HELICITY OF THE NEUTRINO
- THE GOLDHABER'S EXPERIMENT

Grzegorz Brona

THEORETICAL BACKGROUND:

In the relativistic quantum mechanics the Dirac equation is used instead of the Schrodinger equation. For a massless particle Dirac's equation can be rewritten in a form of two independent equations called Weyl's formulas:

$$\frac{\partial \Psi}{\partial t} = \pm \boldsymbol{\sigma} \cdot \frac{\partial}{\partial \mathbf{r}} \Psi \qquad (1)$$

Where $\boldsymbol{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$ and:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \qquad (2)$$

Where $\frac{\partial}{\partial \mathbf{r}} = \left(\frac{\partial}{\partial x}, \ \frac{\partial}{\partial y}, \ \frac{\partial}{\partial z} \right)$

Taking into account equations:

$$E = i\frac{\partial}{\partial t} \qquad \mathbf{p} = -i\frac{\partial}{\partial \mathbf{r}} \qquad (3)$$

equation no. 1 can be rewritten in the following form:

$$E\chi = -\boldsymbol{\sigma} \cdot \mathbf{p}\chi \qquad (4)$$

$$E\Phi = \boldsymbol{\sigma} \cdot \mathbf{p}\Phi \qquad (5)$$

Where χ and Φ are bispinors which are independent solutions of the Weyl's equations.
For a massless particle with positive energy $E = |\mathbf{p}|$ equation no. 4 can be then rewritten as follows:

$$\frac{\boldsymbol{\sigma} \cdot \mathbf{p}}{|\mathbf{p}|}\chi = -\chi \qquad (6)$$

It is thus convenient to define a new quantum operator – the helicity:

$$H = \frac{\boldsymbol{\sigma} \cdot \mathbf{p}}{|\mathbf{p}|} \qquad (7)$$

As it was shown above $H = -1$ for a massless particle with a positive energy. So for a massless particle with a negative energy it comes out of the equation no. 4, that helicity for such particle is $H = +1$. So equation no. 4 describes either left-handed (LH) particle with helicity –1, or right-handed (RH) antiparticle with helicity +1. Dealing with equation no. 5 we find out that it describes either right-handed (RH) particle or left-handed (LH) antiparticle.

Helicity can be interpreted as a spin's projection onto the particle's momentum direction. Helicity is equal +1 if the projection is in the momentum's direction. If the projection is in the opposite direction - helicity equals –1. For a massless particle helicity is conserved. So if in one reference system the helicity of a massless particle is equal –1 (+1), then in another arbitrarily chosen reference system it is also equal –1 (+1). This is because a massless particle moves always with the velocity of light.

Neutrinos are fermions with their mass equal almost zero. So in their case the helicity is conserved (or almost conserved). What is even more interesting only left-handed neutrinos (with helicity –1) and right-handed antineutrinos (with helicity +1) exist in nature.Of course the problem is much more complicated if considering massive neutrinos. The helicity of neutrinos was measured first in the Goldhaber's experiment.

THE THEORETICAL BASIS FOR THE GOLDHABER'S EXPERIMENT:

The first measurement of the neutrino helicity was done by M. Goldhaber, L. Grodzins and A.W. Sunyar in 1957. The results were published in 1958. The scientists investigated photons from the ^{152m}Eu radioactive decay. ^{152m}Eu is a radioactive element with the half lifetime of about 9.3 hours. Nucleus of this element has the spin J = 0 and odd parity. The decay is due to an orbital electron capture, mainly from the K shell. The electron on that shell has the orbital angular momentum equal zero. ^{152m}Eu decays to an excited state of ^{152}Sm* which has the spin J = 1 and odd parity. During this decay a neutrino is emitted. The reaction can be noted as follows:

$$^{152}Eu(J=0)+e^{-}\rightarrow {}^{152}Sm^{*}(J=1)+\nu_{e} \qquad (8)$$

The ^{152}Sm* nucleus is in the excited state.The energy of this state equals 960 keV. After a short period of time a transition to the ground state (E1 transition) occurs with an emission of a photon. The ground state has the spin J = 0 and even parity.

$$^{152}Sm^{*}(J=1)\rightarrow {}^{152}Sm(J=0)+\gamma \qquad (9)$$

The mean lifetime of the excited state is about (3 ± 1)*10^{-14} sec. The process is shown in Fig. 1.

