PHYS 851 – Introductory Nuclear Physics
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Neutrino Helicity Measurement

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1 Introduction

The purpose of this paper is to give an overview of Goldhaber's experiment for measurement of the neutrino helicity [1]. Therefore helicity is defined, and is discussed whether it is a good quantum number or not. The setup and measurement method used in the experiment are explained as well as the results. The paper concludes with recent discoveries and questions that are still currently unanswered.

2 Neutrinos

The neutrino was proposed by Pauli as he tried to explain the observed continuous energy spectrum of electrons in a β decay. Either conservation of energy and momentum had to be violated or a third particle is involved in the reaction, that could carry away energy and momentum.

$$\mathrm{n} \longrightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

The neutrino was experimentally discovered in 1949 by Chalmers Sherwin. It is a neutral lepton that can be found in three families, as the electron, muon and tauon neutrino. It has been discovered only in recent years that it has a finite, albeit very small, mass. The experiment proved neutrino oscillations between the families; these oscillations only can occur, when neutrinos have non-zero mass. Neutrinos only participate in the weak interaction and thus it is not easy to observe them directly. Neutrinos are very abundant throughout the universe and play a important role in stellar evolution. Many physicists hoped to explain the nature of dark matter with the small neutrino mass. But as it turns out, the neutrino mass is too small to account for all the missing mass.

3 What is helicity?

Helicity is strongly connected to the parity operation $\mathcal{P}$, which is a mirror reflection operation followed by a rotation of π, so that $\vec{r}$ changes to $-\vec{r}$. Helicity is defined as the (normalised) spin projected along the momentum direction:

$$H \equiv \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{\sigma}| \cdot |\vec{p}|}$$

A particle with $H = +1$ is called *right handed* (spin and momentum vector parallel), one with $H = -1$ is *left handed* (spin and momentum vector antiparallel). As the spin does not change sign under parity operation (axial vector, just like an angular momentum $\vec{L} = \vec{r} \times \vec{p}$) but the momentum does (polar vector), H changes its sign, thus is a *pseudoscalar*. It is easy to see that helicity is Lorentz-invariant only if the desrcibed particle is massless. Otherwise it is always possible to find a reference frame, where the momentum of the particle points in the other direction, thus the helicity would have a different sign. Therefore speaking of helicity conservation only makes sense for massless particles, i. e. if helicity is well defined. On the other hand it is possible for photons to take both a helicity of -1 and $+1$.

The net polarisation, i. e. the expectation value of the helicity $\langle H \rangle$ is zero, if parity is conserved. Parity breakdown was predicted by Lee and Yang and experimental proven by Wu. The weak interaction only acts on left handed particles (and right handed anti-particles), thus the parity symmetry is broken by the weak interaction. The handedness, which the weak interaction acts on is a result of the neutrino helicity measurement experiment.

4 How to measure the neutrino's helicity?

The measurement of the neutrino helicity is quite challenging but has been done in an elegant way by Goldhaber et al. First we need a neutrino source. We produce neutrinos and photons by means of electron capture in the atom ^{152}Eu and following three body decay. This isotope was chosen because of the spin of the initial and final states – they are both 0. We shall see why this is important.

$$^{152\mathrm{m}}\mathrm{Eu} + \mathrm{e}^- \longrightarrow {}^{152}\mathrm{Sm}^* + \nu_\mathrm{e} \longrightarrow {}^{152}\mathrm{Sm} + \nu_\mathrm{e} + \gamma$$

The state of the $^{152\mathrm{m}}$Eu atom is of spin/parity 0^- and it decays to an excited $^{152}\mathrm{Sm}^*$ state with 1^- by absorbing one of its orbit electrons while emitting a neutrino (see figure 1). The excited state relaxes under emission of a γ-quantum with the energy $E_\gamma = 960\,\mathrm{keV}$ due to an electric dipole transition. It is instructive to look at the spins of the participating particles. The Europium nucleus has spin 0, the absorbed electron has spin $\frac{1}{2}$, of course. The (excited) daughter nucleus is of spin 1 and the emitted neutrino is of spin $\frac{1}{2}$. The Samarium ground state has spin 0, the emitted photon has spin 1. Considering the conservation of angular momentum one can find two possibilities for this reaction, only differing in the spin projection of the participating particles:

