PROJECT OF NEUTRON BETA-DECAY A-ASYMMETRY MEASUREMENT WITH RELATIVE ACCURACY OF $(1\pm2)\times10^{-3}$

A. Serebrov, Yu. Rudnev, A. Murashkin, O. Zherebtsov,
A. Kharitonov, V. Korolev, T. Morozov, A. Fomin,
V. Pusenkov, A. Schebetov, V. Varlamov

*PNPI, St. Petersburg Nuclear Physics Institute, 188300, Gatchina, Russia*

*Corresponding author: A.P. Serebrov*

A.P. Serebrov
Petersburg Nuclear Physics Institute
Gatchina, Leningrad district
188300 Russia
Telephone: +7 81271 46001
Fax: +7 81271 30072
E-mail: serebrov@pnpi.spb.ru
Abstract

We are going to use a polarized cold neutron beam and an axial magnetic field in the shape of a bottle formed by the superconducting magnetic system. Such configuration of magnetic field allows to extract the decay electrons inside a well-defined solid angle with a high accuracy. The electrostatic cylinder with a potential of 25 kV defines the detected region of neutron decays. The protons, which come from this region will be accelerated and registered by a proton detector. The use of coincidences between electron and proton signals allows to considerably suppress the background. The final accuracy of $A$-asymmetry will be determined by the accuracy of the neutron beam polarization measurement which is at the level of $(1+2)\cdot10^{-3}$ as it was shown in the previous studies.

PACS: 28.20.-v

Keywords: Beta-decay
1. Introduction

An improved measurement of neutron $\beta$-decay $A$-asymmetry is extremely important to test the Standard Model of interaction of elementary particles. In frame of the Standard Model of $V-A$- weak interaction the probability of neutron $\beta$-decay is written in the following form:

$$W(E_e, \bar{p}_e, \bar{p}_\nu) = f(E_e)[1 + a \frac{V}{c} \cos(\bar{p}_e, \bar{p}_\nu) + A \frac{V}{c} P \cos(\bar{\sigma}, \bar{p}_\nu) + BP \cos(\bar{\sigma}, \bar{p}_\nu)],$$

where $W(E_e, \bar{p}_e, \bar{p}_\nu)$ is the probability of neutron $\beta$-decay; $E_e, \bar{p}_e$ are the energy and momentum of electron; $\bar{p}_\nu$ is the momentum of antineutrino; $v$ is the velocity of electron; $a, A, B$ are the correlation coefficients; $\bar{\sigma}$ is neutron spin; $P$ is neutron beam polarization.

The coefficient $A$ is the most sensitive to the $\lambda$-value, which is the ratio of fundamental coupling constants ($\lambda = G_A / G_V$). $A_0 = -2\lambda(\lambda + 1)/(1 + 3\lambda^2)$; $\frac{\Delta \lambda}{\lambda} = 0.25 \frac{\Delta A}{A}$. Using the precise measurement of the neutron lifetime and $A$-asymmetry it is possible to determine the $V_{ud}$ element of CKM. Fig. 1 shows analysis of unitarity of CKM from the work [1] with addition of a new result for the neutron lifetime [2]. The necessity of improved accuracy of $A$-asymmetry measurement is evident. The most precise experiment [3] gives $A_0 = -0.1189(7)$ and $\lambda = -1.2739(19)$. The required level of accuracy has to be $2 \cdot 10^{-3}$ and better to reach the comparable accuracy of $V_{ud}$ determination from neutron $\beta$-decay and from high quark generation decay.

We are going to reach the necessary level of accuracy using the new scheme of experiment for the $A$-asymmetry measurement.
2. The scheme of the proposed experiment

The neutron beam goes through a polarizer, a spin-flipper and a collimator. The geometrical size of the beam and its divergence are prepared by the precise collimation system. Then the collimated neutron beam goes through the correlation spectrometer at the $5^\circ$ with respect to axis of spectrometer. The scheme of the correlation spectrometer is shown in the Fig. 2.

The correlation spectrometer is itself a solenoid with uniform magnetic field and with magnetic plug at one of its end. Such type of magnetic system is the magnetic collimator for decay electrons. The electrons with momentum respect to axis inside the solid angle with $\theta_c$ can go through the magnetic plug field and reach the electron detector. The electrons outside this solid angle will be reflected by the magnetic field of the plug. This angle $\theta_c$ is defined by the ratio of the magnetic field in the inform part and in the magnetic plug, and it is not dependant from the energy of electron

$$\sin^2 \theta_c = H_o / H_m,$$

where $H_o$ is the magnetic field value in the point of neutron decay (uniform part), $H_m$ is the magnetic field value in the magnetic plug.