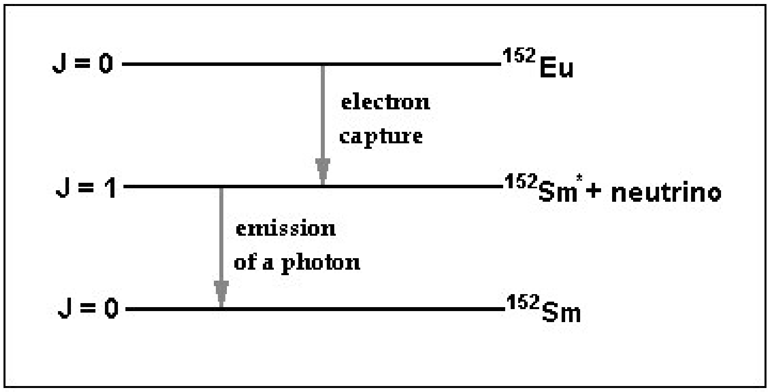

Fig.1 Radioactive decay of ^{152m}Eu

The above described processes can be used to determine the neutrino helicity. For that purpose the angular momentum conservation law should be considered.

The spin of the Europium nucleus is equal to the spin of the Samarium nucleus in the ground state and to 0. But in the excited state Samarium nucleus has the spin equal to 1. Since the captured electron spin equals ½ and its orbital angular momentum equals zero the neutrino which is emitted during the decay has to have spin opposite to the spin of the captured electron. It is then obvious that directions of the excited Samarium nucleus spin and the spin of the captured electron are the same and the direction of the emitted neutrino spin has to be opposite to them.
Due to the momentum conservation law after the decay the nucleus and the neutrino are moving in the opposite directions. The decay process is shown in fig. 2.

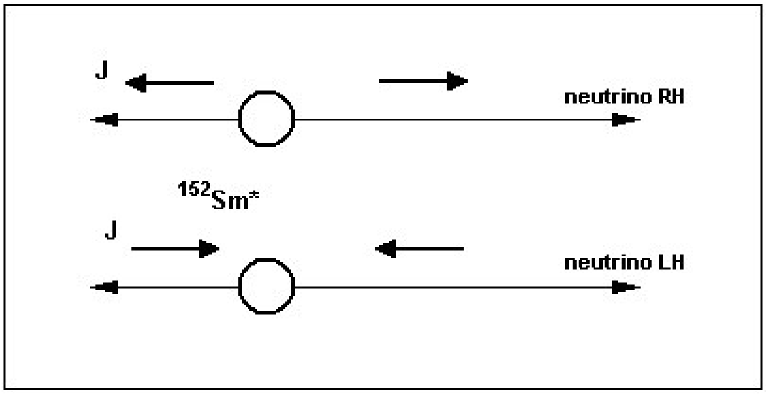

Fig.2 From ^{152m}Eu to ^{152}Sm* with the emission of neutrino

And what about photons emitted in the transition from the excited state to the ground state of the Samarium nucleus? The photons emitted in the direction of the moving nucleus have the same polarization as the neutrinos emitted before, and the photons that are emitted in the opposite direction have the opposite polarization. This is due to the conservation of the angular momentum. Before the transition the spin of the Samarium nucleus is +1 and after the transition it is 0, so the emitted photon has to have parallel spin and to be pointed in the same direction as the spin of the excited Samarium. Fig. 3 shows both possibilities with the assumption that emitted neutrino was LH.

