m}}$ source was placed at the bottom of the magnet and no effect of the magnetic field in this case was observed on counts in region B. In the nine runs, they observed an average value of $\delta = 0.017 \pm 0.003$, which corresponds to the value of $67 \pm 10\%$ for the circular polarisation of the γ-ray. This was consistent with the expected polarisation of 84% without including thermal motion in the source and also capture in other than K-shell. Thus they concluded that the neutrino emitted in K-capture has negative helicity and therefore, the beta decay of the proton proceeds via the axial vector (A) and vector (V) modes of interaction. This combination of V and A was shown to be compatible with lepton number conservation and a universal Fermi interaction by Sudarshan and Marshak and also by Feynman and Gell-Mann [6,7].

On looking back, it appears quite strange that the experiment of Goldhaber which established the helicity of the neutrino to be $-1.0 + 0.2$ was considered conclusive evidence that the neutrino emitted in beta decay was 100% left-handed. With the advent of unified models of interactions, the question of left-right symmetries was reopened as it was rightly felt that possible admixture of right-handedness was not experimentally ruled out. This led to a series of experiments to search for right-handed or V+A component of the weak interaction. Since the direct measurement of the helicity of the neutrino more precisely than that of Goldhaber et al is difficult, three different types of experiments were embarked on. These are: (i) Comparison of $\beta^{\pm}$ polarisations in Fermi and Gamow–Teller transitions; (ii) Decay of the muon and (iii) Double beta decay. The results on longitudinal polarisations in beta decay have yielded limits on V+A admixtures to be $< 10^{-4}$. The limits obtained from muon decay is $<10^{-3}$ and from the double beta decay experiments, the limit so far is $<10^{-4}$. Experiments are continuing even now to refine the limits and establish the true nature of the weak interaction.

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Suggested Reading

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