The long solenoid $L = 3320$ mm produces a magnetic field $H_o = 0.35$ T with homogeneity $\Delta H / H = 2 \cdot 10^{-3}$ inside the volume with sizes $\varnothing 210$ mm, $L=2690$ mm. The short solenoid produces a magnetic field $H_m = 0.87$ T with homogeneity $\Delta H_m / H_m = 2 \cdot 10^{-3}$ inside the volume with sizes $\varnothing 150$ mm, $L=50$ mm. For this configuration of magnetic fields $\theta_c$ is equal to 39. The adiabatic conditions for the motion of an electron have to be fulfilled in an intermediate area between two solenoids. This condition is:
\[ r \cdot \frac{|\text{grad}H|}{H} = K << 1, \quad (3) \]

where \( r \) is the Larmor radius of the electron. For our configuration of magnetic field the adiabatic coefficient \( K < 0.01 \). It guarantees a successful work of the magnetic collimator. The electron and proton detectors are installed on the axis of the magnetic system. The region of detected \( \beta \)–decay events are defined by the intersection of the neutron beam with magnetic field lines which go through the electron detector. This region is crosshatched in the Fig. 2. The size of the proton detector has to be big enough to collect all protons related to the detected electron. Fig. 3 shows the magnetic field lines and trajectories of electrons and protons around the lines. The condition of 100\% collection of proton is very important as average cosine for \( a \) and \( B \) correlation coefficients will be equal to zero in this case. Therefore we can measure the \( A \) correlation coefficient without any correction for admixture of other correlation coefficients. The averaging for all proton momentum means the averaging for all directions of antineutrino escape, therefore \( \overline{\cos(\vec{n} \cdot \vec{p}_\nu)} = 0 \) and \( \overline{\cos(\vec{p}_e, \vec{p}_\nu)} = 0 \). The signals from the electron and proton detectors have to be switched on the coincidence to fulfill this condition. Additionally the using of the coincidence regime of registration of \( \beta \)–decay events allows to considerably suppress the background and separate effect and background by means of the delayed coincidence method.

To detect the protons which have very low initial energy the decay region are placed under the high voltage potential 25 kV. When protons leave the high voltage region they are accelerated up to the energy of 25 keV and they can be registered by the proton detector. The electrostatic system of the correlation spectrometer represents a multisection cylinder with very thin nets at the ends. The sections of electrostatic system
are under different potentials from 21 kV up to 26 kV. Due to the gradient of high voltage potential the electric field appears inside the cylinder with component along the axis of the spectrometer. All protons will be accelerated in the direction of the proton detector independently from their initial momentum. This scheme of the electrostatic system allows to collect all protons and obtain a zero value average cosines of \( a \) and \( B \) correlation. The protons can be collected during the time less than 10 \( \mu \)s. It helps reduce the background of random coincidence.

The main task of experimental procedure is the measurement of the experimental asymmetry defined by the following way:

\[
X = \frac{N \uparrow - N \downarrow}{N \uparrow + N \downarrow} = A \frac{v}{c} \cos(\sigma_n, \vec{p}_e) \tag{4}
\]

where \( N \uparrow \) and \( N \downarrow \) are the counts of coincidences for different directions of neutron beam polarization.

The equation (4) shows that the relative accuracy of \( A \)-asymmetry measurements \( 10^{-3} \) can be reached when all values: the average cosine of \( A \) correlation coefficient \( \cos(\sigma_n, \vec{p}_e) \), the neutron beam polarization \( P \), the electron velocity \( \frac{v}{c} \) and the experimental asymmetry \( X \) will be measured or determined with relative accuracy better than \( 10^{-3} \).

3. Determination of average cosine of \( A \) correlation coefficient \( \overline{\cos(\sigma_n, \vec{p}_e)} \)

The accuracy of determination of average cosine \( \overline{\cos(\sigma_n, \vec{p}_e)} \) depends on the homogeneity of the magnetic fields in the decay region and in the region of the magnetic
plug. The value of average cosine is defined by the critical angle $\theta_c$ or by the ratio of the magnetic fields $\frac{H_0}{H_m}$.

$$\cos(\vec{\sigma}_n, \vec{p}_e) = \frac{1 + \cos \theta_c}{2} = \frac{1 + \sqrt{1 - H_0 / H_m}}{2}$$

(5)

The accuracy of determination of average cosine can be calculated from the following equation:

$$\frac{d\cos \theta_{\sigma}}{\cos \theta_{\sigma}} = \frac{H_0 / H_m}{\sqrt{2} \cdot \sqrt{1 - H_0 / H_m} \cdot (1 + \sqrt{1 - H_0 / H_m})} \cdot \frac{\Delta H}{H}$$

(6)

where $\Delta H / H \approx \Delta H_0 / H_0 \approx \Delta H_m / H_m$.