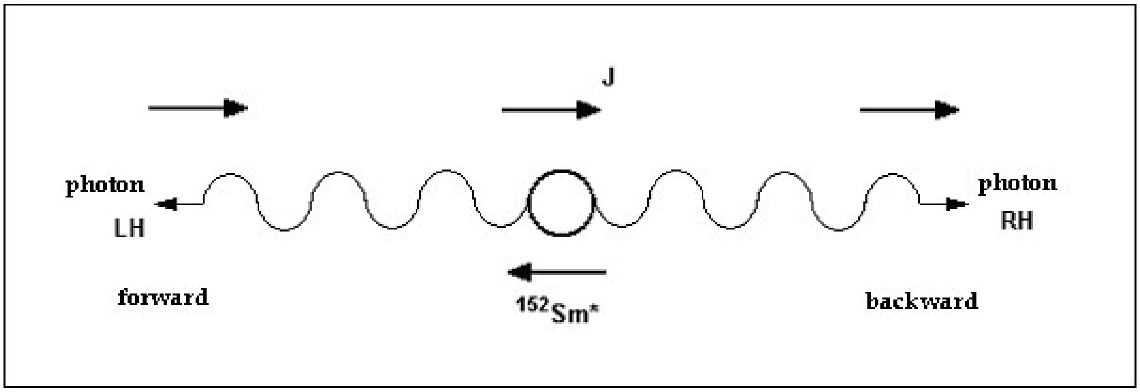

fig. 3 If neutrino is LH then the photon emitted forward is also LH and the photon emitted backward is RH. For RH neutrinos the photon emitted forward is RH, and the photon emitted backward is RH

If we could measure the polarization of photons emitted forward we would be able to determine the helicity of the neutrinos. That is because the photon emitted forward has the same helicity as the neutrino.

Now we should find a method to detect only the photons emitted in the direction of the moving nucleus. To do this resonant scattering on the scatterer made of ^{152}Sm should be used. A ^{152}Sm nucleus can absorb a photon from the decay of ^{152}Sm* into ^{152}Sm. Then after a short period of time the transition to it's ground state occurs and new photon is emitted. The reaction can be written as follows:

$$^{152}Sm + \gamma \rightarrow ^{152}Sm^{*} \rightarrow ^{152}Sm + \gamma \tag{10}$$

The photon absorbed by Samarium has to have energy slightly bigger than 960 keV. This additional energy is needed because energy and momentum conservation laws must be obeyed. In the first approximation photon emitted during nuclear decay of Europium has energy equal 960 keV. Considering the non-zero velocity of the ^{152}Sm* nucleus one can find that photons emitted in the direction of the moving nucleus have energy slightly bigger than 960 keV. And this is what we need. The scatterer can absorb and then reemit only the photons which were originally emitted forward.

Now putting an absorber between the source and the detector we can ensure that detected photons come from the scatterer and not directly from the source.

But how to measure the photons' polarization? Before photons reach the scatterer they go through the iron layer inside the electromagnet. Some of them undergo Compton scattering on the iron electrons. Two from twenty six iron electrons are polarized by the magnetic field in the electromagnet. Spins of these electrons are pointed in the opposite direction to the magnetic fields' direction. A cross section for the Compton scattering depends on spins of the photon and the electron. If the magnetic field polarizes electrons in the same direction as the polarization of the photons, more photons undergo scattering and less of them can be found in the detector. Changing the field direction we will notice increase in the number of detected photons. And this is how the scientists from Goldhaber's group measured the polarization of the photons.

THE EXPERIMENTAL SET:

The Goldhaber's experimental set is shown in fig. 4.