$^{152\mathrm{m}}$Eu	$+$	e^-	$\longrightarrow$	$^{152}\mathrm{Sm}^*$	$+$	ν_e	$\longrightarrow$	^{152}Sm	$+$	ν_e	$+$	γ	
0	$+$	$+\frac{1}{2}$	$\longrightarrow$	$+1$	$+$	$-\frac{1}{2}$	$\longrightarrow$	0	$+$	$-\frac{1}{2}$	$+$	$+1$	$\Rightarrow H_\nu = -1$
0	$+$	$-\frac{1}{2}$	$\longrightarrow$	-1	$+$	$+\frac{1}{2}$	$\longrightarrow$	0	$+$	$+\frac{1}{2}$	$+$	-1	$\Rightarrow H_\nu = +1$
				$\downarrow$		$\uparrow$			$\downarrow$	$\uparrow$		$(\downarrow)$	

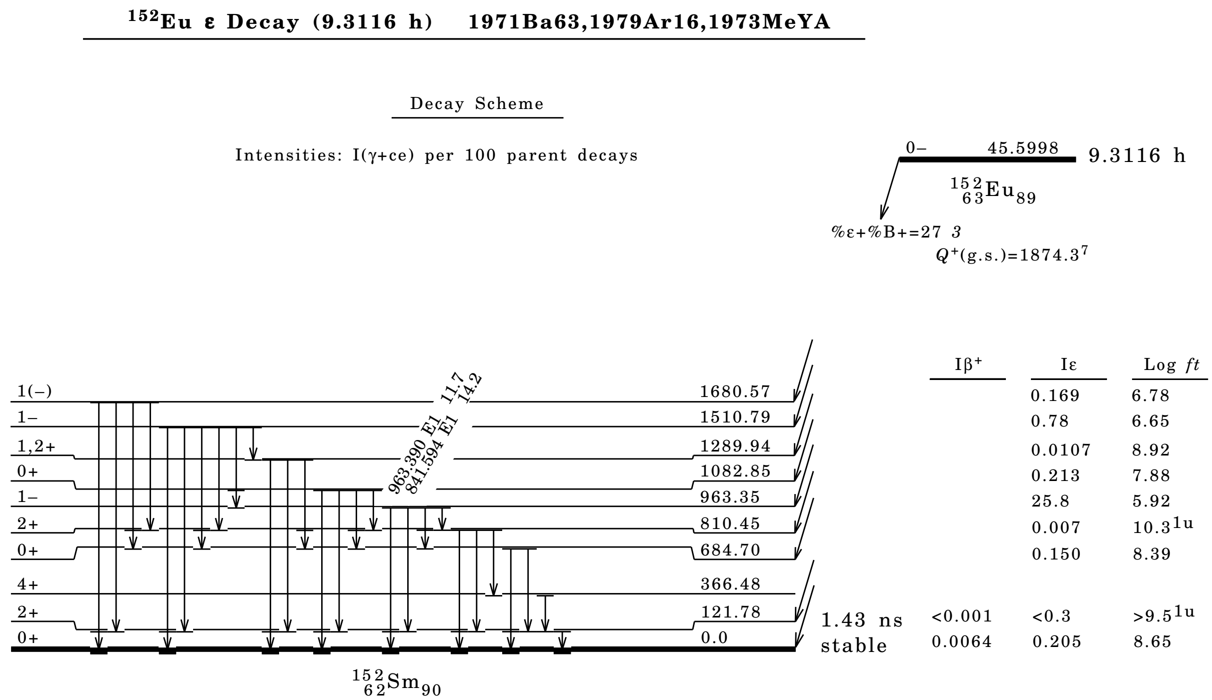

Figure 1: Decay scheme of ^{152m}Eu [3], modified.

Here the spin projection axis is chosen to be the neutrino emission direction and the arrows denote the directions of the particles (the photon can be emitted in all directions, but only the marked direction will be used). Thus a negative spin projection of the neutrino corresponds to left handed helicity and vice versa. Note that the helicity of ^{152}Sm* is the same as the neutrino helicity; the same applies to the emitted photon (both particles are emitted opposite to the neutrino and have opposite spin). If we, therefore, can measure the polarisation of the photon, we will know the helicity of the neutrino immediately. Thus there are two values to be measured: The helicity of the photon and the direction of the neutrino.