For $\frac{H_0}{H_m} = 0.4$ and $\frac{\Delta H}{H} \approx 2 \cdot 10^{-3}$ we have:

$$\frac{d\cos(\vec{\sigma}_n, \vec{p}_e)}{\cos(\vec{\sigma}_n, \vec{p}_e)} = 1.3 \cdot 10^{-4}$$

(7)

Thus the average cosine of the $A$ correlation coefficient can be determined with a very high accuracy. It can be reached by the magnetic collimation method, which is independent from the position of neutron $\beta$–decay.

It should be mentioned that we have to take into account the small correction for calculation of average cosine which arises due to impressed electric field into decay region. The value of this correction is very small $3 \cdot 10^{-3}$ for the electron energy of 100 keV, $4 \cdot 10^{-4}$ for the electron energy of 400 keV and $1.5 \cdot 10^{-4}$ for the electron energy of 700 keV. This correction can be calculated with the accuracy better than 10%, therefore the final accuracy of the average cosine determination will be at the level of $2 \cdot 10^{-4}$.
4. Detectors of electrons and protons. Determination of $\nu/c$ value

The detector of electrons will have the size of $55 \times 160 \text{ mm}^2$. We assume to use $Si(Li)$ – detector for registration of electrons. This detector will be divided in 16 individual sections. Prelviously we realized the test of $Si(Li)$ – detector with a diameter of 70 mm and a thickness of 3.5 mm to measure backscattering effect of electrons from $Si$. The magnetic $\beta$-spectrometer was used for this purpose. It allows us to suppress background of $\gamma$–rays from the source of the conversion electrons $^{207}\text{Bi}$. The divergence of electron beam was about $30^\circ$. Fig. 4 shows the spectrum of $Si$ -detector, the energy line 976 keV with the energy resolution $\pm 3$ keV.

To reduce background we additionally carried out the measurements with shutter of electron beam and without it. The difference between two spectra is shown in Fig. 4. Thanks to these measurements we can distinguish the tail of the energy line 976 keV with total square 12%. In our measurement with a correlation spectrometer the effect of electron backscattering will be even more suppressed because the backscattered electrons will be reflected again from the magnetic plug with probability about 80%. The part of backscattered electrons, which goes through the magnetic plug, will be registered by the proton detector. This part will be about 2.5% only. We can reject these events due to a signal of prompt coincidence from both detectors. Therefore the energy resolution of the electron detector could be high enough. The energy calibration of this detector can be done by means of a set of conversion sources.

As far as correction of average cosine because of rejection of 2.5% of events is concerned we assume that it will be very small correction due to a high value of cosine
in our spectrometer and its weak dependence. More detailed calculations of this effect will be done by means of Monte Carlo simulations of this process.

The detector of proton will have the size of 75×200 mm$^2$, i.e. by 20 mm broader and by 40 mm higher than the spot of the event coinciding with the electron detector. It has to be done for 100% collection of protons. The proton detector will have 16 sections as well as the electron detector. It will help us to suppress the background of random coincidences and it is necessary in any case to reduce the electric capacity of detector. We are going to use the surface barrier detector from the pure silicon. The first test experiment with proton gun and the proton detector (PIN diode) was done. Fig. 5 shows the proton signal with resolution about 3÷5 keV. As the possible alternative version of proton detector we are considering the usage of microchannel plates.

5. Precise collimation of neutron beam

The task of the precise collimation of neutron beam is very important for our experimental scheme because of beam pass near detectors. In case of halo around the neutron beam we can have a problem with the detector background. The halo could appear due to a small angle scattering of neutrons on the collimator material.

The most appropriate collimator material is $^6\text{Li}$, which does not produce practically the $\gamma$-rays after the neutron capture. The $^6\text{Li}$ because its chemical activity is used in form of $^6\text{LiF}$ with some ingredients to reduce the brittleness of $\text{LiF}$-ceramics. The small angle scattering effect from this material was specially studied to obtain initial data for the design of precise collimator.
The experiment has been carried out at the PNPI reflectometer of WWR-M reactor. Using the obtained data of the small angle scattering process the multi-diaphragm collimator has been designed. Fig. 6 shows the calculated distribution of neutron intensity at the distance of 4 m from the collimator. It can be seen that the suppression factor of intensity reaches eight orders of magnitude at the distance of 2-3 cm from the edge of the beam. This result should be checked experimentally to be sure that satisfactory background conditions can be reached.