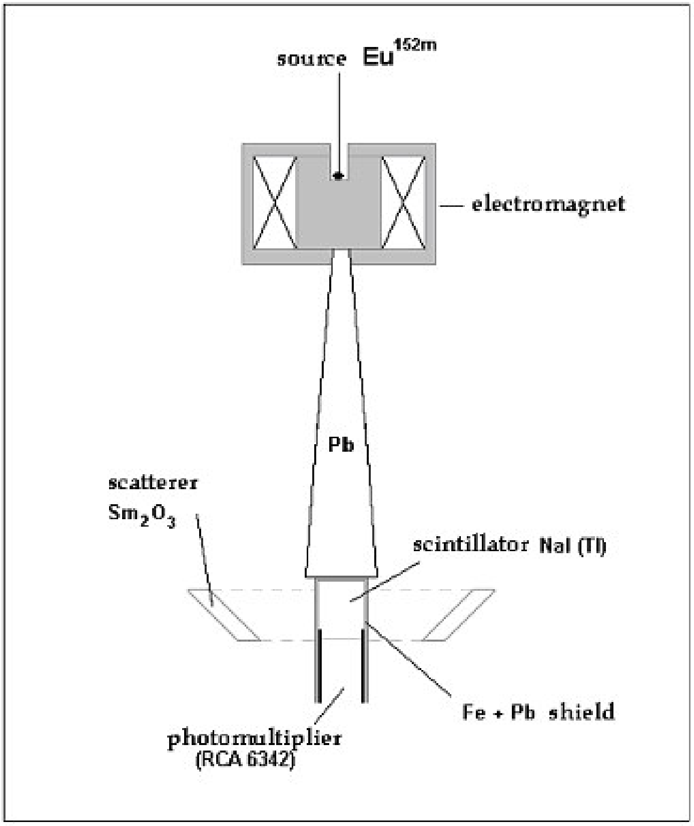

Fig 4. Experimental set

A piece of the radioactive substance (^{152}Sm) was inserted inside an iron shield which was also the core of an electromagnet. A cylindrical scintillation counter (NaI with an admixture of Thallium) measured the number of photons from the decay. The counter was connected to the photomultiplier which was shielded from the magnetic field by an iron-lead cover. There was a thick layer of the lead placed between the counter and the source. This layer isolated the counter from the photons coming directly from the radioactive source. The scatterer was made of Sm_2O_3 (26.8% ^{152}Sm).

Photons produced in the radioactive decay of ^{152}Sm passed through the iron shield of an electromagnet and then they excited the ^{152}Sm nucleons in the scatterer. The scatterer reemitted photons with energy of 960 keV. Some of the reemitted photons had the energy of 840 keV because there is a possibility of transition between the excited state of 960 keV and the excited state of energy 122 keV. Some of these photons could have been emitted in the direction of the scintillation counter. The number of detected photons should be changed when the magnetic field in the electromagnet was inverted.

THE EXPERIMENT AND ITS RESULTS:

The radioactive source of ^{152}Sm was produced by bombarding about 10 mg of Eu_2O_3 in the Brookhaven (USA) reactor. The substance produced during the experiment had radioactive intensity of about 50-100 mC. Nine experimental series were carried out. Each of them was 3 to 9 hours long. The direction of the magnetic field in the electromagnet was changed every three minutes. Before proceeding with the experiment the scientists ensured that changing the field had no influence on the photomultiplier isolated in an iron shield.
As a result of the experiment the physicists detected over $3*10^6$ photons in two maxima that corresponded to the energies of 960 keV and 840 keV.
In the six experimental series the asymmetry was found to be:

$$\boxed{\delta = \frac{(N_- - N_+)}{\frac{1}{2}(N_- + N_+)} = +0.017 \pm 0.003}$$

Where N_- denotes the counting rate with the magnetic field in the electromagnet pointing down, N_+ denotes the counting rate with the magnetic field in the electromagnet pointing up. The asymmetry was calculated after subtracting nonresonant background which had continuous distribution.
The experiment was done with the use of ^{152}Sm source in two different states – solid and dissolved.

One of the main problems in the experiment was measuring the polarization of the iron in the electromagnet. The interaction length for Compton scattering in the iron depends on its polarization. Another uncertainty came from measuring the path lengths of photons in the electromagnet iron – this uncertainty was due to the extent of the source.
Taking into account these uncertainties and assuming 100% polarization of the photons, the scientist estimated the value of δ to be ± 0.025 with an accuracy of 10%. Plus sign corresponds to the negative helicity (LH) and minus to positive one (RH). In the experiment it was found that photons were polarized in (68 ± 15)% and that their helicity was –1 (LH).

In next three experimental series a new smaller magnet was used, with the radioactive source placed at the top of it. In these series it was found that the polarization of photons was (66 ± 15)% and the helicity was still –1 (LH). So both parts of the experiment gave consistent results.

The polarization of photons in Goldhaber's experiment was less than 100%. Scientists made some theoretical corrections which covered, among others, such processes as: a thermal motion of atoms in the radioactive source, changing of the momentum of the recoiling nucleus which interacts with other atoms in the source. After these corrections the predicted polarization was equal about 70%. So the results from the experiment and the theoretical predictions were in a very good agreement.

SUMMARY:

The Goldhaber's experiment has shown that the helicity of the neutrinos is equal to:

$$\boxed{\mathbf{H = -1.0 \pm 0.3}}$$

Later on another experiment was conducted in which the helicity of the antineutrinos was measured. In that experiment scientists investigated the ^{203}Hg decay. They found that antineutrinos have the helicity opposite to the helicity of neutrinos. It is equal +1.

In 1998 the Super-Kamiokande experiment showed that neutrinos have small but non zero mass. So their helicity is not always equal –1. Maurice Goldhaber is taking part also in this experiment.

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