To determine the direction of the neutrino emission the resonance scattering method is used. During de-excitation of ^{152}Sm* a γ-quantum with the energy $E_\gamma = 960\,\text{keV}$ is emitted in a random direction. This photon is incident on a ^{152}Sm target. Usually it could excite the 960 keV level, but one has to consider energy loss due to the recoil during emission and absorption of the photon (see figure 2). Because the width Γ of the resonance is much smaller than the energy difference, excitation does not occur. On the other hand the Samarium atom is in motion and thus photons are Doppler shifted, i. e. the energy distribution is smeared. They have more energy in direction of the ^{152}Sm atom and are now again able to excite another Samarium atom (see figure 3). But the direction of the former

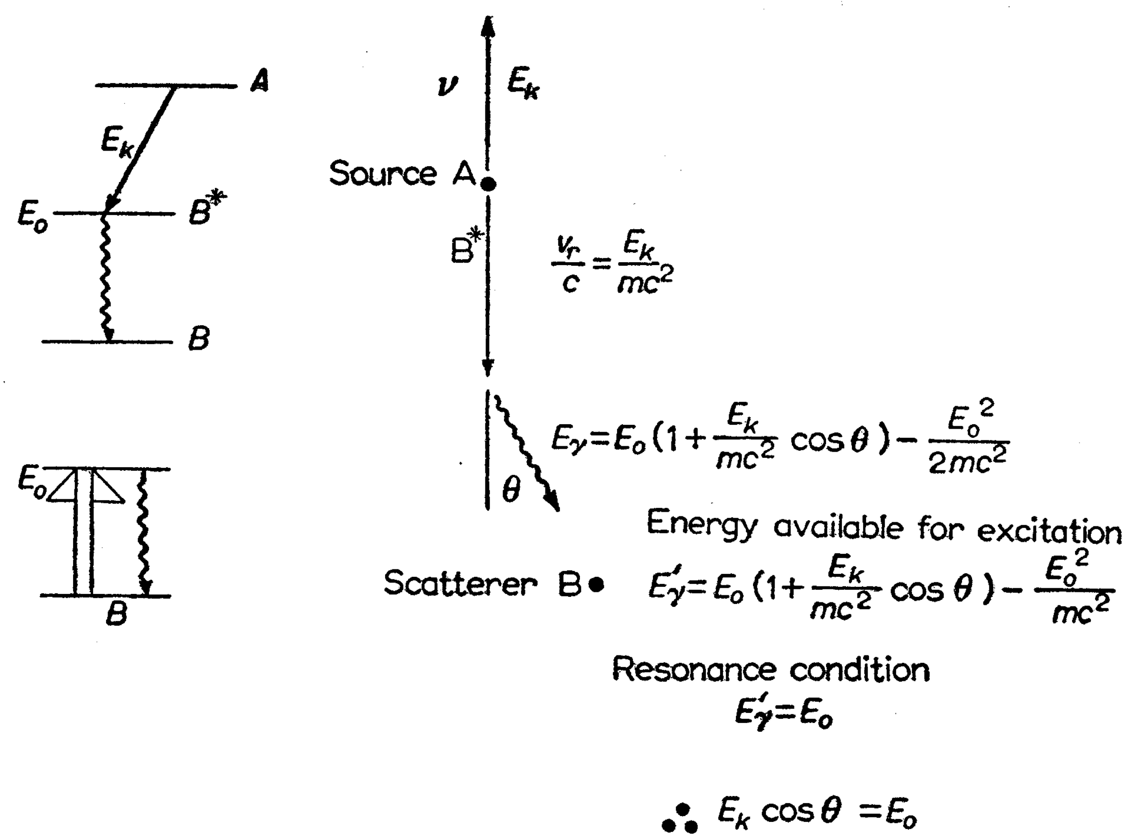

Figure 2: Energy considerations for resonance scattering [2].

Samarium is just the opposite direction of the neutrino. When the latter Samarium atom relaxes, the photon energy is registered in a scintillation detector. A scintillation detector consists of a crystal (e. g. NaI) and a photo multiplier tube. Incident γ-rays deposit their energy due to Compton-, photo- and pair production-effect in the crystal. The atoms relax under emission of photons of a different wavelength which are able to free electrons in the photocathode. These electrons are accelerated in dynodes where they are amplified avalanche-like and eventually get registered as a voltage pulse at the anode.