6. The measurements of neutron beam polarization with the accuracy (1+2)·10^{-3}

The possibility of precise measurements of neutron beam polarization have been studied in our detailed experiments [4,5]. The scheme of proposed method consists from two analyzers and two double flippers. It is shown in Fig. 7.

The given scheme allows to determine the polarization of beam and the analyzing power of system from two analyzers in the case when the spinflip processes in interaction of neutrons and analyzers have not taken place.

Then the neutron polarization and analyzing power is defined by the following equations:

\[
P = \frac{1}{f_i A} \frac{(1 - R_{10})}{(1 + f^{-1}_i R_{10})}, \tag{8}
\]

\[
A = \left[ \frac{1 + \frac{(R_{01} + f^{-1}_i R_{11})}{f_i (1 + f^{-1}_i R_{10})}}{1 + \frac{(R_{01} - R_{11})}{f_2 (1 - R_{10})}} \right] \times \left[ \frac{1 - \frac{(R_{01} + f^{-1}_i R_{11})}{(1 + f^{-1}_i R_{10})}}{1 - \frac{(R_{01} - R_{11})}{(1 - R_{10})}} \right]^{1/2}, \tag{9}
\]

where \( R_{10}, R_{01}, R_{11} \) are the flipper ratios of the detector counting rates.
The first low symbol shows the state of flipper installed in front of the analyzing system, the second low symbol shows the state of flipper inside the analyzing system.

To measure the flipper efficiency the auxiliary flippers are used in both places. Such scheme of double flippers allows to measure the flipper efficiency by means of the following equations:

\[
R_{10} = \frac{N_{10}}{N_{00}}, \quad R_{01} = \frac{N_{01}}{N_{00}}, \quad R_{11} = \frac{N_{11}}{N_{00}},
\]

(10)

where the upper symbols correspond to auxiliary flippers.

The above-described scheme was realized using the multi-slit supermirror assembles. The probability of spin-flip processes inside the analyzers is about $10^{-3}$ or less. It gives small correction to the measured polarization:

\[
P = P_m (1 + 2B)
\]

(12)

where $P$ - is real polarization, $P_m$ - is the measured polarization, $B$ is the probability of a spin-flip. The main reason of the imperfection of analyzers is the non-parallelism between the magnetic field and the surface of magnetic film. The estimation of the correction $B$ can be done by means of rotation of analyzing system to replace the first and the second analyzer and repeat the measurements [4]. The comparison of the two analyzers and two flippers method with the method of $^3$He filter was done in our work [5]. It was shown that the correction for supermirror method is 0.152(18)%. Thus usage of the mentioned methods of neutron beam polarization can give measurements accuracy of $10^{-3}$ and better.
7. Experiment simulation

For the detailed analysis of the processes of the neutron $\beta$-decay event detection the mathematical model of the spectrometer was developed. This model allows to calculate magnetic and electric fields in the spectrometer, and trajectories of electrons and protons in the magnetic and electric fields. As a result, the simulation of the experiment is possible. Fig. 8a,b shows the time dependence of the coincident signal between the electron and proton detectors for different neutron polarization and for different energy of electrons. Fig. 9a,b shows the experimental asymmetry normalized to the neutron polarization as function of the electron energy and $A$-asymmetry coefficient as well. The detailed calculations taking into account the backscattering effects are in progress.

8. Statistical accuracy of the experiment

The statistical accuracy of the experimental asymmetry $X$ is defined by the following equation:

$$\Delta X = \frac{2N \uparrow N \downarrow}{(N \uparrow + N \downarrow)^2} \sqrt{\frac{1}{N \uparrow} + \frac{1}{N \downarrow}}$$

$$A$$-correlation coefficient is about 0.1, $N \downarrow \approx N \uparrow \approx N/2$, where $N$ – is the total number of registered events. In this case $\Delta X \approx \frac{1}{\sqrt{N}}$ and therefore $10^8$ events have to be registered to obtain the accuracy $\Delta X = 10^{-4}$.