Now the only remaining problem is to determine the helicity of the photons that are incident on the Samarium target. This is done by filtering out photons of a specific helicity by means of a magnet between the Europium source and the Samarium target. So how is it possible to stop photons of one helicity and let pass photons of different helicity? The electron spins in the magnet align antiparallel to the magnetic field. If a left handed photon is incident in opposite direction to the electron spins (so electron spin and photon spin point in the same direction), the photon is more likely to be transmitted. A right

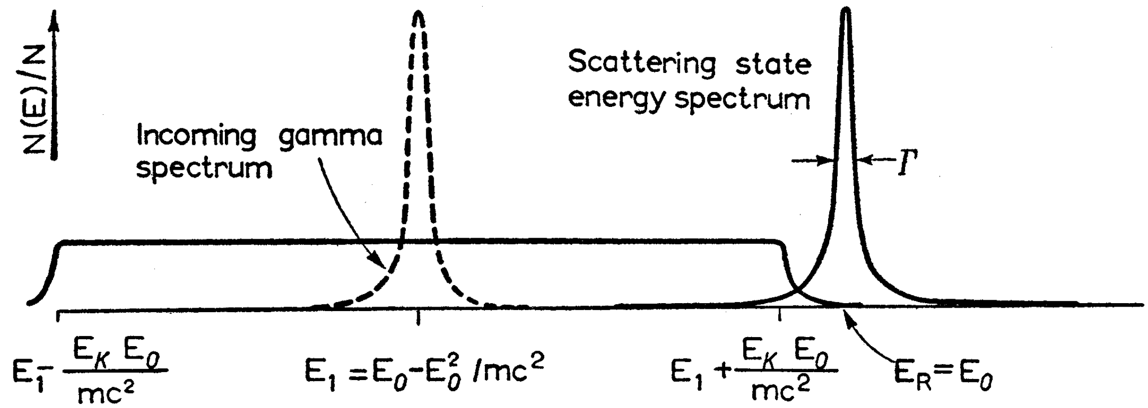

Figure 3: Schematic diagram of incoming photon spectrum and resonance level width [2].

handed photon (electron spin and photon spin in opposite directions) would be able to flip an electron spin, thus lose energy and the ability to excite a Samarium atom. In this configuration only left handed photons can pass unaffected. By reversing the magnet's polarisation only right handed photons can pass unaffected.

By counting the events in the photopeaks observed with the scintillation detector for the two different polarisations of the magnet, one can find out the photon helicity and therefore the neutrino helicity.

5 Goldhaber's experiment

The setup of Goldhaber's experiment is shown in figure 4. The ^{152m}Eu source is embedded in the magnet, that filters the photon helicity. For the photons flying down with their energy high enough to excite the Samarium scatterer, the corresponding neutrino flies up. The scintillation counter for detecting the scattered photons is located in the middle of the Samarium ring, shielded against direct radiation with a block of lead.

For N_+ denoting the counting rate in the photopeaks with the magnetic field pointing up and N_- the rate for the field pointing down, Goldhaber's team measured (after subtraction of the background)