The neutron flux density ($\Phi$) at the exit of the polarized cold neutron beam of PSI fundamental facilities “Funspin” is about $2 \cdot 10^8$ cm$^{-2}$s$^{-1}$. The neutron flux density af-
ter the collimator will be one order of magnitude less ($\Phi_c = 0.15 \cdot 10^8 \text{ cm}^2\text{s}^{-1}$). The average neutron density ($\rho$) is about $1.5 \cdot 10^2 \text{ cm}^{-3}$. The number of neutron in the decay region of the spectrometer:

$$N_{sp} = \rho \cdot L \cdot S \approx 9.5 \cdot 10^5,$$

(14)

where $L = 1.4 \cdot 10^2 \text{ cm}$ – is the length of the decay region, $S = 3.5 \times 13 \text{ cm}^2$ – is the exit cross section of the collimator. The number of neutron $\beta$-decays in the decay region is:

$$N_{\text{decay}} = N_{sp} / \tau_n = 1.08 \cdot 10^3 \text{ s}^{-1}$$

(15)

The solid angle of the capture of electrons by the spectrometer magnetic system

$$\Omega / 4\pi = (1 - \sqrt{1 - x}) / 2 = 0.11.$$ The counting rate of neutron $\beta$-decay event (coincidence) taking into account the registration efficiency of the electron and proton detectors $\varepsilon_e \approx 0.9$, $\varepsilon_p \approx 0.9$ is:

$$N_{\text{coincidence}} = N_{\text{decay}} \cdot \omega \cdot \varepsilon_e = 110 \text{ s}^{-1}$$

(16)

Therefore $10^8$ events will be collected during two weeks. In this estimation it was assumed that the background of the random coincidence is considerably less than the signal.

9. Background of random coincidence

The estimation of the background of the random coincidence can be done using the background counting rate of the electron and proton detectors in the similar experiments [6,7]. The background counting rates for the electron and proton detectors could be at the level of $10^2 \div 10^3 \text{ s}^{-1}$. It should be taken into account that electrons and protons
reflected from the magnetic plug will produce the background counting rate of proton
detector on the level $10^3 \text{ s}^{-1}$. The background of the random coincidence with resolution
time $10 \mu s$ could be about:

$$n_{\text{backg}} = 2n_{\text{r.backg}} n_{\text{p.backg}} = (2\pm20) \text{ s}^{-1} \quad (17)$$

When the background is less than the effect the increase of the measurement time is not
considerable. However, we can suppress background of the random coincidence using
the condition that the real coincidence has to occur in the detector points connected by
the same magnetic line. Therefore the sectioning of detectors will help to suppress the
background of random coincidence. In the best case when radius of the particle orbits is
much less than the size of a section, the factor of the background suppression could be
equal to the number of sections. In our case we can expect to have a suppression factor
of about 3 only.

In order to obtain the exact answer concerning the background conditions the test
experiment with the collimated neutron beam and the electron and proton detectors is
required.

10. Conclusion

The above-mentioned consideration shows that the proposed experiment could
reach the accuracy of $A$-asymmetry measurement at the level of $(1\pm2) \cdot 10^{-3}$. As the first
step of the realization of the experiment test measurements of background should be car-
ried out.

Additionally, it should be mentioned that this spectrometer allows to measure $B$
and $a$ correlation coefficients as well. To do that, it is necessary to switch off the accel-
erating electric field in the spectrometer and to measure the longitudinal proton momentum by means of the time-of-flight method. Another way is to use the electrostatic spectrometer in front of the proton detector.
References

Fig. 1. $|V_{ud}|$ versus $G_A / G_V$. $|V_{ud}|$ was derived from higher quark generation decays via

$$|V_{ud}| = \sqrt{1 - |V_{us}|^2 - |V_{ub}|^2}$$

predicted from unitarity, from $Ft$ value of nuclear-decays, and neutron $\beta$-decay.

Fig. 2. Scheme of correlation spectrometer.

Fig. 3. Magnetic field and trajectories of electrons and protons. (Scales for y and z directions are different by the factor of 30).

Fig. 4. Spectrum of $Si(Li)$-detector for conversion source $^{207}Bi$ obtained by means of magnetic spectrometer $\pi\sqrt{2}$.

Fig. 5. Spectrum of the proton detector obtained by means of proton gun ($V = 25$ kV).

Fig. 6. The calculated distribution of neutron beam at the distance $4m$ from collimator.

Fig. 7. Scheme of the method for the precise measurement of neutron beam polarization. $P$ – polarizer, $F_1, F_1', F_2, F_2'$ - flippers, $A_1, A_2$ - analyzers, $Ch$ - chopper of neutron beam, $D$ - detector.

Fig. 8. The calculated time dependence of coincidences for various electron energies.
Fig. 9. 

a) the calculated $X$ – asymmetry normalized to the neutron polarization; 

b) the calculated $A$ – asymmetry for different energy.
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 5.
Fig. 6.
Fig. 7.
Fig. 8.
Fig. 9.