$$\delta \equiv 2\frac{N_- - N_+}{N_- + N_+} = +0.017 \pm 0.003 \quad .$$

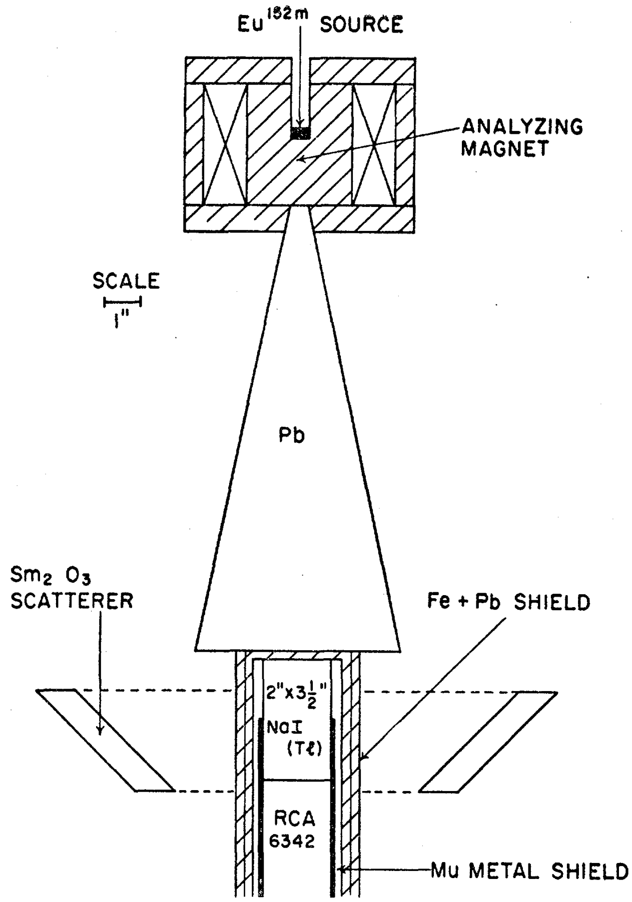

Figure 4: Setup of Goldhaber's experiment [1].

This result shows that more photons could be measured when the magnetic field pointed down, which means the electron spins in the magnet pointed up and only left handed photons were allowed to pass unaffected. The photon polarisation can then be calculated to 0.67 ± 0.15. This is in good agreement with the theoretical expected value of 0.84, which already accounts for the angle dependency of the photon polarisation but does not include thermal effects and capture of non s-electrons. Thus Goldhaber concluded the neutrino helicity must be -1, i. e. left handed (recall that photon and neutrino helicities match) within accuracy of measurement. Similar experiments for antineutrinos showed that they are right handed.

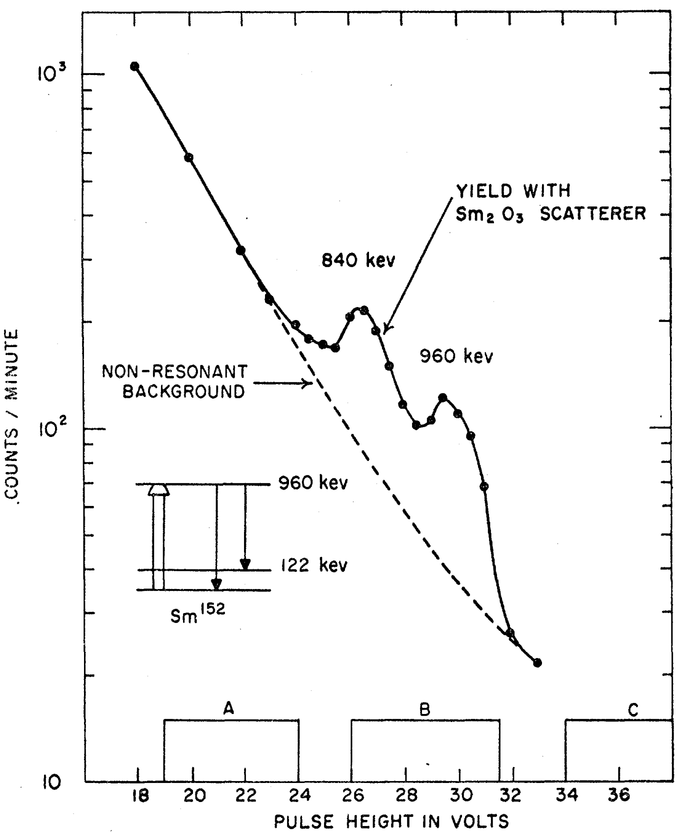

Figure 5: Resonance scattered γ rays. [1]

6 Conclusion

By taking advantage of angular momentum conservation and helicity conservation in electromagnetic processes Goldhaber found an elegant way to measure the helicity of neutrinos, which turned out to be -1. Neutrinos are still subject to experiments and only recently it was found out by a group working at the Superkamiokande detector in Japan that they are not massless [4]. But because the neutrino has a mass the helicity cannot be considered conserved anymore, as it is not well defined. Therefore it could be possible that the neutrino is its own antiparticle (Majorana particle) and the lepton number is not conserved. This is because the only distinction between neutrino and antineutrino is by means of the different helicities. But it also could be possible that it is a Dirac particle. Dirac particles have two possible helicities and a well defined lepton number; their antiparticles also have two possible helicities but opposite lepton numbers (and were applicable, opposite charge). The question is of course, if there exist right handed neutrinos and left handed antineutrinos, as the Dirac model predicts. They would be very hard to observe, because they would not be goverend by the weak interaction. The so called Heidelberg-Moskau experiment suggests the Majorana hypothesis.

References

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